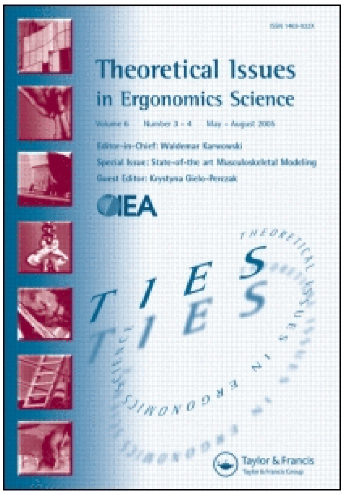

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Human posture simulation to assess cumulative spinal load due to manual lifting. Part II: accuracy and precision

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Human posture simulation to assess cumulative spinal load due to manual lifting. Part II: accuracy and precision

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For assessing a large number of variable manual lifting jobs, posture specification for using the University of Michigan Three Dimensional Static Strength Prediction Program and the revised National Institute for Occupational Safety and Health Lifting Equation may be time-consuming, tedious and subject to human errors. To expedite data analysis with desirable accuracy and precision for the two risk assessment tools, a new data analysis method based on human posture simulation was developed and evaluated. The accuracy and precision of the posture simulation method were evaluated by a repeated measures study design with six postures, three viewing angles and three trial repetitions as experimental factors. The effects of the experimental factors on the average accuracy and precision of the simulation method are reported and discussed. The study results also demonstrated pros and cons of human posture simulation as a means of posture specification for ergonomic risk assessments. The findings about the accuracy and precision of the human posture simulation method for quantifying the risk of musculoskeletal disorders due to manual materials handling may provide researchers with a new way of ergonomic assessments.

Keywords: human posture simulation; lifting index; manual lifting; Three Dimensional Static Strength Prediction Program

1. Introduction

Cumulative spinal load (CSL) has been shown in several studies to have a significant effect on the development of low back disorders (LBDs) due to manual materials handling (MMH) (Kumar 1990, Norman *et al*. 1998, Callaghan *et al*. 2001). To calculate CSL for many MMH tasks over a shift, substantial resources and time are required. In a previous paper, a method of calculating CSL that involves human posture simulation of the individual's working postures in a video is developed and described in detail (Waters *et al*. 2010). The method can also determine several parameters for the revised National Institute for Occupational Safety and Health (NIOSH) lifting equation (RNLE), which can subsequently be used for calculating the lifting index (LI). The human posture simulation method may be a practical tool for determining the risk of LBDs associated with performing a large number of varied MMH tasks during a shift.

In the CSL method, the University of Michigan Three Dimensional Static Strength Prediction Program (3DSSPP) is used to determine CSL. The purposes of the 3DSSPP are

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to predict spinal compressive and shear forces acting at the L4/L5 intervertebral disc during static exertions and to compare the predicted strength demands of a task with the population data (Chaffin 1969, Chaffin and Baker 1970, Garg and Chaffin 1975, Chaffin and Erig 1991). Input data for the 3DSSPP include height and weight of the person analysed, 15 specific body posture angles and hand load information for the task (Regents of University of Michigan 2001). The 3DSSPP has been widely used in many studies as MMH job design criteria or a risk assessment tool for LBDs (Waters *et al*. 1998, Lavender *et al*. 1999).

It is not practical and possible to obtain the 15 body joint angles required to use the 3DSSPP based on posture specification of on-site observations of the task in a short time period. A photograph or a stopped frame of a video record for the 3DSSPP analysis is usually needed. To input posture data based on a photograph or video into 3DSSPP, some posture judgements may be needed. The accuracy and process time of the photographic method for using 3DSSPP have been reported (Liu *et al*. 1997). Depending on the number and complexity of lifts to be analysed, substantial amounts of process time for posture specification for using the 3DSSPP may be needed (Liu *et al*. 1997).

The LI is the outcome variable of the RNLE and provides an estimate of the level of physical stress associated with frequent two-handed manual lifting activities (Waters and Putz-Anderson 1993). The LI is calculated based on several parameters including load lifted, horizontal distance (Hd), vertical distance (Vd) between the origin and destination of the lift, asymmetry (Ay), frequency and coupling of the lift. The recommended weight limit (RWL) resulting from the RNLE is defined as the amount of weight at which most workers are able to perform a lifting task safely without an increased risk of LBDs (Waters and Putz-Anderson 1993). The LI is defined as the ratio of the actual weight lifted to the RWL. Several studies have shown a significant association between the LI and development of LBDs (Waters *et al*. 1998, 1999, Lavender *et al*. 1999, Marras *et al*. 1999).

Similar to using 3DSSPP, measuring the RNLE parameters and processing the measurement data for calculating the LI may require substantial amounts of time and effort. A study showed that measurements for the RNLE parameters, especially Hd and lifting frequency, are sensitive to measurement errors (Waters *et al*. 1998). Proper training is also required for measuring the RNLE parameters accurately (Waters *et al*. 1998, Dempsey *et al*. 2001). In addition, errors in measurements for the RNLE parameters may accumulate over a large number of lifting tasks analysed, especially for calculating cumulative risks for LBDs in large-scale epidemiological studies. The human postures simulation method that the authors have developed aims at expediting the data processing for calculating the LI and CSL data with desirable accuracy and precision. Therefore, the purpose of the present study is to evaluate individuals' ability to accurately and precisely simulate various postures for using 3DSSPP and RNLE.

