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Ergonomic Study of VDT Workstations for Wheelchair Users

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Abstract: This study presents a three-dimensional computer-modelling system based on Transom JACK software, with 3D objects/equipment and human subjects with specific anthropometric measurements to visualize and evaluate human-machine interaction. A computer simulation method is then adopted to evaluate some VDT (Visual Display Terminal) workstations to determine whether they are appropriate for use by wheelchair users. The study indicates that currently available commercial computer desks present difficulties, in terms of both spatial design and reachability of peripheral devices, to wheelchair users. Some VDT tasks result in awkward body postures in virtual subjects. New VDT workstations are designed and recommended to solve the shortcomings found.

Keywords: VDT; wheelchair users; computer simulation; JACK; postural analysis.

1. Introduction

Wheelchair users generally have to perform daily and professional activities exclusively in their wheelchairs. Therefore, wheelchair users should be considered as integral with their chairs [1]. Visual display terminal (VDT) tasks are becoming increasingly common in modern workplaces, and, due to their work characteristics, they are often performed by wheelchair users. However, interaction between the operators (with the chair) and workstation components is an important issue when VDT tasks are operated by wheelchair users. The potential worker who cannot ‘fit’ into the workstation is significantly disadvantaged in workplaces in terms of employability, decreased productivity and increased risk of injury [2]. Ashworth et al. [3] considered the extent to which older and disabled people are being ‘designed out’ of workplaces. The suitability of existing VDT workstation designs and the appropriate or best design for wheelchair users are interesting topics for study.

VDT workstations have been extensively studied recently, with most studies focusing on occupational hazards such as perceived fatigue, visual discomfort and musculoskeletal stresses for normal VDT operators (e.g., [4-10]). Ergonomics issues for the physically challenged individuals, e.g., wheelchair users, have also been studied, as have anthropometric measurements for wheelchair users [1-2, 11-14]. However, the interaction between wheelchair users and specific workstations has not often been considered. Feeney [15] conducted a survey on the reach capabilities of disabled people, and studied the design of automatic teller machines (ATMs). Tilley [16] demonstrated the anthropometric require-

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ments of facilities such as lavatories, drinking fountains, urinals, toilets and telephone booths for wheelchair users.

Wheelchair users can perform VDT tasks, as recommended by Taiwanese governmental authorities and private enterprises. Many training courses for skills in operating computers and software applications, as well as specific assistant devices to help physically challenged individuals operate computers, have been designed and developed [17]. However, VDT workstations for wheelchair users have rarely been systematically studied in Taiwan.

Products and facilities, e.g., VDT workstations, must be tested by operators at the final stage of design and manufacture. Inadequate design may reduce work efficiency, increase human error and lead to awkward postures, resulting in poor productivity and reliability, and musculoskeletal disorders. However, ergonomics information about users cannot easily be incorporated into the design processes of workplaces and products, since it is often poorly presented and evaluated [18]. Conventional methods of evaluating human-machine compatibility involve the use of flat cardboard manikins and layout drawings, or constructing a prototype or physical mockup with evaluation by live subjects [18-19]. With the rapid development of information technology, computer-aided ergonomics offers the assistance in the creation, modification, presentation and analysis of design [18, 20]. The design can be modified at an early stage once problems are identified. The development of three-dimensional computer-modelling systems to construct 3D objects/equipment and human models with specific anthropometric measurements, and to evaluate the human-machine interaction, has been frequently studied in the literature [15, 18-21].

This study presents a novel simulation system to evaluate the effectiveness of VDT workstations. The objects used with 3D graph forms included presently available, widely-used models of personal computers, peripheral equipment, and wheelchairs. The study focuses on how wheelchair users perform their work. The adequacy, as well as the advantages and disadvantages of currently available workstations, are investigated with computer simulation. Moreover, the design and evaluation of new models of VDT workstations is explored, in the hope of providing a reference for designing and selecting workstations for wheelchair users.

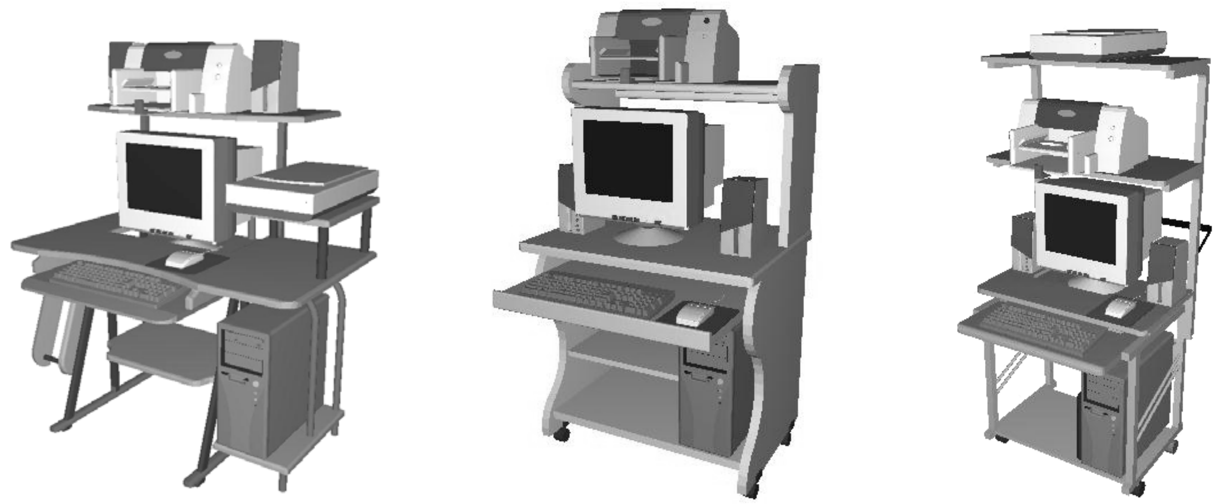
2. Materials and methods

2.1. Construction of a VDT computer simulation system

This study used the Transom JACK, which has a module called AutoCAD translator and was developed by the Ergonomics Research Center of University of Pennsylvania [22], to build an environment for VDT workstation simulation. A human model can be placed in three-dimensional images within a large variety of worksites and equipment to simulate the activities of the workers. Some ergonomic issues in the literature, such as the design of a space station and workstations in a bus assembly plant [23-24], and activities of manual materials handling [25-26], were studied with JACK.

