IASDR07
INTERNATIONAL ASSOCIATION OF SOCIETIES OF DESIGN RESEARCH THE HONG KONG POLYTECHNIC UNIVERSITY 12TH TO 15TH NOVEMBER 2007

RECONSTRUCTING MOTION DATA FOR EVALUATION IN DESIGN PROCESS

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ABSTRACT:

Biomechanical study of posture is one of the most referenced aspects for ergonomic evaluation processes in workplace design. The aim of this paper is to present approaches for analysis of task performance and to illustrate ergonomic interpretation of the results. The proposed method, based on the optical system for motion capture, has allowed the measurement of a large set of subject postures and parameters in a continuous time basis and convenient manner. Statistical analysis can be done on the captured data to identify specific body part characteristics for posture and ergonomic analysis. Based on the results, a mock-up design can be evaluated against human factors in early design phases.

1. INTRODUCTION

Prototypes and physical mock-ups are usually built for evaluation and ergonomic tests. These are essential in the early phase of product design, but are expensive, time-consuming to build and non-reusable (Chaffin, 2001). Computer aided design and virtual reality technologies are used nowadays for simulation and evaluation. Integration of digital human modeling (Sundin, 2006) and anthropometric data (Pheasant, 1996) in the design process makes it possible to perform ergonomic analysis (Kuo, 2005). Commercial human simulation software tools, such as Jack (UGS, 2007), Safework (Safework, 2007) and Ramsis (Ramsis, 2007) are built to embed statistical analysis of human motion data. Unfortunately, simulation of human motion is not a perfect replica of a person, neither in motion control nor in presentation of joint movements. Instead of acquiring motions by simulation, optical motion capture has been a promising motion tracking technology in capturing body postures (Andreoni, 2002) and movements (Jayaram, 2006; Faupin, 2006) in an accurate and convenient manner. Subjects are equipped with sufficient optical markers applied on proper anatomical landmarks. Based on these markers, body segments with kinematic (Zatsiorsky, 1998) descriptions are defined. Together with a digital mock-up of physical experimental environment, realistic movements are presented and visualized in 3D space with temporal information. In this way, product evaluators and designers can extend themselves from using traditional 2D and 3D body dimension data into 4D information that is tailored and more appropriate for evaluation and analysis.

However, captured human movements cannot be easily manipulated to evaluate the fitness into different workplace settings and different physical interactions between a product and its user. In this research, we set up an experimental mock-up environment and define tasks for subjects to perform. Movements are captured by a optical motion capture system. A digital mock-up of the environment is built in conjunction with the captured movements, so that subject movements can be evaluated in detail in three dimensional spaces and on continuous time basis. Space-time analysis and joint angle analysis are described to evaluate the subject posture while performing the task. The goal is to enable a cost-effective, convenient and realistic preview and evaluation in early design phases; and to adopt motion data from real subjects in evaluating ergonomics and analyzing kinematic configuration along a continuous temporal dimension.

2. ACQUIRING HUMAN MOTION

The importance of applying ergonomics to workplace design is illustrated by the U.S. Department of Labor, Bureau of Labor Statistics (2005). According to the report, there were 4.2 million occupational injuries and illnesses among U.S. workers, and at a rate of 4.6 cases per 100 full-time workers experiencing workplace injuries and illnesses. Musculoskeletal disorders, for example, shoulder pain, neck disorders and low back disorders, occur if postures of the working person are not taken into consideration properly while doing workplace design. In fact, the decisions that will be taken during workplace design will affect to a great extent the postures that the working person will or will not be able to adopt (Marmaras, 2006).

Experiments are performed for evaluating a proposed design of a workstation. The design deals with the shape, dimensions and layout of the various material elements that surround one or more working persons. Part of the objectives for designers are to ensure that most people will be able to perform tasks safely and effectively, while staying comfortably at the workplace. These objectives can be supported by ergonomic principles which aim at minimizing the physical strain and workload of a working person, facilitating task execution, ensuring occupational health and safety, and achieving ease of use of various workplace elements (Marmaras, 2006). Reaches, size, muscle strength, and visual capabilities are common attributes to be considered when developing design criteria and guidelines for product development phases. Anthropometrical data then provides statistical descriptions of various population attributes, such as size, shape, strength, and range of motion of a specific group of people.

2. 1. DESCRIPTION OF SUBJECTS

Subjects of different anthropometrics are captured. Experiments are performed by each subject according to the setup and experimental matrix which will be described later. In the context of this paper, only data concerning the upper torso, neck, head and upper limbs are measured and captured. 36 anthropometric data (Pheasant, 1996) are selected to allow flexibility in adopting the human model for people of different sizes and shapes. Table 1 presents sample subject information concerning anthropometrical data. Based on these data, a virtual human model of particular size and shape can be created and visualized in 3D software (figure 1). Although it is found that the humanlike appearance is generally not a central issue, it appears to be important to achieve successful communication with different departments, managers, and so on.