2. Materials and methods

2.1. *Description of human posture simulation*

The human posture simulation involved acquisition of body posture data with an electromagnetic motion capture system (Flock of Birds MotionStar® with Motion Monitor software; Ascension Technology Corporation, Burlington, VT, USA). The system was calibrated and adjusted for metal distortion in an approximately $3 \times 3 \times 3$ m working space on a raised wooden platform. Detailed information on the procedure and steps for using the human posture simulation method is described in a previous paper (Waters *et al.* 2010).

2.2. *Accuracy of the motion capture system*

The accuracies of calibrated position and rotation data measured by the motion capture system within a 10-foot distance from the transmitter (Flock of Birds MotionStar®) on the working wooden platform were approximately 1 cm and 0.3°, respectively. The system was calibrated based on an accuracy test conducted on a 2.4×2.4 m computer-generated grid paper with grid spacing of 0.2 m laid out on the platform. A total of 1320 calibration points (11, 12 and 10 points in x, y and z directions, respectively) were used for the calibration test. As shown in Figure 1, an anthropometer was used to locate the actual position and orientation of the calibration points. A sensor was securely positioned on a 7.5×7.5 cm square of Plexiglas that was used as a mounting surface to the anthropometer for adjustments of various heights (i.e. z direction) for the calibration points. Two line levels were attached to the surface of the Plexiglas to assure that the sensor was level in both x and y directions while taking measurements. The mean of root mean square (RMS) accuracy values for x, y and z coordinates was calculated as the accuracy for position data (1 cm). Similarly, the RMS values for three orientations of the sensor rotating around x, y and z axes were calculated as the accuracies for roll, elevation and azimuth. The overall accuracy (0.3°) of rotation data was the mean of the three RMS values in roll, elevation and azimuth.

2.3. *Accuracy and precision test of human posture simulation*

2.3.1. *Subjects*

Eight healthy subjects (three females, five males) within NIOSH were recruited to participate in the human posture simulation study. The means and standard deviations of their age, height and weight were 36 ± 11 years, 174.6 ± 9.5 cm and 75.8 ± 13.4 kg,

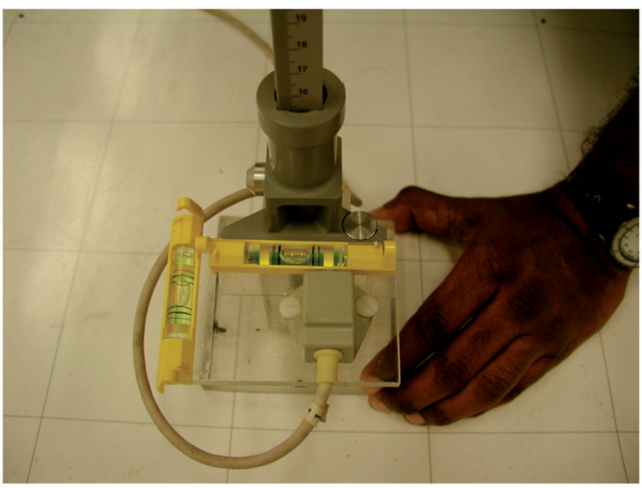

Figure 1. Two level meters mounted on a Plexiglas attached an anthropometer used for calibration.

respectively. The consent documents signed by the subjects were reviewed and approved by the NIOSH human subjects review board. Prior to posture simulation, the subjects were informed of the risks involving simulation and were trained to simulate a variety of postures to ensure that they were able to simulate postures in confidence.

2.3.2. *Training for posture simulation*

Prior to the accuracy test, the subjects received 30-min training for posture simulation. During the training, the subjects were instructed by a trainer to adjust their postures according to several near real-sized photographs of postures for varied lifting tasks. They were instructed by the same trainer to adjust their postures by positioning their feet, legs, arms, hands and trunk in order. If the posed postures did not match the postures in the photographs by visual comparisons of the trainer, the trainer coached them how to correct the postures to 'best match' the postures in the photographs. Because the trainer was able to see the differences in the posed posture of the simulator and the posture presented in the photograph, the trainer generally had better judgements about how to match the postures in the photographs. The visual comparisons were qualitative for the purpose of training the subjects to best postural simulation. After the 30-min training session, the subjects were asked if they felt confident about simulating postures accurately on their own. All the subjects expressed their confidence in simulating postures 'accurately' before they participated in the accuracy test.