Specification information about currently available and widely-used models of personal computers (PCs) and peripheral equipment such as CPU system units, monitors, color printers, scanners and desks was first collected and summarized from some large PC supermarkets in Taiwan. Discussions and comparisons were then made to select some kinds of PC components according to their specification differences in order to build three different VDT workstation environments.

The desktop PC components and three commercial desks selected were all built as three-dimensional graphs using AutoCAD 2000. The major dimensions and models of desktop PC components used in the study were shown in Table 1. The PC components were then arranged to build three VDT workstations due to the dimensional constraints of PC components and desks selected. Figure 1 shows the three VDT workstation setups, and Table 2 lists their major dimensions. The ergonomic features to access, reach and posture were demonstrated for these three simulated environments.



(a) WS I (b) WS II (c) WS III

Figure 1. Configuration of three VDT workstations arranged by commercial desks

Table 1. The dimensions and models of PC components applied in the study

Components	Models	Specifications (cm) (total breadth×total depth×total height)
Monitor	View Sonic 17”	40.5×41.0×42
PC case	5.25” drive bays: 3 3.5” drive bays: 3	19×43×43
Color printer	HP Deskjet 640c	43.6×40.5×20
Scanner	Micro Tek	28×48×9
Keyboard	Standard 104	45×18×4
Mouse	LogiTech	6×12×3
Speakers	AS-480	10×14×25

Table 2. Major dimensions of the three commercial desks studied (in mm)

	WS* I	WS II	WS III
Total height	1175	1300	1600
Total breadth	1080	800	660
Total depth	600	600	450
Desk height	740	800	745
Surface height for keyboard	640	680	670
Surface height for monitor	680	800	720

*WS: workstation

2.2. Virtual subjects and wheelchairs

Two virtual wheelchair users were created for simulated VDT tasks within the JACK environment; these were a 95th percentile (i.e., 95%ile) male, named Jack, and a 5th percentile (5%ile) female, Jill. Table 3 shows the local anthropometric data adopted from Wang et. al [27] in the study and used as input to JACK.

Table 3. Anthropometric characteristics obtained from a Taiwanese Database (Wang et al. [27], 1999) (in mm)

Measurement	5%ile female	95%ile male
stature	1482.26	1778.92
weight	42.02*	81.51*
shoulder breadth	286.23	412.79
Sitting height	798.65	952.72
Elbow height for sitting posture	216.43	302.20
Shoulder height for sitting posture	521.17	641.93
Eye height for sitting posture	685.93	834.03
Knee height for sitting posture	430.77	560.49

*: the unit is kg

The wheelchair specifications needed for this study were obtained from Chinese National Standards (CNS) and some professional wheelchair stores in Taiwan. Comparisons for the wheelchair dimensions were made, and then two kinds of wheelchairs (large- and small-scale) were chosen in the study. To simulate the extreme conditions and meet the real situations, the 95%ile male subject was assigned to sit on large-scale wheelchair and the 5%ile female sat on the small wheelchair while VDT simulation tasks were performed in this study. The major dimensions of large- and small-scale wheelchairs used are shown in Fig. 2 and Table 4.

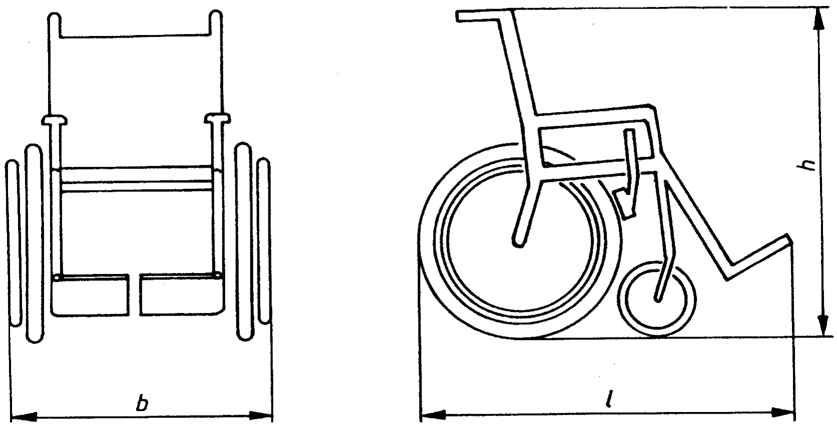


Figure 2. Draft of a wheelchair

Table 4. Major dimensions of the two wheelchairs used (in mm)

Measurement	Large-scale*	Small-scale
Total length (*l*, in Fig. 2)	1200	1010
Total height (*h*, in Fig. 2)	1090	910
Total breadth (*b*, in Fig. 2)	700	630
Seat height	500	480
Seat breadth	500	430
Armrest height	775	710

*: obtained from Chinese National Standard

2.3. Computer simulation

After a VDT computer simulation system was constructed and virtual subjects/wheelchairs were established, as described above, JACK functions were then executed in the system. The basic activities performed by the virtual subjects included detecting collision with computer desks, operation with keyboard and mouse, and turning devices such as CPU system units, monitors and printers on and off. The major parameters such as access, reach and posture were observed in the JACK environment. Moreover, the angles of virtual subjects' right shoulder and lumbar joints were obtained to study the postural risks.

A real VDT workstation was constructed in the laboratory as the same as Workstation I environment, shown in Fig. 1, to validate the simulation results. A female subject of 5th percentile stature in Taiwan (stature and weight of 148 cm and 45 kg, respectively) was recruited and sat on the small-scale wheelchair with the dimensions shown in Table 4. The female subject was asked to perform the same activities as those shown in simulation system, and the behavior differences between the JACK system and lab facility were then observed.