Data Type	Quantity	Data Type	Quantity
Stature (mm)	1710	Hip breadth (mm)	428
Eye height (mm)	1591	Chest (bust) depth (mm)	230
Shoulder height (mm)	1415	Abdominal depth (mm)	205
Elbow height (mm)	1086	Shoulder-elbow length (mm)	349
Hip height (mm)	855	Elbow-fingertip length (mm)	450
Knuckle height (mm)	757	Upper limb length (mm)	770
Fingertip height (mm)	655	Shoulder-grip length (mm)	688
Sitting height (mm)	894	Head length (mm)	190
Sitting eye height (mm)	752	Head breadth (mm)	182
Sitting shoulder height (mm)	613	Hand length (mm)	166
Sitting elbow height (mm)	265	Hand breadth (mm)	80
Thigh Thickness (mm)	152	Foot length (mm)	262
Buttock-knee length (mm)	549	Foot breadth (mm)	96
Buttock-popliteal length (mm)	463	Span (mm)	1655
Knee height (mm)	520	Elbow span (mm)	852
Popliteal height (mm)	457	Vertical grip reach (standing) (mm)	1972
Shoulder breath (bideltoid) (mm)	492	Vertical grip reach (sitting) (mm)	1683
Shoulder breath (biacromial) (mm)	322	Forward grip reach (mm)	745

Table 1. Sample Anthropometrics data of a subject.

During the experiments, each subject is asked to perform reach motions. A reach (RE) motion is one of the therbligs concluded by Gilbreths (Niebel, 2003). A therblig is a fundamental motion element that is subdivided in a cycle of motions in the sense that it cannot be further subdivided. RE is an element used to move the hand from a location to a destination, for example, reaching for a part or a tool. The subject begins its motion from a seated position, then performs the reach motion and finally returns to its initial position. The reach is then repeated for a total of 30 times. A motion pattern (Meyer, 1999) is produced and shown in figure 2. It shows the path taken by the hand in the process of performing a task and also serves as a blueprint of the work method. We are using five humans of different anthropometrics to carry out the experiments. Three physical parameters regarding the workstation design are identified to be investigated. Different combinations of those 3 parameters are listed and become the experiments performed by each subject. A total of 1200 reach motions are produced.

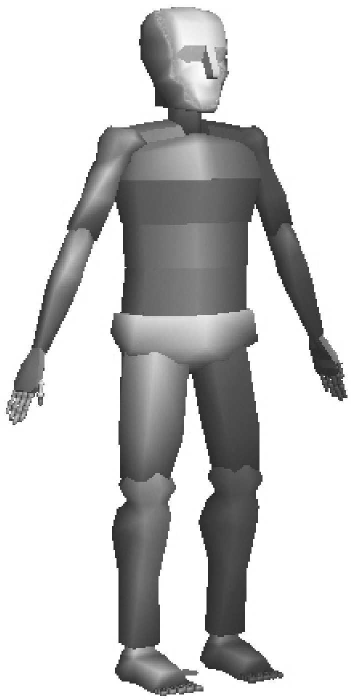

Figure 1. Virtual human model.

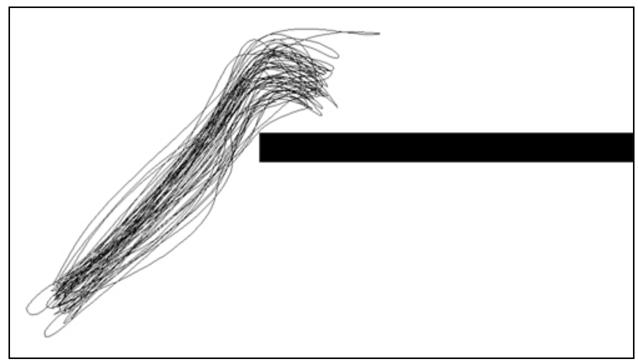

Figure 2. Motion pattern of reach (side view).

2. 2. SELECTION OF PARAMETERS

Sitting workspace is considered where the environment is laid out with a chair and a table in front. In such, there are a number of physical variables that we can investigate for assessment (Hoboken, 2004). As shown in figure 3, the heights, clearances, footrest depth (G) and work surface thickness (H) of a seated workplace are illustrated. The heights here include seat height (A), work surface height (B) and footrest height (C). The clearances include leg clearance (D), thigh clearance (E) and knee clearance (F). In the context of this paper, our experiments focus on the seat height (SH), work surface height (WSH) and reach distance (RD) by an arm of the subject.