2.3.3. *Posture data collection*

A total of 13 sensors were attached to various body segments to track whole body movement. The sensors' anatomical locations included back of skull, thoracic vertebrae 1, lumbar vertebrae 1, left and right deltoid tuberosity of humerus, dorsal radius, mid anterior femur, mid anterior border of tibia, intermediate cuneiforms. Each sensor, measuring $2.5 \times 2.5 \times 2$ cm, was placed in a plastic pocket attached to a Velcro strap. The Velcro straps were securely wrapped around the anatomical locations to protect the sensors from motion artefacts. The cables connected to the sensors were also securely wrapped around the body segments to eliminate any tension that might cause motion artefacts. The position and orientation data collected with the system were calibrated with the regression equation determined by the accuracy test. The data collection sampling rate and duration for each trial were set at 45 Hz and 3 s, respectively.

2.3.4. *Experimental procedure*

To acquire measurable postures to be used as references for testing the accuracy of human posture simulation, the subjects posed six different reference postures according to six example postures that were identified as common lifting postures in a large dryer manufacturing company. The example postures covered a range of vertical height and horizontal distances as well as various levels of trunk flexion (0–75°) and lift asymmetry (0–45°) for two-handed lifting. The pictures and characteristics of the six example postures are presented in Table 1. The subjects reviewed the six example postures projected approximately full-scale on to a large screen (1.5×2.1 m) approximately 3 m in front of them. They posed themselves without instructions to match the example postures. These posed postures were photographed approximately at each subject's shoulder height from the back, front and side viewing angles, resulting in 18 reference views. The subjects'

Table 1. Characteristics of the example postures.

	Posture	Trunk flexion*	Lift asymmetry*
1		~75° (A)	~45° (Yes)
2		~60° (A)	~0° (No)
3		~30° (B)	~0° (No)
4		~30° (B)	~45° (Yes)
5		~0° (C)	~0° (No)
6		~0° (C)	~45° (Yes)

Notes: *Trunk flexion angle was measured from the neutral (vertical) line; lift asymmetry was measured according to the National Institute for Occupational Safety and Health Lifting Equation definition for asymmetry angle.

assumed postures were measured with the motion capture system and used as reference postures for evaluating the accuracy of posture simulation that was performed subsequently in a separate testing session. To avoid learning effects, the simulation session was performed 1 week after the initial session. In the subsequent simulation session, the subjects were asked to pose and match the 18 reference views as accurately as possible. The 18 reference views were simulated three times, resulting in a total of 54 trials.

2.3.5. *Experimental design*

The experimental design for the accuracy test in the separate testing session employed a $6 \times 3 \times 3$ within-subject design with posture, viewing angle and trial repetition as experimental factors. The 54 photographs of the reference postures were presented to the subjects in a random order to avoid any learning effects during simulation. Posture data were collected in the same manner as those for posing the reference postures.

2.3.6. *Posture data for 3DSSPP and RNLE*

The posture data acquired from the data collection system were processed and calculated with the Motion Monitor program to determine 15 body angles (trunk flexion, trunk lateral bending, trunk axial rotation, left and right upper arm vertical and horizontal angles, left and right lower arm vertical and horizontal angles, left and right upper and lower leg vertical angles) required for using 3DSSPP. Three parameters (Hd, Vd and Ay) for RNLE were also calculated during the same data-processing procedure. Other non-posture-related 3DSSPP input variables (load, load direction at hands and gender) and RNLE parameters (lifting frequency, coupling of lift and work duration) were not analysed in this study. The mean values of the 3DSSPP body angles and RNLE parameters were calculated for each simulation trial.

2.3.7. *Data analysis*

The calculated 3DSSPP body angles and the three RNLE parameters for the 54 trials were compared with those for the six respective reference postures. Each reference posture data was used nine times (3 views $\times$ 3 repetitions) for comparisons. The authors believe that the same magnitude of simulation error in different directions, either positive or negative, would generally provide the same information about the ability to accurately simulate and match a posture perceived on the projection screen. Therefore, for each posture, the absolute value of the difference between each calculated body angle and the corresponding calculated body angle of the reference posture was used as the accuracy measure for the human posture simulation (i.e. simulation error). The mean of the posture simulation errors for the 15 3DSSPP body angles was used as the average posture simulation error (Liu *et al.* 1997). In addition, three additional posture simulation errors for trunk flexion, lateral bending and axial rotation were calculated and analysed individually due to their important role in the increasing risk of LBDs, indicated by several review papers (Bernard 1997, Burdorf and Sorock 1997, Hoogendoorn *et al.* 1999). Likewise, the absolute value of the difference between each calculated RNLE parameter and its corresponding reference value was used as the simulation error for each RNLE parameter.

For the accuracy test, the mean values of the three trials for the average posture simulation error, three trunk posture simulation errors and the errors for the three RNLE parameters were used as the dependent variables in the statistical analysis. For evaluating the precision of the human posture simulation method, the standard deviation of the three trials was used as the precision measure. Within-subject variables, including trunk flexion, lift asymmetry and viewing angle, were used as the independent variables in the statistical models for both accuracy and precision tests. For purposes of the statistical analyses, trunk flexion and asymmetry were grouped into three (see Table 1A: postures 1 and 2; Table 1B: postures 3 and 4; Table 1C: postures 5 and 6) and two (yes: postures 1, 4 and 6; no: postures 2, 3 and 5) groups, respectively. The Personal Statistical Analysis Software, version 9.1 (SAS Institute Inc, Cary, NC, USA) was used to perform the statistical analyses. A repeated measures ANOVA with post hoc Fisher's least-significant-difference test ($p < 0.05$) was performed to determine the effects of the within-subjects variables and their two-way interactions on each dependent variable.

