

Identifying Less Stressful Work Methods: Computer-aided Simulation vs. Human Subject Study

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ABSTRACT

Engineering analyses of work methods can help identify approaches to reduce the risk of occupational injuries; computer-aided simulation technology is effective in terms of time and cost for evaluating multiple work methods. This paper analyzed scaffolding, a common activity in construction with high frequency of overexertion injuries, through a computer simulation model (3DSSPP) to identify less stressful work strategies. A laboratory study was also performed to verify the appropriateness of using the model for scaffolding job analyses.

Seven commonly used end-frame lifting techniques were evaluated. Computer simulations of these work techniques show that considerable biomechanical stress occurs to most of the workers at their shoulders and elbows. A symmetric front-lifting at knuckle height appears to be the less stressful work technique, as determined by computer simulation. The laboratory study of the seven lifting methods, by measuring whole body isometric strength, confirmed the 3DSSPP simulation results. The simulation model is suitable for identifying less stressful work methods; the net benefit achieved from the use of the model is a reduction in testing cost as compared to traditional prototyping methodologies. The "at risk" estimation of the model seems to be conservative when compared to the laboratory experiment results. This is probably because the isometric strength of construction workers is higher than that of workers in manufacturing, which was used in the 3DSSPP model.

INTRODUCTION

Computer-aided simulations are increasingly being used in evaluating the match between human capabilities and the requirements of tasks. The advantages of these simulations include 1) a reduction of time and thus cost as compared to the expense of making a full model, 2) the potential to offer more accuracy than the traditional manikins, and 3) an effective tool for communication among members of a design team [1].

Studies on injuries in the construction industry have indicated that workers using various types of scaffolds in residential and commercial construction sites are exposed to an increased hazard of overexertion [2]. A field study of overexertion risks to workers erecting and dismantling frame scaffolds has identified major scaffolding activities and seven typical lifting techniques [3].

The objectives of the study are to compare the biomechanical stress levels of the seven commonly used scaffold-end-frame disassembly techniques via a computer simulation model and to verify the suitability of using the model for identifying less stressful scaffold handling methods through a human subjects study.

METHODS AND PROCEDURE

Computer-aided simulation

The project researchers visited 12 construction sites to observe and videotape worker tasks involved with the erection and dismantling of frame scaffolds. Seven common scaffold-handling methods were identified through video analyses (Figure 1) of 29 construction workers' scaffold erection and dismantling techniques and strategies [3]. These scaffold-handling methods (human postures) were then reconstructed in a computer, using the University of Michigan 3D Static Strength Prediction Program (3DSSPP, version 4.2) [4]. The 3DSSPP allows analysts to create human work postures, via computer, that closely match those identified in the videotapes. With the posture information and other inputs, such as the weight of objects being handled and worker anthropometry information, the 3DSSPP reports biomechanical stresses on body parts for each simulation (Figure 2). The body weight of 75.2 kg, body height of 177 cm (the 50th percentile male), and hand-loads of 223 N, 312 N, 445 N, and 624 N were used for the simulations. The 223 N load is equivalent to an end-frame mass, whereas the 312N load represents the force needed to disassemble frame sections that are stuck together. The 445 N and 624 N loads represent twice the weight of the above two conditions, respectively.



Posture 1
Symmetric Front
Lifting (Chest Ht)



Posture 2
Asymmetric
Overhead Lifting



Posture 3
Symmetric Front
Overhead Lifting



Posture 4
Asymmetric



Posture 5
Symmetric Front
Lifting (Acromial Ht)



Posture 6
Symmetric Front
Lifting (Elbow Ht)



Posture 7
Symmetric Front
Lifting (Knuckle Ht)



Baseline posture
46 cm Hand Sep.
Lifting (Elbow Ht)



Step 1: Use video analysis to characterize scaffold-handling techniques.



Step 2: Use computer to reconstruct/simulate current scaffold-handling techniques.



Step 3: Estimate biomechanical stresses on body parts.

Figure 2. Steps for analyzing scaffold-handling techniques during computer simulation

The biomechanical information was then used to determine the magnitude of overexertion problems associated with scaffolding tasks and to identify less stressful work methods.