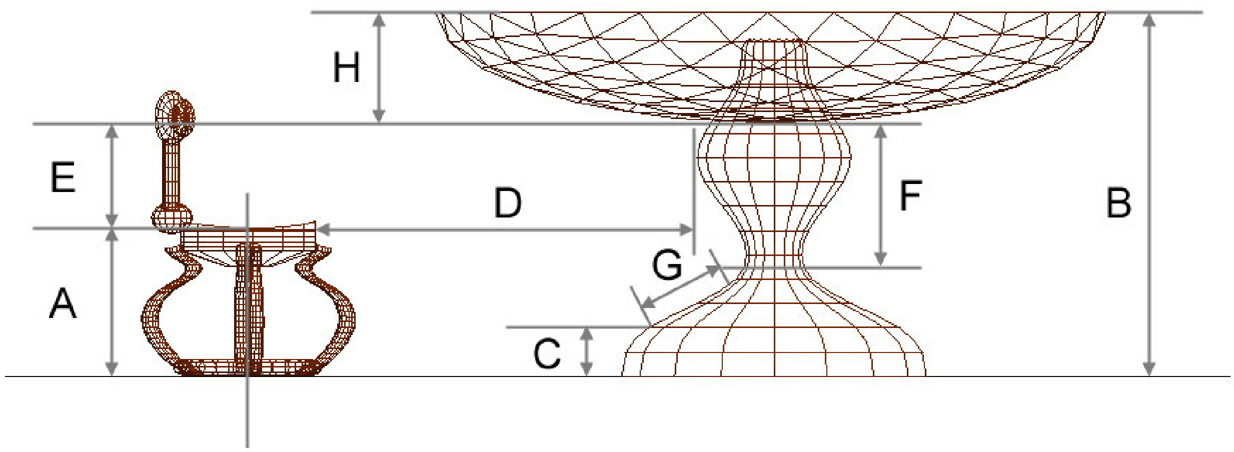

Figure 3. Seated workplace.

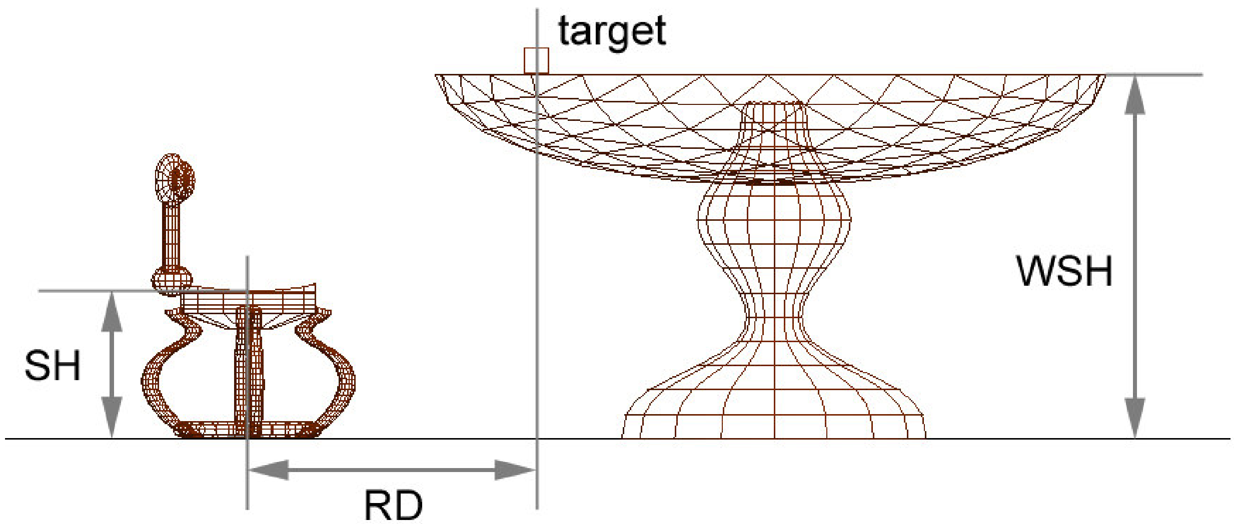

Figure 4. Digital mockup.

A physical mockup is built to allow subjects to perform tasks according to the scenarios. Based on the measurements of the mockup, a digital version of the workspace is also created inside a 3D visualization environment. The environment offers the possibility of evaluating the whole workspace from different point of view controlled by virtual cameras. On the table, there is a target zone marked to define the reach point for the subject to reach when seated (figure 4). The RD is the distance between the seat and the target zone. Two levels for each parameter have been defined and are listed in table 2. The level 1 numerical measurement is made according to the specification of the proposed design of a workstation, while level 2 defines values proposed for altering to see the difference subjected to evaluation.

Parameter	Level 1	Level 2
Seat height (SH) – cm	42	64
Work surface height (WSH) – cm	74	104
Reach distance (RD) – cm	60	78

Table 2. Physical factors and their levels.

According to the number of selected parameters and their levels, the ready-to-use orthogonal array L_4 (Phadke, 1989) is used for the conduction of the experiments. Table 3 shows the experimental matrix including combinations on levels of parameters for evaluation.

Experiment	SH	WSH	RD
1	L1	L1	L1
2	L1	L2	L2
3	L2	L1	L2
4	L2	L2	L1

Table 3. L_4 experimental matrix.