3. Results

3.1. *Accuracy of human posture simulation*

Table 2 shows the average accuracy measures (i.e. errors) grouped by arms, trunk and legs as a function of the six different postures simulated. The three body sections were presumed to work independently in terms of postural simulation errors, although they were anatomically linked. The average posture simulation error for the six postures ranged from 9–16°. Simulation errors tended to occur the most for simulating arm postures, compared with those for trunk and legs. Specifically, large errors tended to occur (>20°) in simulating the arm angles when the subjects' arms were positioned vertically with increased trunk flexion (postures 1 and 2 in Table 1). The average errors for Hd, Vd and Ay ranged from 2.6 to 4.9 cm, 2.3 to 4.5 cm and 10.1 to 20.5°, respectively. The average errors for the three RNLE parameters did not seem to be related to any specific posture.

Panels A and B in Table 3 present the accuracy measure as a function of viewing angle and trunk flexion group, respectively. Trunk flexion, viewing angle and lift asymmetry × viewing angle two-way interaction were found to have a significant effect on the average posture simulation error. As compared with the back and front viewing angles,

Table 2. Descriptive statistics (mean ± SD) of the human posture simulation accuracy measures for 3DSSPP body angles (grouped by three body sections) and three NLE parameters.

	Postures					
	1	2	3	4	5	6
Hd (cm)	3.3 ± 1.4	4.5 ± 3.5	4.6 ± 3.9	4.9 ± 4.2	2.6 ± 1.9	3.7 ± 2.3
Vd (cm)	4.5 ± 2.3	2.8 ± 1.1	3.0 ± 2.0	3.0 ± 2.6	2.3 ± 2.0	3.4 ± 2.2
Ay (°)	15.1 ± 12	10.1 ± 5.9	13.3 ± 9.2	13.1 ± 7.3	12.9 ± 9.2	20.5 ± 15.0
Arms (°)	21.8 ± 7.6	25.1 ± 9.2	12.7 ± 7.6	15.9 ± 5.7	15.6 ± 8.0	14.7 ± 6.2
Trunk (°)	8.5 ± 3.8	7.5 ± 3.1	3.9 ± 1.5	5.5 ± 2.4	4.2 ± 1.6	5.4 ± 2.3
Legs (°)	6.0 ± 2.8	3.9 ± 1.5	5.3 ± 2.6	5.0 ± 2.0	5.3 ± 1.8	5.0 ± 2.0
Average postural simulation error (°)	14.9 ± 4.5	15.9 ± 5.3	9.0 ± 1.4	10.9 ± 3.2	10.6 ± 4.4	10.3 ± 3.7

Notes: 3DSSPP = University of Michigan Three Dimensional Static Strength Prediction Program; NLE = National Institute for Occupational Safety and Health Lifting Equation; Hd = horizontal distance; Vd = vertical distance; Ay = asymmetry.
For characteristics of postures, see Table 1.

Table 3. ANOVA results for the accuracy and precision measures ($n = 48$).

	Panel A: Accuracy measures as a function of viewing angle			Panel B: Accuracy measures as a function of trunk flexion group			Panel C: Precision measures as a function of trunk flexion group		
	Mean (SD)			Mean (SD)			Mean (SD)		
	Back	Front	Side	A (>60°)	B (~30°)	C (~0°)	A (>60°)	B (~30°)	C (~0°)
Average postural simulation error (°)	12.0[a] (4.7)	12.8[a] (4.8)	11.0[b] (5.1)	15.4[a] (4.9)	9.9[b] (3.8)	10.4[b] (4.0)	2.7[a] (2.4)	2.4[a] (2.6)	1.5[b] (1.4)
Trunk lateral bending error (°)	6.5 (6.2)	6.1 (6.0)	7.4 (6.3)	11.1[a] (8.3)	4.5[b] (3.0)	4.3[b] (2.5)	3.9[a] (3.6)	1.7[b] (1.2)	1.9[b] (1.2)
Trunk flexionerror (°)	5.5 (4.3)	6.4 (4.5)	5.6 (5.7)	8.2 (6.8)	4.8 (3.0)	4.5 (2.9)	3.3[a] (2.1)	2.4[b] (1.9)	1.7[c] (1.1)
Trunk axial rotation error (°)	4.2 (2.3)	5.3 (3.8)	5.5 (4.2)	4.7 (3.4)	4.7 (3.0)	5.6 (4.2)	1.6[a] (0.8)	2.6[b] (2.6)	2.3[b] (1.2)
Error for Hd (cm)	4.1 (3.0)	4.2 (3.5)	3.5 (2.90)	3.9 (2.8)	4.8 (4.0)	3.1 (2.2)	1.8 (1.3)	1.7 (1.60)	0.3 (1.0)
Error for Vd (cm)	3.0 (1.9)	3.3 (2.4)	3.1 (2.1)	3.6 (2.0)	3.0 (2.3)	2.8 (2.2)	5.2 (3.8)	4.5 (3.8)	5.7 (3.3)
Error for Ay (°)	15.1 (9.3)	13.4 (11.4)	14.0 (10.9)	12.6 (9.7)	13.2 (8.2)	16.7 (12.9)	1.4 (0.9)	1.3 (1.1)	1.1 (1.0)