Human subject study

Thirty-six male construction workers were used to study the same seven postures associated with scaffold end frame disassembly. Ten subjects were used for exactly

Figure 1. The seven common scaffold-lifting methods and a simulated baseline posture

two postures and the remaining subjects were used for one posture. Subjects were recruited from the local construction industry in Morgantown, WV. The average height and weight of the subjects were 178.7 cm (S.D. = 5.5 cm) and 92.2 Kg (S.D. = 16.9 Kg), respectively, and their ages ranged from 18 to 49 years.

A strength-testing apparatus was designed and fabricated at the NIOSH facility in Morgantown for quantification of isometric strength during simulated scaffold end-frame disassembly. This apparatus consisted of a computer-controlled data acquisition system, Bertec force platforms, and a custom fabricated fixture and scaffold end frame [5]. The data acquisition system sampled six channels of data from each force platform at a sampling frequency of 100 Hz per channel and displayed isometric force in real time on the biofeedback screen while the subject performed an isometric exertion. The software was configured to determine in real time if each individual exertion and set of three exertions met the project's acceptance criterion. The acceptance criterion was defined by the force deviation being less than 10% of the calculated mean isometric force derived from the intermediate 3 seconds of the exertion [6]. To determine if the three "successful" isometric exertions were maximal and consistent in each task, the test-retest coefficient of variation (defined as the standard deviation of the test-retest mean values divided by the mean of the test-retest values) should be no greater than 10% [7].

The experiment used 7 subjects each for postures 1 to 4 and 6 subjects each for postures 5 to 7. Each subject performed three successful isometric exertions in the experiment as well as three successful isometric exertions in a baseline posture (symmetric lift at elbow height, 46 cm hand separation distance, 90° elbow flexion; Figure 1). Exertions were performed for a duration of 5 seconds each at 2-minute intervals. The postures in which subjects were assigned to tasks were randomized.

RESULTS

Computer Simulation

All of the seven postures were assimilated for the 50th percentile of the population using the 3DSSPP program manufactured by the University of Michigan [4]. The program evaluated the lifting capacity of six body parts (elbow, shoulder, hip, knee, trunk and ankle) and helped identify the limiting factor (the body part with lowest capability) in a specific lifting task.

Table 1 presents the results of computer simulation involving the elbow, shoulder and hip in seven postures; the knee, trunk, and ankle body parts were excluded from the table because they did not serve as the limiting

factor for any posture. Results are in the form of estimated population percentages with hand-load strength ability for each posture and corresponding body part. As expected, percentages decreased with hand-load magnitude.

The limiting factor for postures 1, 3 and 7 was mainly the shoulder whereas the limiting factor was the elbow in postures 5 and 6. The shoulder and hip were the limiting factors in postures 2 and 4.

Posture 7 was the least stressful work technique followed by postures 3 and 6. Posture 7 accommodated 98 percent at the 223 N hand load and 76 percent at the 445 N hand load. Posture 3 accommodated 98 percent at 223 N and 70 percent at 445 N. Posture 6 accommodated 97 percent at 223 N and 62 percent at 445 N.

	Hand-Load	624 N	445N	312N	223N
Posture 1	Elbow	13	56	89	97
	Hip	96	96	97	97
	Shoulder	18	38	46	72
Posture 2	Elbow	26	75	94	98
	Hip	59	75	85	87
	Shoulder	29	55	75	96
Posture 3	Elbow	20	75	96	99
	Hip	100	99	99	99
	Shoulder	23	70	93	98
Posture 4	Elbow	12	71	95	99
	Hip	64	76	83	87
	Shoulder	8	53	88	97
Posture 5	Elbow	72	93	98	99
	Hip	95	96	97	98
	Shoulder	2	29	38	73
Posture 6	Elbow	13	62	90	97
	Hip	100	100	99	99
	Shoulder	47	84	95	98
Posture 7	Elbow	40	83	96	99
	Hip	100	100	99	99
	Shoulder	29	76	94	98

Notes:

1. The numerical values are in percentage.
2. The body part with the lowest percentage in a certain posture is considered the limiting factor for a particular task because this factor defines the percentage of population capable of performing this task.
3. In addition to the elbow, hip and shoulder, the computer assimilation evaluated the knee, torso and ankle for their respective capacity. However, since none of these body parts is the limiting factor, they are not included in this table.

Table 1. Computer assimilation of the capacity for lifting a scaffold end frame among males of 50th percentile of the population. Results are percentages of workers with strength greater than specified hand load

Summary statistics for whole body isometric strength are given in Table 2. Through calculation of two-sided 95% tolerance bounds [8], the percentages of male construction workers with strength ability at each hand-load and posture were estimated (Table 2).