The Rapid Upper Limb Assessment (RULA) tool in JACK was used to evaluate the exposure of virtual subjects to the postural risk of upper limb disorders for both commercial and new designed workstations. The RULA method, developed by McAtamney and Corlett [28], is a validated tool that assesses postural and biomechanical loading on the upper limbs. The RULA scoring system generates the action level that indicates the degree of intervention needed to reduce the risk of injury. The grand score of 1 or 2 denotes an acceptable human-computer level and there is no action required. The score of 3 or 4 presents slightly harmful posture and action is required in the near future. The score of 5 or 6 shows distinctly harmful posture and action is required as soon as possible. For a grand score of 7, the posture is at a completely unacceptable level, indicating the need to make immediate improvements. The new designed workstations in the study were then modified to reduce the postural risks based on the RULA results.

2.4. Design of VDT workstations

New VDT workstations were designed and then simulated in JACK environment to solve the shortcomings that were discovered in the above simulation with commercial desks. The new design is intended to fit the workspace to wheelchair users, considering their restricted working space and the difficulty in movement while sitting. The main objective of this study was to consider the dimensions of new designed workstations and functional operations, but not the structural issue of workstations. Major guidelines for the design of new computer desks were introduced in the following.

The desk surface and monitor pedestal were designed to be split and height-adjustable to meet different anthropometric requirements, and to keep proper neutral seated postures for VDT operators. The computer keyboard should be on a surface that is about seated elbow high or slightly above, and lower than the desk surface. Hence, the height of the keyboard tray, which was attached 9cm beneath the desk, was recommended to be in the range 67−77cm, based on the seated elbow heights of the local 95th percentile male and 5th percentile female, which as shown in Table 3 were about 30cm and 22cm, respectively, and the seat heights of large- and small-scale wheelchairs, which were 50cm and 48cm, respectively, as shown in Table 4.

The total height of keyboard was assumed to be 3cm which is a normal dimension observed in the matket. Therefore, the adjustable height of desk surface ranged between 76cm and 86cm. The mouse was placed on the same surface adjacent to keyboard. The breadth of the keyboard tray was recommended to be 70cm, since the room for the keyboard (about 45cm breadth), mouse (about 6cm breadth) and operational area should be considered together. Moreover, the depth of keyboard tray was set to 25cm, so that the keyboard tray would not keep the operator too far away when it was pulled out to perform VDT tasks.

As mentioned previously, monitor pedestal was recommended to be height-adjustable and split from the desk surface. The height of the monitor pedestal was designed between 64cm and 110cm. This range was determined as follows. The monitor is often recommended to be located below the eye level between 15^0 and 25^0 [29-30]. This study used a viewing distance of 45-60cm, as recommended by the government unit in Taiwan [30]. The minimum height of the monitor pedestal is 64cm, which equals 68.6cm (i.e., eye height for 5%ile female shown in Table 3) plus 48cm (seat height for small-scale wheelchair) minus 25.4cm (calculated from the viewing distance, 60cm, and the line-of-sight angle, 25°) minus 27cm (the distance from the center to the bottom of the monitor screen). The maximum height, 110cm, was determined from 83.4cm (eye height for 95%ile male) plus 50cm (seat height for large-scale wheelchair) minus 27cm (the distance from center to bottom of monitor screen). Some wheelchair users with spinal cord injury were observed to look upwards occasionally while sitting. Therefore, the third term, for the minimum height, was omitted here to extend the adjustable height range for the monitor pedestal.

Moreover, the monitor tilt angle is generally recommended to be adjustable, and ranging between 0^0 and 30^0. The neck angle was found to be smaller when the tilt angle of the monitor was within this range according to the simulation results of this study. The function of the adjustable tilt angle may provide a means to meet ergonomic demands for the users with different statures. The breadth and depth of monitor pedestal were recommended to be 50cm for a 17-inch CRT monitor, as adopted herein this study.

The printer and scanner were designed to be located at the right side of the monitor, and the trays for each can be moved forward and backward. They became closer and easier to the users for operation as they were moved out by the sliding rails. The breadth and depth of the trays for the scanner were designed to be 40cm and 65cm, respectively. The height of scanner tray was 3cm higher than the desk surface, and its total height (relative to the ground) could be changed while the desk surface height was adjusted. The height of 3cm mentioned above comprised the thickness of scanner tray and the operation space. The height of the printer tray was designed to be 15cm above the scanner tray, which included the total height of the scanner and some space for operation. The depth of the printer tray was 15cm less than the scanner tray depth so that the users can be easier to use the scanner.

The CPU system unit was placed at a surface that 53cm below the desk surface. The thickness of the desk was assumed to be 3cm. The total height of CPU system unit was about 50cm, and power switch is generally placed at some height above the bottom of the unit. Therefore, the positioning of the CPU system unit can still meet the requirement that the minimum low reach for wheelchair users be 38cm [16].

3. Results

3.1. Accessibility and reachability

Table 5 shows the accessibility and reachability for two virtual subjects performing in sitting posture at three different workstations. The 5%ile female easily accessed Workstation I (i.e., WS I). However, the 95%ile male subject's knees would hit the keyboard tray, since the surface height for keyboard was lower, so that the subject had difficulties to access the operational area. For Workstations II (WS II) and III (WS III), both virtual subjects were incapable of entering the operational area, since the footstep of Jill's wheelchair and Jack's foot would hit the bottom of the desk. Turning devices on and off indicated that both subjects could reach all the switch positions of the CPU system unit and the printer except for the 5%ile female to operate the printer on Workstations II and III. Moreover, the operations for the monitor switch and the mouse were all reachable, and two-thirds of the operations were easy to perform with subjects' erect back in sitting posture. The keyboard for all three VDT workstations was also found to be easy to use without the subjects' trunk bent forward. Figure 3 shows some examples of simulation.

Figure 4 shows that the observations of their activities yielded similar conclusions from the viewpoint of postures, suggesting that the use of simulation technique may be a valid tool for evaluating proposed VDT workplace designs.