Notes: Hd = horizontal distance; Vd = vertical distance; Ay = asymmetry.
[a,b,c]Different superscript letters represent a significant difference; $p < 0.05$.

the side viewing angle caused a significant decrease in the average posture simulation error by approximately 1° and 2°, respectively. There was no significant difference in the average posture simulation errors between the front and back viewing angles. In addition, viewing angle did not significantly affect the remainder of the accuracy measures, including trunk flexion, trunk lateral bending, trunk axial rotation, Hd, Vd and Ay. As compared with two other trunk flexion groups B and C (flexion <30°), trunk flexion group A (flexion >60°) caused a significant increase in the average posture simulation error and trunk lateral bending error by approximately 5° and 7°, respectively. Trunk flexion group, however, did not significantly affect the errors in simulating trunk flexion, trunk axial rotation, Hd, Vd and Ay.

Two-way interactions of viewing angle × trunk flexion and viewing angle × lift asymmetry are graphically illustrated in Figures 2 and 3, respectively. As shown in Figure 2, the average posture simulation error occurred the most (16.3°) for simulating trunk flexion group A in the front viewing angle, while the average posture simulation error occurred the least (8.7°) for simulating trunk flexion group B in the side viewing angle. For simulating a relatively full range of trunk flexion (0–70°) in the three different viewing angles, the average posture simulation error was found to be the smallest for the side viewing angle, followed by the back and front viewing angles. Furthermore, Figure 2 also shows that the average posture simulation error for trunk flexion group A was approximately 5° greater than for trunk flexion groups B and C for all three viewing angles.

It is worthy to note that there was a significant effect of the two-way interaction of viewing angle and lift asymmetry on the average posture simulation error, as shown in Figure 3. Presence of lift asymmetry did not significantly affect the average posture simulation error when the reference postures were presented in the front viewing angle. Lift asymmetry, however, significantly affected the average posture simulation error when the reference posture was presented in the side or back viewing angles. Lift asymmetry presented in back view caused a significant decrease in the average posture simulation

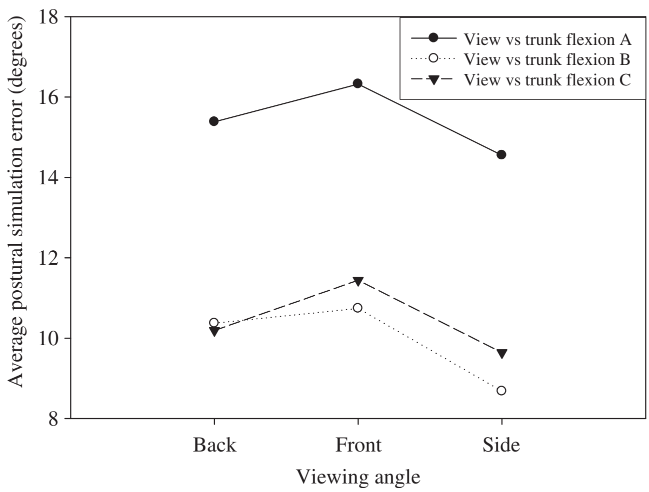

Figure 2. Trends in the average postural simulation error for three viewing angles and three trunk flexion groups.

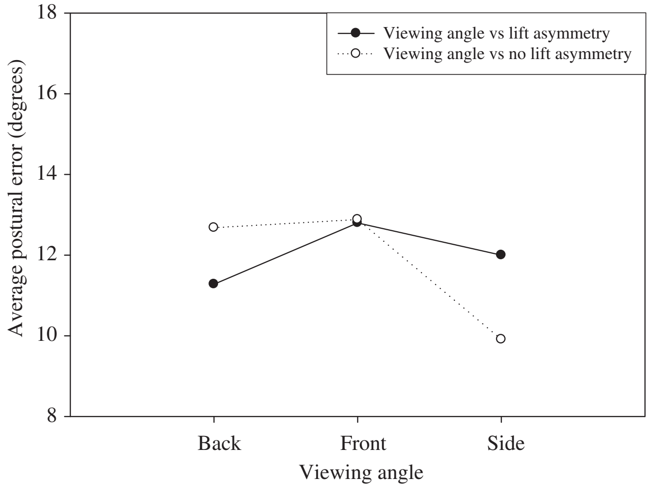

Figure 3. Effects of a two-way interaction between viewing angle and lift asymmetry on the average posture simulation errors.

error by 1.8°. Conversely, lift asymmetry presented in side view caused a significant increase in the average posture simulation error by 2.2°.