2. 3. DIGITAL HUMAN MODEL

55 markers are attached onto the subjects' bodies, covering the torso, neck, head, upper and lower limbs. The configuration of markers is shown in figure 5. Most of the markers are positioned according to different anatomic landmarks (Andreoi, 2002; Cappozzo, 1995). Trajectories are described by three degrees of freedom along the x, y and z axes. An optical motion capture (Motion Analysis) with 12 cameras is used in order to capture the trajectories of the markers, which are indicative of the motions of the subjects. For the execution of each experiment, a number of frames are captured with a sampling rate of 60 Hz. Each frame consists of the x, y, z coordinates of the 55 markers. Figure 6 shows the real-time visualization in EVa and the trajectory data of left ankle marker. Apart from the captured trajectory data, movement visualization in Motion Builder and 3D Studio MAX are also available for data manipulation and qualitative analysis of the experiments.

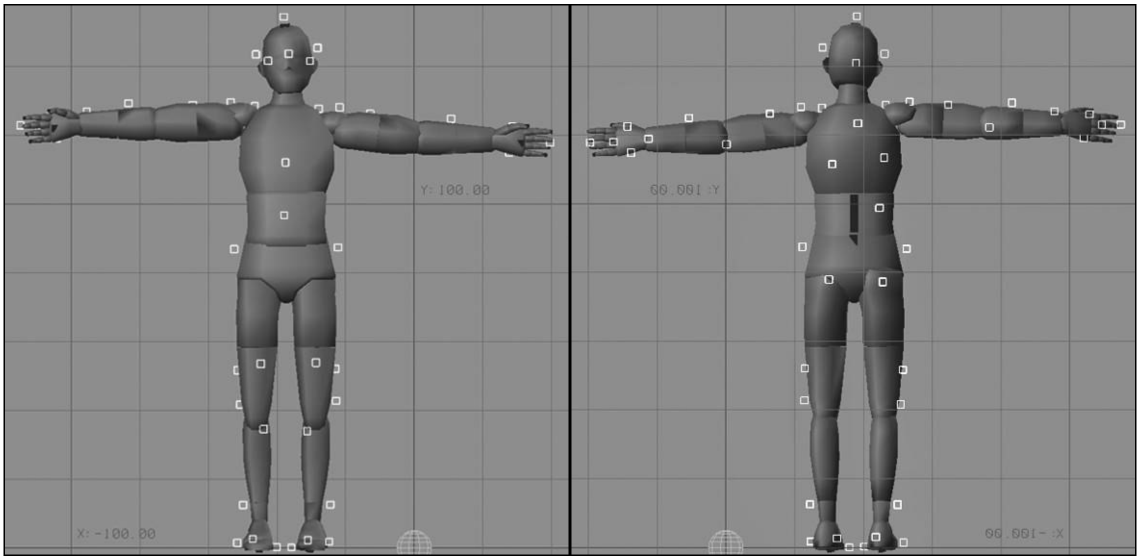

Figure 5. Configuration of markers.