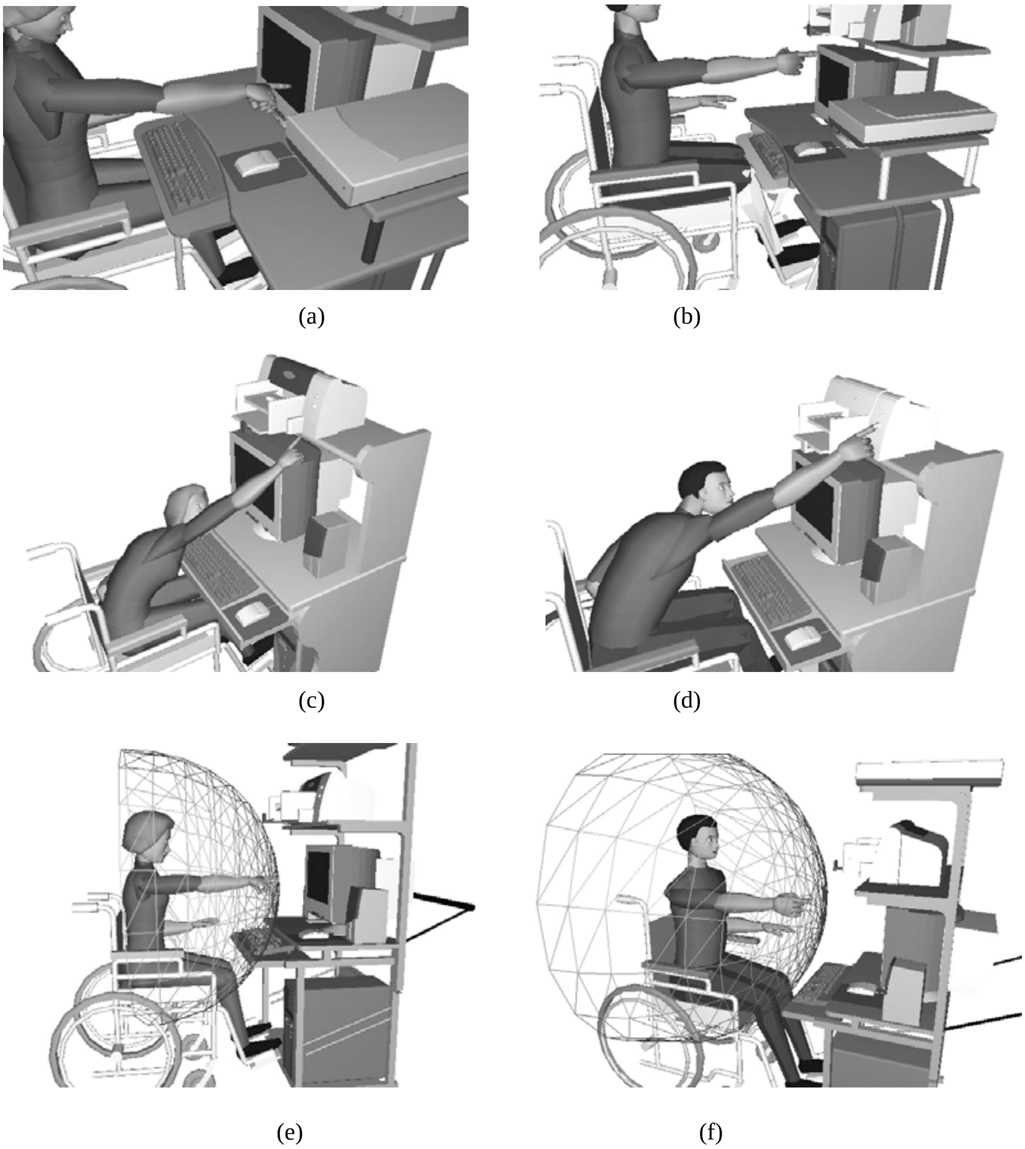
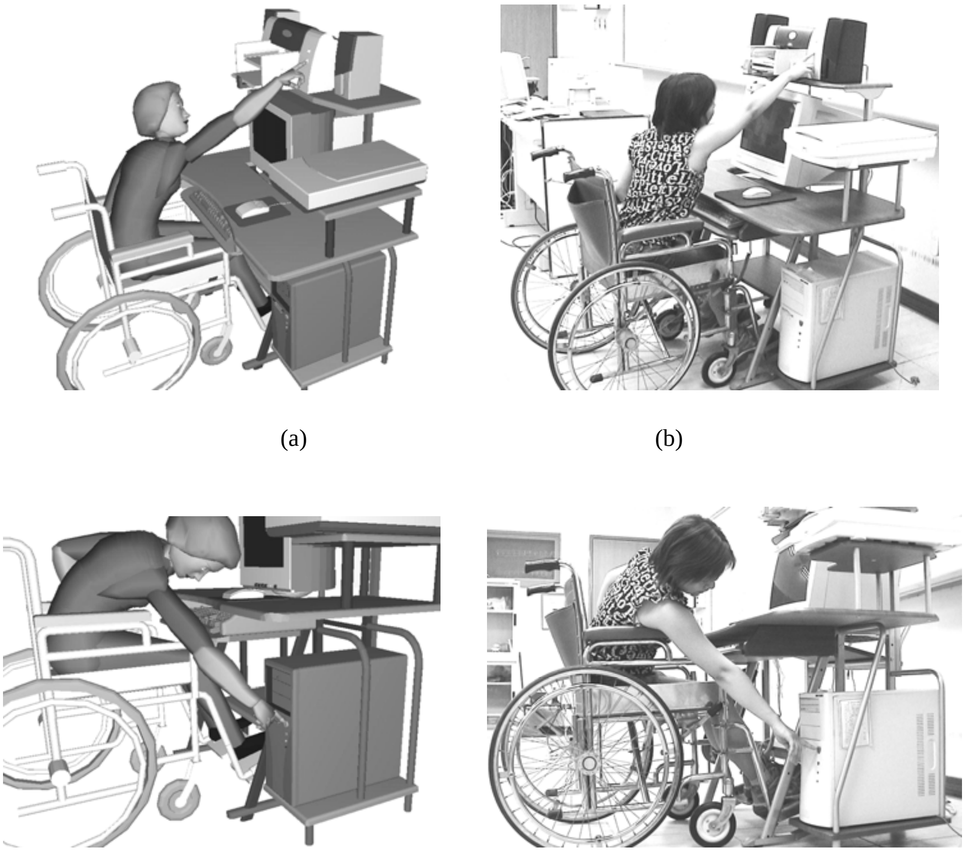