3.2. *Precision of human posture simulation*

The average precision measure for the average posture simulation error across all test conditions and subjects was found to be 2.4°. This indicates that the subjects appeared to be able to simulate the various postures in different views repetitively without generating a large variation in the overall posture simulation error. Results of ANOVA showed that only trunk flexion was found to have a significant effect ($p < 0.05$) on selected precision measures. Panel C in Table 3 shows the effect of trunk flexion on the selected precision measures. As compared with trunk flexion groups B and C, the trunk flexion group A (>60°) caused significant but small increases (approximately 1–2°) in the precision measures for the average posture simulation error, trunk flexion error and trunk lateral bending error. Trunk flexion did not cause any significant effect on the precision measures for the three RNLE parameters. The average precision measures for Hd, Vd and Ay across all simulation conditions were approximately 1.5 cm, 5 cm and 1°, respectively.

4. Discussion

The accuracy of posture specification via human posture simulation in the present study is comparable with the accuracy of posture specification that is determined by manual manipulations of a mannequin on a computer screen in the 3DSSPP to match the posture in a photograph (Liu *et al.* 1997). In a study by Liu *et al.* (1997), the average posture specification error (calculated with the same method used in the present study) for one photograph with or without lift asymmetry ranged approximately from 8° to 12°; whereas in the present study, the average posture simulation error for a similar setting ranged approximately from 10° to 13°. The errors in the manual posture specification using

3DSSPP in Liu's study appeared to be a bit smaller than those found in the human posture simulation in the present study. However, the process time for manual posture specification on a computer screen was significantly greater. Human subjects are capable of simulating several body postures simultaneously while on-screen mannequin manipulations for postural specification are typically accomplished for one body segment at a time. On average, 200 s were needed to complete one posture specification in Liu's study, as compared with approximately 20 s to complete one posture simulation via human posture simulation in the present study (Liu *et al.* 1997). For an epidemiological study, where a large number of lifts needs to be analysed with 3DSSPP, researchers may benefit from the human posture simulation method with a desirable accuracy. In addition, without additional process time, the three RNLE parameters (Vd, Hd, Ay) can also be obtained with this human posture simulation method. The disadvantage of this method, however, is a required large laboratory space and high cost of the instrumentation.

The simulation errors for trunk and leg angles were generally smaller than the average posture simulation error by 5–10°. The improved accuracy (~5.8° error) in simulating trunk flexion, one of the most commonly used postural risk factors for assessing LBDs, appears to be promising. The decreased trunk movement errors also indicate that the sources of the average posture simulation error came from the errors in simulating arm postures, especially arm horizontal position. To determine the arm horizontal angles, the method used in 3DSSPP must project the 3-D arm angles on the horizontal/transverse plane from a bird's eye view. When the arm vertical angles approach ±90°, the arm horizontal angles calculated may vary greatly due to the mathematical constraints imposed by converting the 3-D orientation of the arm segments to the 2-D angles defined by 3DSSPP. This may explain why the large errors in simulating the arm horizontal angles found in the present study tended to occur for simulating trunk flexion group A (postures 1 and 2), where the right and left vertical arm angles for both upper and lower arms were close to –90°. In this case, however, the varying arm horizontal angles do not cause large variations in the back compression force calculated by the 3DSSPP, as indicated by the 3DSSPP manual (Regents of University of Michigan 2001). In fact, when the arm vertical angles are at ±90°, the arm horizontal angles do not have any bearing on determining the posture and therefore do not cause any changes in the calculated back compression force (Regents of University of Michigan 2001).

As compared with other significant independent variables from the ANOVA results, including viewing angle ($p < 0.003$) and lift asymmetry × viewing angle two-way interaction ($p < 0.03$), it appears that trunk flexion angle ($p < 0.0005$) emerged as the most significant factor for causing increases in the average posture simulation error and other important posture simulation errors, such as trunk lateral bending and trunk flexion errors. One possible explanation is that the subjects were unable to watch and recall the reference postures with their heads facing down while simulating the reference postures. It may also be due to the subjects' limited ability to accurately perceive larger trunk flexion angles within the range tested. For the latter explanation, some data were used from a study by Genaidy *et al.* (1993), evaluating visual perception of shoulder elevation angles ranging from 8 to 179°. The errors in perceiving shoulder elevation angles from 8 to 72° were grouped for comparisons with the range of the trunk flexion angles (0–70°) evaluated in the present study. It was found that the absolute errors in the shoulder elevation angles for the three trunk flexion groups (0–30°, 30–60° and >60°) were approximately 6°, 7°and 13°, respectively. The finding seems to agree with the trends of errors in trunk lateral bending, trunk flexion and axial rotation found in present study. As the simulated trunk flexion angle increased, the trunk posture errors increased (Table 3, Panel B). Therefore, cautions should be exercised when simulating larger trunk flexion angles using the human postural simulation method.