As expected, percentages decreased with hand-load magnitude. Percentages were highest for posture 7, followed by postures 6 and 3. Posture 7 (knuckle height) was the least stressful work technique, accommodating greater than 99 percent at the 223 N hand load and 92 percent at the 445 N hand load. Posture 3 accommodated 98 percent at 223 N and 85 percent at 445 N. Posture 6 accommodated 99 percent at 223 N and 70 percent at 445 N.

The percentages of workers with strength ability for each hand-load and study are summarized in Table 3. In general, the estimated percentages are lower for the computer simulation study results.

Percentage similarity between studies is high for hand-loads up to 445N and low for 624N. For the 624N hand-load, the average percentage difference between studies was 17 percentage points and in one instance, there was a 38-percentage point difference between studies. For hand-loads less than or equal to 445N, the average percentage difference between studies was 5 percentage points and all differences were lower than 16 percentage points.

Percentages between studies were most similar for postures one, two, and five where the average percentage difference between studies were 3.5, 1.5, and 4.8 percentage points, respectively. Percentages were less similar for postures three, four, six, and seven, where the average percentage difference between studies were 14.3, 13.0, 8.8, and 11.8 percentage points, respectively.

Whole Body Isometric Strength (N)							
	Posture						
	1	2	3	4	5	6	7
Mean	366.3	466.7	676.3	547.5	334.4	543.7	644.7
Std Dev	91.5	117.6	194.0	136.2	110.4	62.7	71.1
Coeff. Of Variation	0.25	0.25	0.29	0.25	0.33	0.12	0.11
Minimum	212.5	350.3	463.9	341.8	221.9	441.2	540.5
Maximum	543.1	768.6	1088.3	830.7	578.0	628.9	759.8
Number of Subjects	7	7	7	7	6	6	6
^{1,2} Percent of Forces Above 624N	12%	27%	58%	39%	2%	33%	55%
^{1,2} Percent of Forces Above 445N	38%	53%	85%	65%	27%	70%	92%
^{1,2} Percent of Forces Above 312N	58%	73%	96%	85%	55%	95%	99%
^{1,2} Percent of Forces Above 223N	71%	86%	99%	94%	73%	99%	>99%

Notes:

1. Values are based on normal distribution two-sided 95% tolerance bounds for population of male construction workers.
2. Standard deviations were pooled together for postures 1 to 4 and 5 to 7. Degrees of freedom were 24 for postures 1 to 4 and 15 for postures 5 to 7.

Table 2. Summary statistics for the Human Subject Study

		^{1,2} Percent of Forces Above			
		624N	445N	312N	223N
Posture 1	CS ³	13%	38%	46%	72%
	HS ³	12%	38%	58%	71%
Posture 2	CS ³	26%	55%	75%	87%
	HS ³	27%	53%	73%	86%
Posture 3	CS ³	20%	70%	93%	98%
	HS ³	58%	85%	96%	99%
Posture 4	CS ³	8%	53%	83%	87%
	HS ³	39%	65%	85%	94%
Posture 5	CS ³	2%	29%	38%	73%
	HS ³	2%	27%	55%	73%
Posture 6	CS ³	13%	62%	90%	97%
	HS ³	33%	70%	95%	99%
Posture 7	CS ³	29%	76%	94%	98%
	HS ³	55%	92%	99%	>99%

Notes:

1. Human subject study percentages are based on normal distribution two-sided 95% tolerance bounds for population of male construction workers. For the Human Subject Study, standard deviations were pooled for postures 1 to 4 and 5 to 7. Degrees of freedom were 24 for postures 1 to 4 and 15 for postures 5 to 7.
2. CS = Computer Simulation Study, HS = Human Subject Study.

Table 3. Percentage of workers (for both studies) with strength greater than specified hand load

DISCUSSION

It is recognized that when the strength requirements of a task exceeded the isometric strength of workers, the mean injury incident and severity rate increased by a ratio of 3:1 [7]. The computer simulation results indicated that postures 7, 3, and 6 would be the most favorable methods, 97 to 98 percent of "average" persons would be able to handle the task at minimum overexertion risk when using these postures for non-excessive lifting of the 223N scaffold end-frames. If we give a safety factor of 2 for frequent disassembly, then the maximum lifting strength required by the job should not exceed 50% of maximum isometric strength. Using this paradigm, 445 N (based on a 222.5 N scaffold) would be a critical check-point for evaluating scaffold-end-frames disassembly postures. The computer simulation results showed that posture 7 would be the most acceptable posture; 76 percent of "average" males would be able to handle the task at minimum overexertion risk.