Figure 3. Some simulation examples: (a) 5%ile female in WS I (easy to access desk); (b) 95%ile male in WS I (hitting the keyboard tray); (c) 5%ile female in WS II (hard to operate the printer); (d) 95%ile male in WS II (reachable to the printer), and (e) and (f) the reach envelope of 5%ile and 95%ile subjects with normal upright posture in WS III, respectively.



(a) (b) (c) (d)

Figure 4. Comparison of simulation system and lab setup for WS I: (a) and (b) reach of printer, (c) and (d) turning the CPU system unit on and off

Table 5. Accessibility and reachability of subjects operating at three workstations

Workstation elements	WS I		WS II		WS III	
	95%ile male	5%ile female	95%ile male	5%ile female	95%ile male	5%ile female
Desk*	×	○	×	×	×	×
CPU system unit	⊖	⊖	⊖	⊖	⊖	⊖
Printer	⊖	⊖	⊖	×	⊖	×
Monitor	○	○	○	○	⊖	⊖
Mouse	○	○	○	○	⊖	⊖
Keyboard	○	○	○	○	○	○

*: easy to access to VDT workstation (i.e. without desk-hitting)
○: easy to reach (i.e., performing with erect back in sitting posture)
⊖: reachable
×: incapable of reach

3.2. Comparison of shoulder and lumbar joint angles

Table 6 shows the angles of subjects' right shoulder and lumbar joints when the subjects performed VDT tasks at three different workstations. The positive (negative) directions (x, y, z) of right shoulder joint coordination system in Table 6 denote abduction (adduction), flexion (extension) and medial rotation (lateral rotation), respectively. For lumbar joints, the positive (negative) directions (x, y, z) denote right bending (left bending), flexion (extension) and right rotation (left rotation), respectively.

The right shoulder and lumbar joints for the operations in Table 6 indicated larger flexion (i.e., y-direction) in Workstation III than in the Workstations I and II, for both male and female subjects. The main reason was that Workstation III had very little access to the desk, and the locations of some PC components were far away from the subjects, which are shown in Table 5. For turning the printer on and off, larger flexion angles of the right shoulder and lumbar joints were also encountered in Workstation II, since the female subject was incapable of reaching the printer and the male needed to flex forcefully to operate. The female's right shoulder and lumbar angle values for the keyboard operation were found to be small at all workstations, since the surface heights of the keyboard tray (64, 68, and 67 cm, respectively, in Table 2) were appropriate for the 5%ile female.

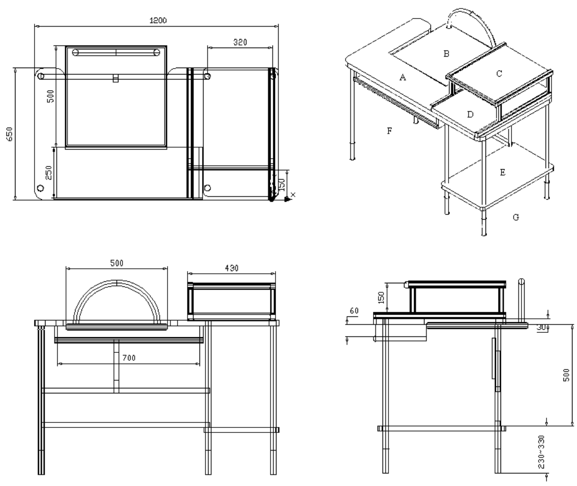
Some shortcomings were found for all three commercial workstations. The major difficulty was generally that the subjects could not access to the desk due to low keyboard tray height of Workstation I and the poor bottom design and narrowness of the desks in Workstations II and III, respectively. The location of the CPU system unit was low in all three workstations, forcing the subjects to bend their trunks. The keyboard tray was too narrow to place both keyboard and mouse on the same surface. In addition, the location of printer was high so that the female subject could not reach it.

3.3. New VDT workstation design

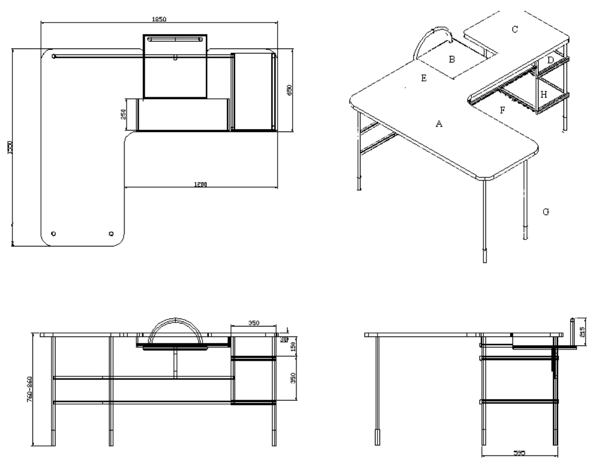
Two new computer desks were designed as shown in Fig. 5 to solve the shortcomings of commercial desks and to meet the major guidelines described in Section 2.4. The main difference between these two new designed desks was in the desk space. The desk in Fig. 5a is suitable for restricted space in the office, and that in Fig. 5b is appropriate spare space for some other documentation tasks.