To minimise the average posture simulation error, simulating a posture presented in side view is suggested. The average posture simulation errors for the side viewing angle were found to significantly and constantly decrease by approximately 1–2° for a variety of postures, as compared with those for the back and front viewing angles. It is unclear why the posture simulation errors were generally smaller for the side viewing angle. One possible explanation is that the postures simulated mostly concerned lifting motion on the sagittal plane. The subjects appeared to have a better ability to simulate and match the overall postures on the sagittal plane or a plane that is perpendicular to the viewing angle. Viewing angle, however, appears to be irrelevant if one is to assess only trunk postures (flexion, lateral bending and axial rotation) using the human postural simulation method.

Based on the finding regarding the two-way interaction between viewing angle and lift asymmetry presented in Figure 3, postures with lift asymmetry presented in the back viewing angle seemed to produce smaller errors than those presented in the side viewing angle. This approach, however, may not be appropriate if postures without lift asymmetry are simulated in such a setting because subjects appeared to be able to simulate postures without lift asymmetry more accurately if postures were presented in the side viewing angle. This finding suggests that viewing angle and lift asymmetry may not be the deterministic factors for the simulation errors. The viewing angle that is perpendicular to the plane of motion may be the most important factor for accurate posture simulation.

Unlike the average posture simulation error and trunk lateral bending error that were significantly affected by simulated trunk flexion, the RNLE parameters (Hd, Vd and Ay) were not significantly affected by it. The errors in the RNLE parameters were likely to be caused by multiple posture factors such as the arm and leg angles, which may have caused an offset to the errors in the three RNLE parameters.

The results of the errors in the three RNLE parameters calculated with human posture simulation can be compared with some manual measurement errors reported in two studies. Waters *et al.* (1998) found that the maximum errors in the manual measurements for Vd, Hd and Ay of 27 subjects for an asymmetrical lifting posture were 10.5 cm, 7.4 cm and 17°, respectively, while the maximum average errors (the maximum value of the average errors of eight subjects for 18 test conditions; referred to Table 2) in Vd, Hd and Ay for simulating six different working postures found in the present study were 5 cm, 5.7 cm and 27.7°, respectively. The maximum errors in Vd and Hd in the present study seemed to be smaller than those in Waters' study, while the maximum error in Ay in the present study seemed to be larger. The average errors in Vd, Hd and Ay can be compared with the results of another validation study for measurements for the three RNLE parameters. In a study by Dempsey *et al.* (2001), the differences in Vd, Hd and Ay between the reference and measured values for five different lifting tasks were reported. With the reported data, the average absolute differences (i.e. posture specification errors) were calculated between the reference and measured values across the five tasks. It was found that the average absolute errors in Vd, Hd and Ay for the five tasks were approximately 8.5 cm, 7.8 cm and 10°, respectively; whereas in the present study, the average absolute errors across all simulation conditions were 3.1 cm, 3.9 cm and 14.2°, respectively (Dempsey *et al.* 2001). Based on the comparisons of the maximum and average errors found in the three studies, it appears that the measurement errors in two RNLE parameters, Vd and Hd, using human posture simulation were smaller than those using manual measurement, whereas the measurement errors in Ay using human posture simulation were approximately 5–10° greater than those using manual measurements.

The increased errors in Ay using the human posture simulation should not have a significant impact on the LI because the tolerance of error in Ay is 15° (Waters *et al.* 1999). Any 15° increase in Ay causes a 5% error in LI calculations (Waters and Putz-Anderson 1993). The decreased errors in Vd and Hd using the human posture simulation would probably offset the increased errors in Ay and may increase the overall accuracy of LI calculations for the reason that Vd and Hd have more significant influences in calculating the LI than Ay (Waters *et al.* 1998).

There is no information available in the literature on the time required for measuring Vd, Hd and Ay. It is likely to be dependent on the complexity of the lift being analysed and the training that the analyst received. Both Dempsey's and Waters' studies indicate that proper training and sufficient measurement time are required to accurately measure the RNLE parameters (Waters *et al.* 1998, Dempsey 2002). The findings from the present study suggest that without understanding RNLE or receiving training for measuring the complex RNLE parameters, these parameters can be measured using the human posture simulation in a shorter time period (~20 s) with an improved accuracy, especially in estimating Vd and Hd. If 3DSSPP and RNLE are to be used simultaneously for evaluating a large number of lifting tasks, the human posture simulation method provides a very efficient way with desirable accuracy and precision.

The accuracy of the human posture simulation in the present study was determined by the subjects' ability to match their own simulated body postures to the reference postures that they had previously posed. Therefore, in the present study, differences in anthropometry between the simulators and their own simulated postures would not come into play. However, differences in the anthropometry between simulators and the workers they are simulating may affect the accuracy of simulation results. Future research is recommended to investigate the effects of anthropometrics of both simulators and workers being simulated on the overall accuracy of the human posture simulation method.