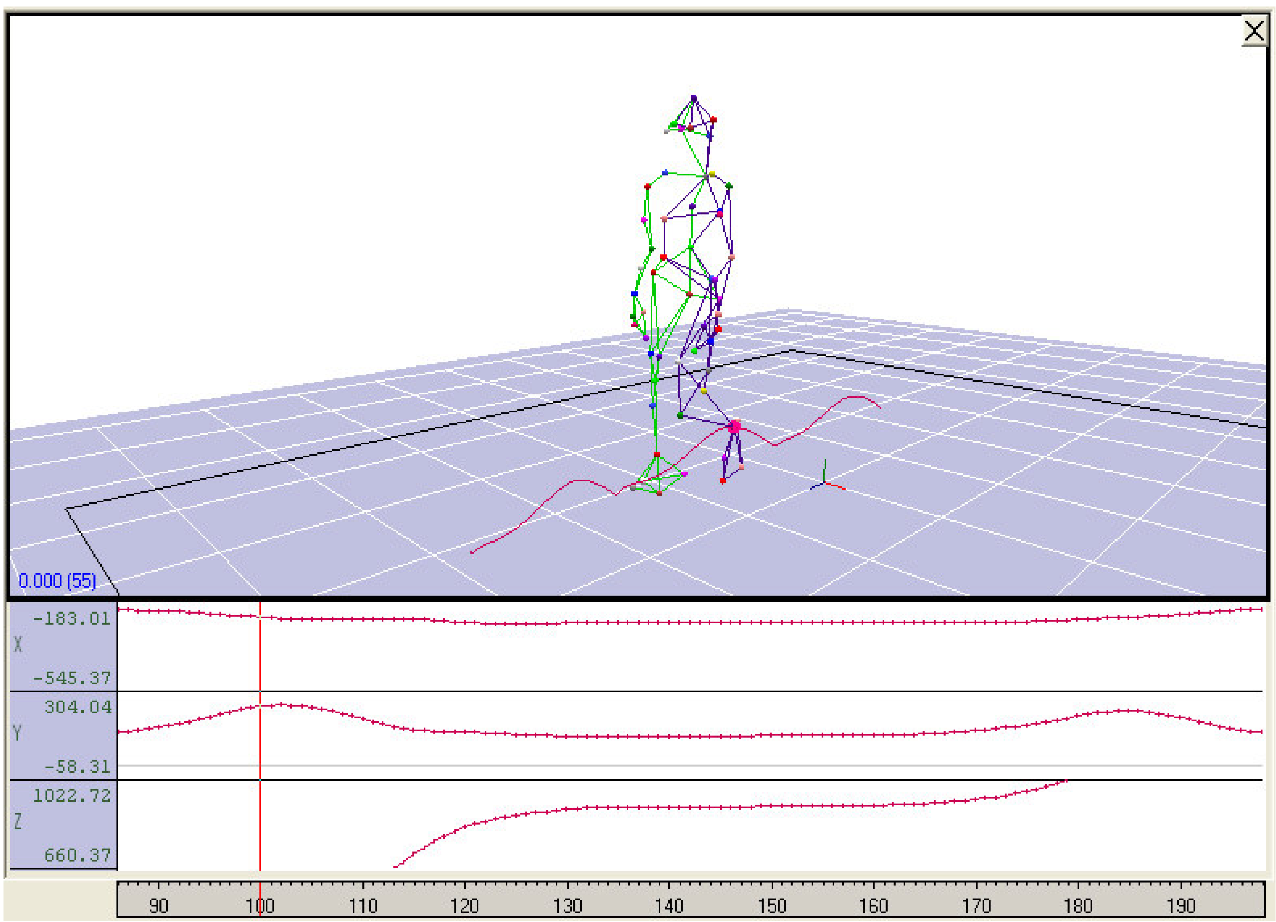

Figure 6. Real-time visualization and trajectory data of a marker

A skeletal system is created by capturing an initial pose having arms straight out, thumbs facing forward, and legs facing forward at shoulder width apart. The process involves the definition of joints (a connection between two bone segments) and close proximity of markers on the equivalent joints. There are 8 types of joints (table 4) that we can define for the virtual human model, each having different spatial constraints and relationship along the hierarchy (MAC, 2002).

Joint Type	Description
Hinge	Freedom of rotation along one axis
Universal	Freedom of rotation along two axes
Spherical	Freedom of rotation along three axes
Gimbal	Freedom of rotation in any direction or suspended so that it will remain level with its support tipped
6-DOF	Total freedom of motion
Shared hinge	Same as hinge, although rotation is shared with another joint
Shared universal	Same as universal, although rotation is shared with another joint
Shared spherical	Same as spherical, although rotation is shared with another joint

Table 4. Definition of different types of joint for the virtual human model.

A parent-child hierarchy is established for the human model with torso being the root and descendants being defined outward to limb extremities (figure 7). The local rotation angles for each joint is represented by BVH format (Lander, 1998) with rotation sequence z, x and y. The segments on the hierarchy are oriented accordingly to form a body posture in the virtual environment by applying the computed transformation (figure 8). Since the marker data is captured in discrete instances along a temporal dimension with high frame rate, continuous movement is made possible by interpolating between frames. Smooth visualization of subject motion is then available for realistic preview and quality analysis in continuous time basis.

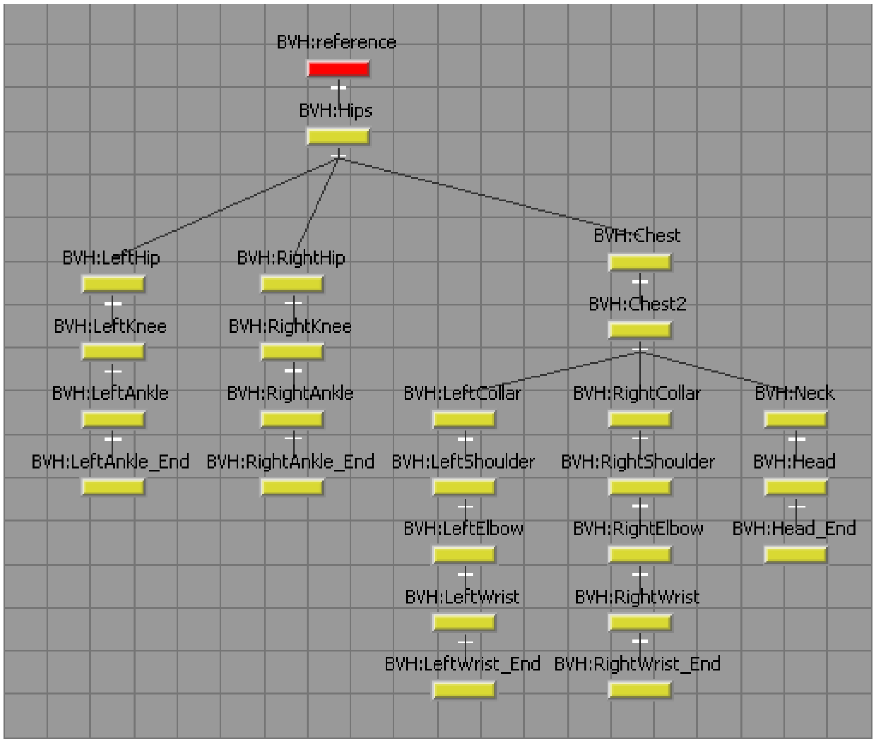

Figure 7. Parent-child hierarchy.