The total breadth and depth of the desk were 120cm and 65cm, respectively, for the Type I workstation shown in Fig. 5a. The breadth beneath the desk surface was 80cm. The comfortable reach of a 5%ile female wheelchair user is about 41cm for one side [31], i.e., 82cm for both sides, and the shoulder breadth of a 5%ile female is about 29 cm. Therefore, a desk breadth of 120cm was then suggested, while some operational area was also considered. Since the forward comfortable reach and maximum reach for 5%ile female wheelchair users were 53cm and 76cm [31], respectively, the desk depth was determined as 65cm. Two factors were considered to determine the breadth beneath the desk of 80 cm. The breadth of large-scale wheelchair was about 70cm shown in Table 4. Additionally, Tilley [16] recommended a minimum clear space requirement for wheelchair movement of 76.2cm.

The desk for Type II workstation was designed as an L shape, and the heights of the desk surface, keyboard tray, monitor pedestal and tilt angle of monitor were all adjustable within the same ranges as the Type I workstation. The total dimensions for the desk surface were 185cm, 155cm and 65cm, as shown in Fig. 5b, mainly due to the need for turning space for a wheelchair. Tilley [16] recommended that the diameter for wheelchair turning should be about 152.5cm. The printer and CPU system unit were arranged on the desk surface as shown in Figs. 5b and 6b. The scanner tray was designed beneath the desk surface at 15cm, and could be moved forward and backward. Some non-VDT tasks, e.g. documentation work, could be performed in spare desk space.



(a) Type I



(b) Type II

Figure 5. (a) Type I VDT workstation, where:
A: working desk with adjustable height;
B: tray for monitor with adjustable height and angle
C: tray for printer (forward and backward)
D: tray for scanner (forward and backward)
E: location for desktop case
F: tray for keyboard (forward and backward)
G: six columns for support (the height is adjustable);
(b) Type II, the letters shown in the figure represent the same components as in Type I, and H denotes a room for free use.

Table 6. Angles (x, y, z) of right shoulder and lumbar joints while operating VDT tasks with commercial and new designed desks (in degrees)

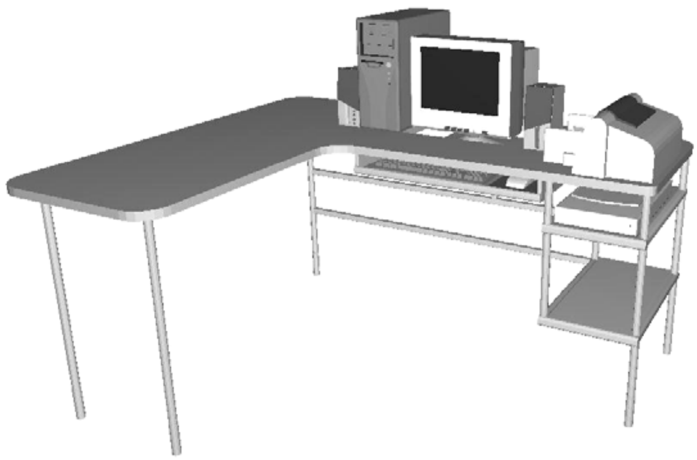
Mouse				Keyboard				CPU system unit				Printer				Monitor				Item
Lumbar		Shoulder		Lumbar		Shoulder		Lumbar		Shoulder		Lumbar		Shoulder		Lumbar		Shoulder		Joint
Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female**	Male*	Subjects
0	1.2	10.3	10	0	0	5.4	5.3	3.5	1.9	60.7	60.4	-2.8	-0.9	69.5	46.6	0	0	27.3	24.3	WS I
1.7	2.5	59	65.3	0	4.8	5.4	40.3	8.6	9.4	89.9	63.2	6.7	4.8	158	118.8	3.7	4.1	71	77.5	
0	0.4	-7.3	-18	0	0	3.4	11.2	0.2	1.1	25.2	15.6	-0.3	0.6	28.8	37.5	0	0	39.3	38.2	
0	0	21.3	19.8	0	0	3.7	2.1	4	2.7	52.5	56.4	-4	-3.3	79.2	67.1	0	0	15.1	15	WS II
1.1	2.6	32.2	58.9	0	3	12.1	33	7	7.4	88	68.5	10.4	9.1	162.8	171.6	0.4	2.1	72.9	77.1	
0	0	-12	-9	0	0	3.9	8.8	0.3	1.5	27	9.3	-1.3	0.2	26.8	38.5	0	0	36.8	39.1	
1.8	1.1	53.2	52.8	0	0	2.2	5.5	3.6	3.5	64.4	60.6	-3.4	-2.5	55.1	53.3	0	0	50	45.5	WS III
7.5	8.8	117	114.5	2.2	5	46.9	65.4	9.2	10.2	93.4	96.3	10	9	162	166.8	8	8	122.6	113.8	
1.5	1.6	-10.7	-21.7	0	0	2	7	1.5	1.8	28.6	17	-1.7	1.3	35.1	43.3	0	0.2	36	36.9	
0	0	13.2	2	0	0	0	3.2	2.8	2.3	61	34.2	0	0	45.2	32.5	0	0	17.2	12.6	Type I (new design)
0	0	15.4	0.9	0	0	0	0	7.1	2.7	64.6	28.3	0	0	56.3	18.7	0	0	43	30.7	
0	0	-40.3	-33.7	0	0	31.2	47.7	0.1	0.1	-51	-49	0	0	-30.4	-32	0	0	6.5	7.3	
0	0	13.2	2	0	0	0	3.2	0	0	27.3	14.6	0	0	41.6	23.2	0	0	17.2	12.6	Type II (new design)
0	0	15.4	0.9	0	0	0	0	0	0	48.5	32.2	0	0	44.6	14.1	0	0	43	30.7	
0	0	-40.3	-33.7	0	0	31.2	47.7	0	0	-14.3	-17.5	0	0	-29.8	-31.5	0	0	6.5	7.3	

*95th percentile male subject; **5th percentile female subject

3.4. Simulation of new designed VDT workstations

Before the simulation was performed, the CPU system unit and peripheral equipment were arranged as shown in Fig. 6 for two newly designed workstations. Two virtual subjects, Jack and Jill, were again required to sit on large- and small-scale wheelchairs, respectively, and to perform some VDT activities as simulated previously for commercial workstations. Simulation results reveal that they could easily touch all the components to perform VDT tasks without moving their trunks, except with the Type I workstation, in which the subjects had to bend forward at small angles to operate the CPU system unit. These results can be examined in Table 6.