A limitation of the present study is that the direction (overestimate or underestimate) of the posture simulation errors was not analysed. Absolute errors, rather than algebraic errors, were used for testing the accuracy and precision of the human posture simulation method. Both positive and negative posture errors were treated the same in the statistical analysis. With algebraic errors, it would have been possible to investigate the subjects' ability to over- or under-simulate certain body angles. Using algebraic errors, however, may result in underestimations of the posture errors because a summation of random positive and negative posture simulation errors may cancel out the errors that occurred in different directions. This effect would be enhanced by collecting a larger number of trials for simulating the same posture. One of the goals of the human posture simulation method is to use one trial data for posture specification to save data process time. The evaluation of this goal using absolute posture errors seems to be a reasonable measure. Nevertheless, further investigations of humans' ability to over- or underestimate and simulate certain body angles should undoubtedly provide a deeper understanding of human posture simulation.

Factors such as weight of load, direction of hand exertion and frequency of the task and subject's anthropometric data can invariably affect the outcome variables of 3DSSPP and RNLE. Therefore, the effects of the posture simulation errors on the outcome variables (i.e. injury risk) cannot be determined completely with only the posture data collected in the study. It is agreed, however, that errors in posture specification are very important for determining the accurate outcome variables for injury risk estimation (Chaffin and Erig 1991, Liu *et al.* 1997, Dempsey *et al.* 2001). Quantifications and characterisations of errors in the human posture simulation found in the present study may provide useful information for researchers or practitioners who are interested in utilising human posture simulation to quantify postural stress and obtain the outcome variables of the 3DSSPP or RNLE.

References

Bernard, B.P., ed., 1997. *Musculoskeletal disorders and workplace factors, a critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity and low back*. Cincinnati, OH: NIOSH, US Department of Health and Human Services.

Burdorf, A. and Sorock, G., 1997. Positive and negative evidence of risk factors for back disorders. *Scandinavian Journal of Work Environment and Health*, 23, 243–256.

Callaghan, J.P., Salewytsch, A.J., and Andrews, D.M., 2001. An evaluation of predictive methods for estimating cumulative spinal loading. *Ergonomics*, 44, 825–837.

Chaffin, D.B., 1969. A computerized biomechanical model-development of and use in studying gross body action. *Journal of Biomechanics*, 2, 429.

Chaffin, D.B. and Baker, W.H., 1970. A biomechanical model for analysis of symmetrical sagittal plane lifting. *AIIE Transactions*, 2, 16–27.

Chaffin, D.B. and Erig, M., 1991. Three dimensional biomechanical static strength prediction model sensitivity to posture and anthropometric inaccuracies. *AIIE Transactions*, 23, 215–227.

Dempsey, P.G., 2002. Usability of the revised NIOSH lifting equation. *Ergonomics*, 45, 817–828.

Dempsey, P.G., *et al.*, 2001. Influence of measurement accuracy on the application of the 1991 NIOSH equation. *Applied Ergonomics*, 32, 91–99.

Garg, A. and Chaffin, D.B., 1975. A biomechanical computerized simulation of human strength. *AIIE Transactions*, 7, 1–15.

Genaidy, A.M., *et al.*, 1993. Can visual perception be used to estimate body part angles? *Ergonomics*, 36, 323–329.

Hoogendoorn, W.E., Poppel, M.N.M., and van Bongers, P.M., 1999. Physical load during work and leisure time as risk factors for back pain. *Scandinavian Journal of Work Environment and Health*, 25, 387–403.

Kumar, S., 1990. Cumulative load as a risk factor for back pain. *Spine*, 15, 1311–1316.

Lavender, S.A., *et al.*, 1999. Comparison of five methods used to determine low back disorder risk in a manufacturing environment. *Spine*, 24, 1441–1448.

Liu, Y., Zhang, Z., and Chaffin, D., 1997. Perception and visualization of human information for computer-aided ergonomic analysis. *Ergonomics*, 40, 818–833.

Marras, W.S., *et al.*, 1999. The effectiveness of commonly used lifting assessment methods to identify industrial jobs associated with elevated risk of LBDs. *Ergonomics*, 42, 229–245.

Norman, R., *et al.*, 1998. A comparison of peak vs. cumulative physical work exposure risk factors for the reporting of back pain in the automotive industry. *Clinical Biomechanics*, 13, 561–573.

Regents of University of Michigan, 2001. *Three Dimensional Static Strength Prediction Program manual*, version 4.3. Ann Arbor, MI: University of Michigan.

Waters, T.R., Baron, S.L., and Kemmlert, K., 1998. Accuracy of measurements for the revised NIOSH lifting equation. *Applied Ergonomics*, 29, 433–438.

Waters, T.R. and Putz-Anderson, V., 1993. Revised NIOSH equation for the design and evaluation of manual lifting tasks. *Ergonomics*, 36, 749–776.

Waters, T.R., Putz-Anderson, V., and Baron, S., 1998. Methods for assessing the physical demands of manual lifting: a review and case study from warehousing. *American Industrial Hygiene Association Journal*, 59, 871–881.

Waters, T.R., *et al.*, 1999. Evaluation of the revised NIOSH lifting equation. A cross-sectional epidemiologic study. *Spine*, 24, 386–394.

Waters, T., *et al*., 2010. Human posture simulation to assess cumulative spinal load due to manual lifting. Part I: methods. *Theoretical Issues in Ergonomics Science*, iFirst, doi:10.1080/14639221003639921.

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