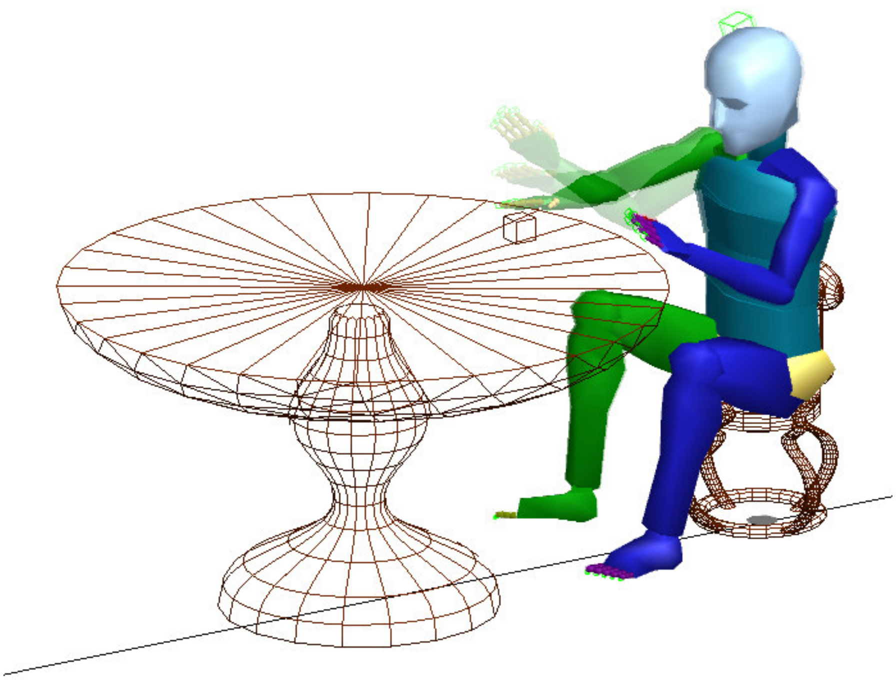

Figure 8. Visualization of segments.

3. DATA ANALYSIS AND EVALUATION

The basic concepts and principles of biomechanics can now be applied to subject evaluation under different workstation design situations. Due to differences in structure, different body parts are affected by work design in different ways. Various analyses and evaluations are carried out. As a result of the application of these techniques, a proposed workstation design can be evaluated in the early design process before any expensive, time-consuming and non-reusable prototype is built.

3. 1. SPACE-TIME ANALYSIS

The trajectories of captured marker data provide accurate indicators of subject motions in a continuous time basis. It is optimal for analyzing postures that relate to both absolute and relative locations of body parts. Since the marker configuration is based on anatomical landmarks, the system is able to capture the changes of position on the body accurately while time changes. The method of using different markers to track the entire human resulted in a couple of different options for calculating and displaying awkward posture relative to anthropometric data.

As an illustrative example, the sitting shoulder height can be defined by means of markers on left and right acromia. Since the location of each marker is obtained independently in global coordinates, the y axis of the left acromia marker and right acromia marker completely defines the vertical level of the shoulders. The sitting shoulder height at each time instance can be computed by deducting the seat height from each marker data. Table 5 shows the computed relationships between left and right sitting shoulder height at experiment 2 of L_4 compared to anthropometric data measured.

	Mean	Max	Min	S.D.
Captured left sitting shoulder height (mm)	568	575	560	3.6
Captured right sitting shoulder height (mm)	581	598	550	13.4
Measured sitting shoulder height (mm)	613	-	-	-

Table 5. Captured sitting shoulder height compared to measured data at experiment 2 of L_4.

The objective of this analysis is to quantify the shoulder position from selected external landmarks and to propose evidence for evaluating the subject posture during task performance. The results indicate that both captured left and right sitting shoulder heights are generally lower than the anthropometric measurement, and the maximum values are still capped a little bit below. This implies that the spinal cord is on average not at the natural vertical position. The abnormal posture may be due to the general flexion / extension on lumbar. The mean values also indicate that the left shoulder height is slightly lower than the value on the right. This may imply that the subject has an imbalanced height level of shoulder while performing the task. There is a high standard deviation value of right shoulder height as compared to that on the left. Since the subject is right-handed, the right hand is used to do the reach motion. While performing the tasks, there is a significant variation on height level at the right shoulder.

	Mean	Max	Min	S.D.
Captured left sitting shoulder height (mm)	555	562	550	2.6
Captured right sitting shoulder height (mm)	556	570	541	7.2
Measured sitting shoulder height (mm)	613	-	-	-

Table 6. Captured sitting shoulder height compared to measured data at experiment 4 of L_4.