(a) Type I



(b) Type II

Fig.ure 6. Two new designed VDT workstations where the major dimensions are shown in Figure 5

3.5. RULA postural analysis

Table 7 shows the grand scores of the RULA analysis, revealing that the scores obtained from newly designed workstations were lower than those from the three commercial workstations. These results imply that the commercial workstations would result in more dangerous postures than the designed workstations. Most of the grand scores of the new designed workstations were around 2-3. However, the operation of turning the CPU system unit on and off on the Type I workstation obtained scores of 4 for male and 6 for female, representing high postural risks. Table 8 summarizes the RULA analysis of Groups A and B for current design, where the total scores were 4 in both Groups for 95th percentile male, and 4 in Group A and 7 in Group B for the 5th percentile female. The neck flexion was found to be larger than 20° and trunk flexion was between 20° and 60° for 95th percentile male. The reason for the highest score in Group B for the female subject was the neck extension and truck flexion, where the flexion angle was larger than 60°.

Table 7. Grand scores of RULA analysis for commercial and new designed desks

Workstation elements	Commercial desks						New designed desks			
	WS I		WS II		WS III		Type I		Type II	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
Monitor	3	3	4	3	6	7	3	3	3	3
Printer	6	7	7	7	7	7	3	3	3	3
Keyboard	3	3	3	3	3	3	2	2	2	2
Mouse	4	3	4	7	7	7	3	3	3	3
CPU system unit	6	6	6	6	7	7	4	6	3	3

Table 8. RULA scores for turning the CPU system unit on and off at current and modification stages

RULA score	Current design		Modification		
			A	B	C
	Male	Female	Male	Male	Female
Group A					
Upper arm	3	4	3	3	3
Lower arm	3	3	3	3	3
Wrist	1	1	1	1	1
Wrist Twist	1	1	1	1	1
Total	4	4	4	4	4
Group B					
Neck	3	4	3	1	3
Truck	3	4	2	3	2
Total	4	7	3	3	3
Grand Score	4	6	3	3	3

Some simulations were performed to reduce the high RULA scores. Three recommendations were made: for the 95%ile male, the CPU system unit needed to be raised 5cm (i.e., Modification A in Table 8), or the subject was advised to turn the CPU system unit on and off without watching it (Modification B), and for the 5%ile female the unit case was raised 5cm and the subject was advised to operate it without watching (Modification C). The grand scores then became 3 for all three modifications, as shown in Table 8. This implied that the postural risks of VDT workstations could be examined and suggested to reduce from the more critical levels to mild levels with the application of the RULA method.

4. Discussion

The anthropometric data shown in Table 3 and used in the study were obtained from Wang et al. [27]. The database was recently completed with a large-scale anthropometry survey in Taiwan, comprising of 1200 normal worker subjects (735 males and 465 females with ages ranging from 18 to 65). Few anthropometry surveys of local disabled people with small- and medium-scale in Taiwan have been performed recently, some of these do not even include female subjects. One fairly large survey [32] in the literature involved 132 male and 57 female spinal cord injury (SCI) subjects, however, some measurements, e.g. the elbow and shoulder heights in the sitting position required for VDT simulation, were not investigated. Current measurements obtained from handicapped population still had to be further verified. Additionally, comparisons were made at the beginning of the study, indicating that anthropometric differences between normal and current disabled subjects were small. Therefore, the anthropometric database from Wang et al. [27] was applied in the study. However, the effects of subjects' dimension bias on the results of the study would exist but might be weak.

Postural stress is a major risk factor for cumulative trauma disorders, and many studies have recommended reducing it. The new designed VDT workstations in the study were demonstrated to be easily performed by wheelchair users almost without bending their trunks. The new design of VDT workstations can reduce the angles of right shoulder and lumbar joints, which may result in some cumulative trauma disorders, especially while VDT tasks were performed for long periods of time.

Some recently developed computer simulation methods provide functions to assess postural stress. This study indicates that the design of VDT workstation for wheelchair users can be improved through postural evaluation tools such as RULA, even though the original design was obtained by ergonomics principles. However, a prototype or large-scale physical mockup may still be recommended for further assessment to complete design process for new products.

Previous sections of this study consider some design guidelines and postural evaluation for the design of new computer workstations. Ergonomics play a prominent role in determining the workstation dimension and layout decisions in current workstation design. Therefore, these guidelines and evaluations should provide general rules for designing VDT workstations for specific purposes. Moreover, the 3D graphs of peripheral equipment were stored in a database, and can be further developed in the future. Once ergonomics evaluation is needed, the analytical process developed herein this study can be followed, and the equipment database can be applied, to help people access VDT workstations at the design stage.

5. Conclusion

Three VDT workstations have been simulated and assessed with selected commercial desks in this study. It has been found that the commercial workstations have some drawbacks - the work space and reach are insufficient, and working postures become awkward and have to be redesigned, when wheelchair users perform VDT tasks. Two new computer desks have been designed and obtained to solve the above shortcomings of three commercial desks and to meet the design guidelines proposed in the study. With the application of the RULA method, the commercial and newly designed workstations have been examined for subjects' postural risks. It has been shown that the postural risks of the modified workstations can be reduced to a mild level. The simulation technology applied in the study indeed offers the assistance in the creation, modification, presentation and analysis of VDT workstation design before the prototype is manufactured and evaluated.

References

[1] Jarosz, E. 1996. Determination of the workspace of wheelchair users. *International Journal of Industrial Ergonomics*, 17: 123-133.

[2] Kozey, J. W., and Das, B. 2004. Determination of the normal and maximum reach measures of adult wheelchair users. *International Journal of Industrial Ergonomics*, 33: 205-213.

[3] Ashworth, J. B., Reuben, D. B., and Benton, L. A. 1994. Functional profile of healthy older persons. *Age and Aging*, 23: 34-39.