The human subject study confirmed that posture 7 was the least stressful method. The net benefits achieved from computer model use are a reduction in testing cost as compared to traditional prototyping methods and an understanding of limiting factors (body parts/joints) for different work postures. The consistent results from both computer simulation and human study indicate that the 3DSSPP model is suitable for scaffolding job analyses.

The "at risk" estimation from the computer model seems to be conservative when it is compared to the human subject experiment results. The difference was more obvious at heavier loads. This is probably because isometric strength of construction workers in our laboratory study was higher than that of workers in the manufacturing industry (which was used in the 3DSSPP model). Whole body isometric strength values (457 N mean) in a baseline posture for the construction industry subjects (used in human subject study) were somewhat higher than those found by Chaffin et al. [7] in 551 male industrial workers between 20 and 50 years of age (322.6 N – 430.5 N mean).

As described in the methods section, the authors used a function provided by the 3DSSPP to manipulate human work postures, via computer, to obtain postures that matched those identified in the videotapes. Several trials were performed for each posture to obtain the best match. In some instances, there were several similar posture matches. We chose the posture with the highest percent capable of performing the task. This procedure was based on an assumption that a person will optimize his/her linkage system when a gross posture is defined. We believe this approach is reasonable.

In scaffolding fields, workers sometimes lift or carry an end frame with hand locations away from the center-of-mass. If researchers want to analyze the posture using the 3DSSPP model, they need to manually calculate a correct input hand force. Possibly, the model could be enhanced to include a subroutine that calculates this

hand force. The subroutine would be useful for analyzing worker biomechanical stress during the large-size material handling that commonly occurs in the construction and agricultural industries.

CONCLUSION

Based on the computer simulations, posture 7 would be the most favorable postures for use in scaffold end frame disassembly. The laboratory human subject study confirmed the appropriateness of using the 3DSSPP model for scaffolding job analyses. The "at risk" estimation from the computer model seems to be conservative when it is compared to the laboratory experiment results, especially at high load conditions. This is probably because the isometric strength of construction workers is higher than that of workers in manufacturing industry, which was used in the 3DSSPP model.

Although both the computer simulation and human subject studies identified posture 7 as the least stressful technique for scaffold end frame disassembly, workers need to be aware that the likelihood of fatigue and injury exists for some individuals. Likelihood of fatigue and injury can increase when using a higher disassembly force for frame sections that are stuck together.

REFERENCES

1. Porter, J.M., Man Models and Computer-aided Ergonomics. *Computer Applications in Ergonomics, Occupational Safety and Health*, Proceedings of the International Conference on Computer-Aided Ergonomics and Safety. pp13-20. Tampere, Finland May 18-20, 1992.
2. National Constructors Association, *An Assessment of Carpenter Injury Risks Needing Research*, NIOSH DSR task order report, Washington, D.C., 1985.
3. Hsiao, H. and Stanevich, R., Biomechanical Evaluation of Frame Scaffolding Tasks, *International Journal of Industrial Ergonomics*, vol. 18, pp407-415, 1996.
4. University of Michigan, *3D Static Strength Prediction Program Version 4.2*, University of Michigan, 1999.
5. Cutlip, R., Hsiao, H., Becker, E., Garcia, R., and Myers, J. Isometric Strength During Scaffold End Frames Disassembly, *Society of Automotive Engineers Technical Paper #1999-01-1907*, 1999.
6. Caldwell, L.S., Chaffin, D.B., Dukes-Dobos, F.N., Kroemer, K.H.E., Laubach, L.L., Snook, S.H., and D. E. Wasserman, A Proposed Standard Procedure for Static Muscle Strength Testing, *American Industrial Hygiene Association Journal*, vol. 35, no. 4, 1974.

7. Chaffin, D.B., Herrin, G.D., and Keyserling, W. M., Preemployment Strength Testing, *Journal of Occupational Medicine*, vol. 20, 1978.
8. Hahn, G. J. and Meeker, W. Q., *Statistical Intervals: A Guide for Practitioners*, Wiley, 1991.

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