For further comparison, similar calculation is also done under experiment 4 of L_4 as shown in table 6. The results indicate that the captured mean values of both shoulders are even lower than that of experiment 2 as compared to the measured value. In experiment 4, since the height difference between the chair and table is less than that in experiment 2, the subject may not need to keep the lumbar straight when achieving the task. Hence, the subject may pose at a more relaxed state under experiment 4 situation. From the mean values between left and right shoulders, we can also observe that the subject keeps the shoulder in a more balanced manner throughout this experiment as compared to the previous one. Because the work surface is located comparatively lower in experiment 2, the subject does not need to keep a high position in order to perform the task. It is reflected in the maximum height on right shoulder of experiment 4. Moreover, it is obvious that the standard deviation is nearly half in this experiment. This implies that the variation on height level at the right shoulder is dropped significantly.

Similar space-time analysis can also be constructed by making use of the trajectory data captured from different markers. The computed posture values of the subjects can also be compared with the postural values available in literature in order to evaluate the influence on subjects under different design situations.

3. 2. JOINT ANGLE ANALYSIS

In order to better understand the posture of the subject during the performance of task under proposed design situation, besides the space-time analysis discussed above, kinematics of subject motion can also be obtained to examine how motions of each joint involved.

Starting from the three dimensional position of the markers placed on the anatomical landmarks of the subject, under the context of upper body, a number of postural angles can be computed. These include neck flexion, lumbar flexion, shoulder flexion and abduction and elbow flexion, wrist flexion, etc. The anatomical reference system is based on the computation of the sagittal plane of the subject. The averages and standard deviations of all parameters are calculated for each experimental situation. Figure 9 illustrates an example of postural angles on right shoulder flexion (RSF), right shoulder abduction (RSA) and right elbow flexion (REF) for one subject at experiment 2 of L_4. The corresponding motion data is shown in figure 10. Tabulated statistical results of experiment 2 and 4 of L_4 are computed and shown in table 7.

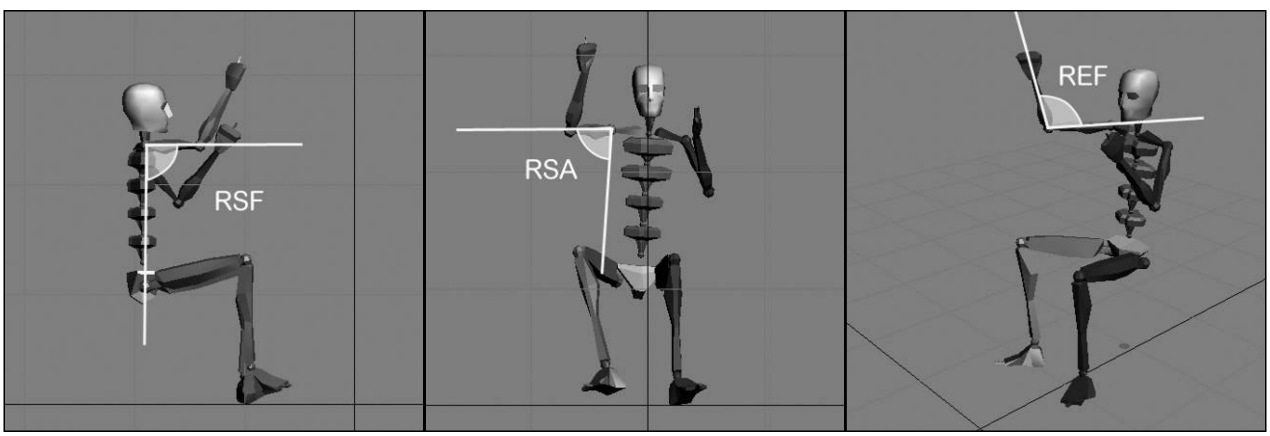

Figure 9. The postural angles on shoulder and elbow.