[4] Babski-Reeves, K., Stanfield, J., and Hughes, L. 2005. Assessment of video display workstation set up on risk factors associated with the development of low back and neck discomfort. *International Journal of Industrial Ergonomics*, 35: 593-604.

[5] Fogleman, M., and Lewis, R. J. 2002. Factors associated with self-reported musculoskeletal discomfort in video display terminal (VDT) users. *International Journal of Industrial Ergonomics*, 29: 311-318.

[6] Gerr, F., Marcus, M., and Monteilh, C. 2004. Epidemiology of musculoskeletal disorders among computer users: lesson learned from the role of posture and keyboard use. *Journal of Electromyography and Kinesiology*, 14: 25-31.

[7] Leung, A. W. S., Chan, C. C. H., and He, J. 2004. Structural stability and reliability of the Swedish occupational fatigue inventory among Chinese VDT workers. *Applied Ergonomics*, 35: 233-241.

[8] Murata, A., Uetake, A., and Takasawa, Y. 2005. Evaluation of mental fatigue using feature parameter extracted from event-related potential. *International Journal of Industrial Ergonomics*, 35: 761-770.

[9] Park, M. Y., Kim, J. Y., and Shin, J. H. 2000. Ergonomic design and evaluation of a new VDT workstation chair with keyboard-mouse support. *International Journal of Industrial Ergonomics*, 26: 537-548.

[10] Psihogios, J. P., Sommerich, C. M., Mirka, G. A., and Moon, S. D. 2001. A field evaluation of monitor placement effects in VDT users. *Applied Ergonomics*, 32: 313-325.

[11] Das, B., and Kozey, J. W. 1999. Structural anthropometric measurements for wheelchair mobile adults. *Applied Ergonomics*, 30: 385-390.

[12] Gyi, D. E., Sims, R. E., Porter, J. M., Marshall, R., and Case, K. 2004, Representing older and disabled people in virtual user trials: data collection methods. *Applied Ergonomics*, 35: 443-451.

[13] Paquet, V., and Feathers, D. 2004. An anthropometric study of manual and powered wheelchair users. *International Journal of Industrial Ergonomics*, 33: 191-204.

[14] Reed, M. P., Van Roosmalen, L. 2005. A pilot study of a method for assessing the reach capability of wheelchair users for safety belt design. *Applied Ergonomics*, 36: 523-528.

[15] Feeney, R. 2000. Approach with special

reference to the needs of the disabled person. Proceedings of the IEA 2000/HFES 2000 Congress.
[16] Tilley, A. R. 2002. "*The measure of man and woman: human factors in design*". John Wiley & Sons, New York, 36-37.
[17] Chi, C. F. 1998. *The Task Redesign Manual for Handicapped People*, Bureau of Employment and Vocational Training, Council of Labor Affairs, Executive Yuan. (In Chinese)
[18] Feyen, R., Liu, Y., Chaffin, D., Jimmerson, G., and Joseph, B. 2000. Computer-aided ergonomics: a case study of incorporating ergonomics analysis into workplace design. *Applied Ergonomics*, 31:291-300.
[19] Sengupta, A. K., and Das, B. 1997. Human: An autocad based three dimensional anthropometric human model for workstation design. *International Journal of Industrial Ergonomics*, 19: 345-352.
[20] Mattila, M. 1996. Computer-aided ergonomics and safety - A challenge for integrated ergonomics. *International Journal of Industrial Ergonomics*,17: 309-314.
[21] Porter, J. M., Case, K., Marshall, R., Gyi, D., and Oliver, R. 2004. 'Beyond Jack and Jill': designing for individuals using HADRIAN. *International Journal of Industrial Ergonomics*, 33: 249-264.
[22] Univ. of Pennsylvania. 1997. JACK. Center for Human Modeling and Simulation, Department of Computer and Information Science, Univ. of Pennsylvania, U.S.A.
[23] Sundin, A., Ortengren, R., Sjoberg, H. 2000. Proactive human factors engineering analysis in space station design using the computer manikin Jack. *Proceedings of SAE Conference on Digital Human Modelling DHMC 2000*, Dearborn, Michigan.
[24] Sundin, A., Christmanson, M., and Ortengren, R. 2000. Use of a computer manikin in participatory design of assembly workstations. In K. Landau (ed.) "*Ergonomic Software Tools in Product and Workplace design*", Stuttgart: Ergon Verlag, 204-213.
[25] Leskinen, T., and Haijanen, J. 1996. Torque on the low back and the weight limits recommended by NIOSH in simulated lifts. *Proceedings of the Fourth International Symposium on 3-D Analysis of Human Movement*, France.
[26] Haijanen, J., Leskinen, T., Kuusisto, A., and Laitinen, H. 1996. Redesign of lifting work using a 3-D human modelling software and the revised NIOSH lifting equation. *Advances in Occupational Ergonomics and Safety*, Finland, 339-344.
[27] Wang, E. M. Y., Wang, M. J., Yeh, W. Y., Shih, Y. C., and Lin, Y. C. 1999. Development of anthropometric work environment for Taiwanese workers. *International Journal of Industrial Ergonomics*, 23: 3-8.
[28] McAtamney, L., and Corlett, E. N. 1993. RULA: a survey method for the investigation of work-related upper limb disorders. *Applied Ergonomics*, 24: 91-99.
[29] AT&T Bell Laboratories. 1983. Video display terminals. Short Hills, N. J.
[30] Institute of Occupational Safety and Health (IOSH), 1999. "*Occupational safety and health Guide for VDT workstations*", Publication No. IOSH88 -T-027. (in Chinese)
[31] Woodson, W. E., Tillman, B., and Tillman, P. 1992. "*Human Factors Design Handbook*", McGraw-Hill, London.
[32] Guan, S. S., Lin, Y. C., and Ke, L. T. 2001. A study of computer workstation of ergonomics. *Proceedings of 8th Annual Meeting & Conference of Ergonomics Society of Taiwan*, 229-234. (In Chinese)