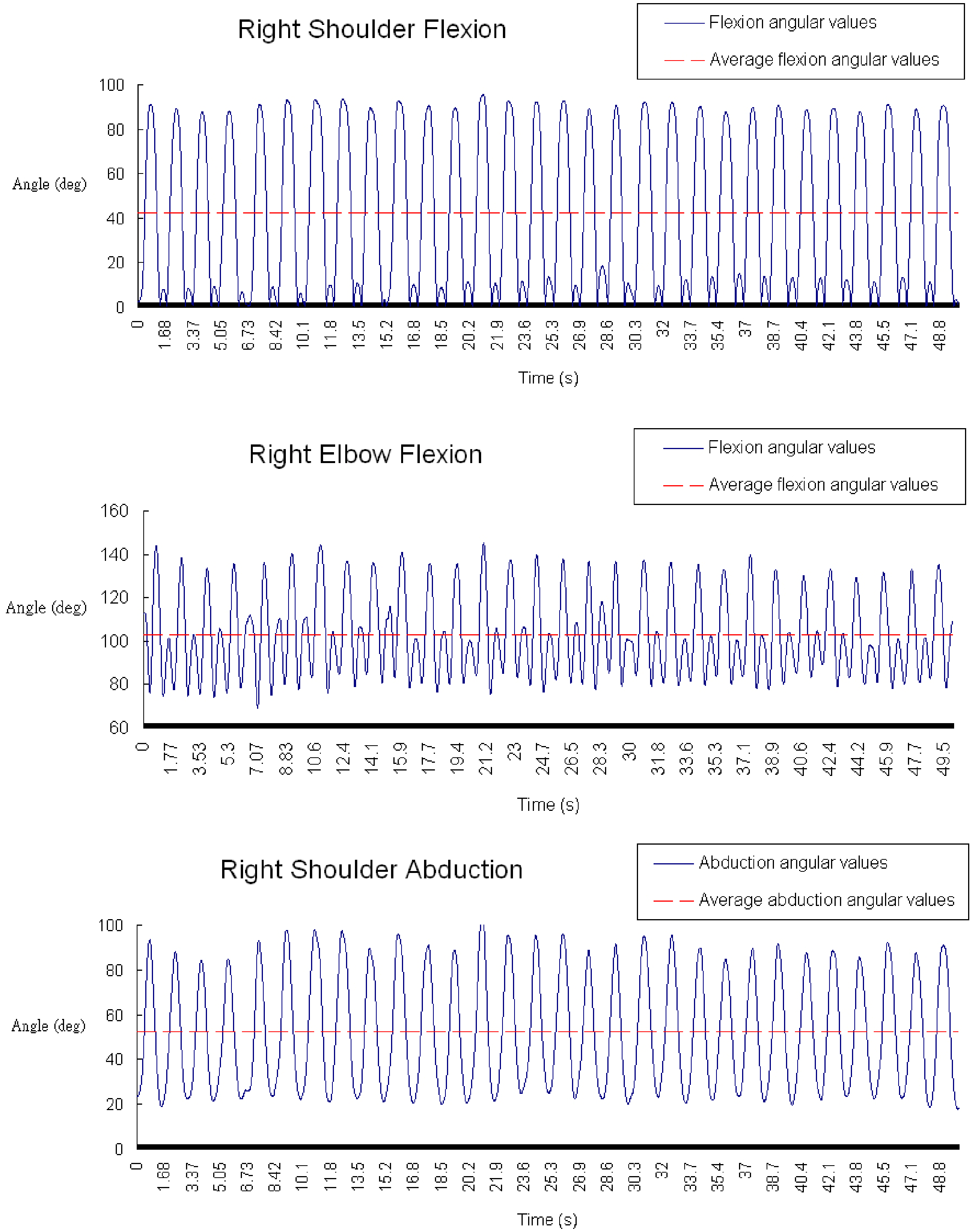

Figure 10. The motion data of the shoulder and elbow on experiment 2.

		Mean	Max	Min	S.D.
Experiment 2 of L_4	Right shoulder flexion (°)	42	91	0	34.4
	Right shoulder abduction (°)	53	92	18	24.9
	Right elbow flexion (°)	101	135	78	16.3
Experiment 4 of L_4	Right shoulder flexion (°)	22	56	0	19.5
	Right shoulder abduction (°)	26	37	15	6.7
	Right elbow flexion (°)	95	118	78	10.6

Table 7. Statistical data of shoulder and elbow flexion.

A significant influence of experimental situation on angular values of shoulder and elbow can be observed. The mean values of shoulder flexion, shoulder abduction and elbow flexion decreased from 42°, 53° and 101° to 22°, 26° and 95° respectively between experiment 2 and 4. Among the two joints, the shoulder joint shows a decrease of around 50% on both flexion and abduction. At the same time, the maximum of those two angular values also shows a decrease of around 50%. This indicates that the design of experiment 4 requires the subject to deviate more on the shoulder joint from neutral position, causing the shoulder muscles to fatigue more rapidly since it goes beyond 30° (Marras, 2005). Regarding the elbow flexion, the mean, maximum and minimum values are fallen within the close-in and extended arm position. That means both the design of experiment 2 and 4 can support subjects to perform the task while maintaining a posture for a long period of time and hold a significant external load at one hand (Marras, 2005).

Similar computation can be done on other joints involved in performing the tasks. This type of joint angle analysis provides a basis for biomechanical standpoint to be considered in proper ergonomic design of a workplace.

4. CONCLUSION

This paper has described approaches and methods of motion analysis for ergonomics evaluation on proposed workstation design. Real motion data have been captured in order to carry out the experiments for task performance and giving input on anthropometric parameters. Different forms of data have been reconstructed and computed from the motion capture data. Examples have also been shown and illustrated to demonstrate how space-time and joint angle analysis can be performed. Analysis on the results and discussion has also been made among different experiments and design situations. Although this study was performed on a specific therblig and for a given population of humans, its applicability is general and can be extended to other motions. The output results from the analysis can be further interpreted with the assistance of designers and human factors engineers to evaluate their product designs and concepts.

ACKNOWLEDGEMENTS:

The authors thank Leung Wing Sang for its technical assistance during the experiments. This study is partially support by the Departmental General Research Fund, funded by School of Design.

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