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Biomechanical evaluation of scaffolding tasks

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Abstract

A field study was conducted to identify tasks and activities that increase the risk of overexertion injury associated with the erection and dismantling of frame scaffolds, and to determine strategies that would prevent or reduce the worker's risk of injury. Twelve construction sites involving 29 workers were visited. The investigation identified that lifting scaffold end frames, carrying end frames, handling scaffold planks, removing cross braces, and removing guardrails are activities that increase the risk of overexertion injuries during task performance. This paper has focused on end-frame handling problems. Although the techniques used to handle end frames varied among the construction sites and subjects, six lifting and five carrying strategies were commonly used. Computer simulations of these work techniques show that considerable biomechanical stress occurs to most of the workers at their shoulders, elbows, and hips. To reduce overexertion injuries during erection and dismantling of frame scaffolds, design of an assistive device to lift scaffold end frames and modifications to the end-frame fixtures are suggested. Future research areas for the prevention of injury during scaffolding work are also proposed.

Relevance to industry

The construction industry is characterized by high frequencies of musculoskeletal injuries. This paper analyzes scaffolding, a common activity in construction, evaluates stresses associated with different methods used, and develops recommendations on changes in scaffold design, training and accessory equipment necessary to reduce accidents and injuries.

Keywords: Construction; Scaffolding; Musculoskeletal injuries

1. Introduction

The construction industry has the highest injury rate among the major U.S. industry divisions (U.S. Department of Labor, 1992). The prevalence of large construction equipment, the constant use of machinery and powered tools, working on elevated work

surfaces, and the manual handling of heavy construction materials are factors which contribute to making construction one of the most hazardous industries. In addition to these hazardous factors is the ever-changing work environment. In other industries, the environment and work methods remain essentially unchanged from day to day. At construction sites, however, the environment, the work to be completed, and the composition of the crews change continuously, exposing workers to unforeseen and unfamiliar hazards.

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Scaffolding work, featuring many of the above working conditions, is one of construction's highest risk jobs. Scaffolds are used in all aspects of construction, including building construction, heavy construction, and special trades. Laborers, roofers, plasterers, brickmasons, and a variety of other trade workers utilize scaffolds in the performance of their jobs. However, carpenters normally erect and dismantle the scaffolds used by the trades. The National Constructors Association (1985) identified the tasks of erecting and dismantling frame scaffolds as two of the most stressful tasks for the carpenter trade. The major risks associated with these tasks are overexertion and fall hazards. OSHA has promulgated construction safety standards for scaffolds to reduce fall injuries during erection and dismantling of scaffolds (OSHA, 1991). However, the overexertion problems and ergonomics concerns of manually handling scaffolding have not been well explored. With the recognition of ergonomics as a construction safety solution, the need for additional research on the application of ergonomics principles to reduce overexertion injuries in the construction industry is becoming evident. A study of overexertion risks to workers erecting and dismantling frame scaffolds was initiated by the National Institute for Occupational Safety and Health (NIOSH). The objectives of the study are to identify the activities which increase a worker's risk of exposure to overexertion hazards during the erection and dismantling of frame scaffolds and to determine strategies to reduce the occurrence of these hazards.

2. Methods

The project researchers conducted site visits of twelve construction sites to observe and videotape worker tasks involved with the erection and dismantling of frame scaffolds. These construction sites were located in northern West Virginia and western Pennsylvania. Ten of the twelve construction sites were using welded-tubular end-frame scaffolds of the open-type design (Fig. 1). A welded-tubular end frame is a hollow metal structure with two legs that can be inserted into the top of the lower end frame to establish scaffold tiers. These ten sites were selected for video analysis to categorize current worker tech-

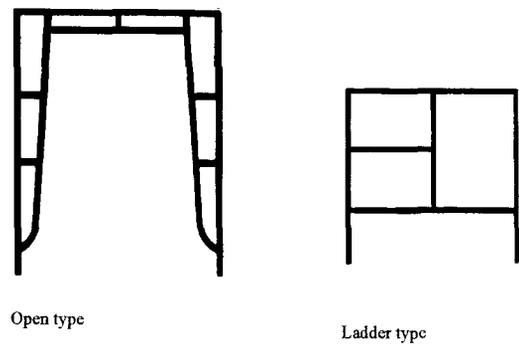


Fig. 1. Typical styles of welded-tubular scaffold end-frames.

niques and methods of handling scaffolding components. Scaffold erection and dismantling techniques and methods for twenty-nine construction workers were studied. The videotapes were time coded to allow accurate and quick access to specific video frames. Different scaffold-handling methods, as well as the frequency of occurrence of each method, were identified through video analyses. The human postures associated with each of these scaffold-handling methods were reconstructed in a computer simulation, using the University of Michigan 3D Static Strength Prediction Program [3DSSPP] (University of Michigan, 1993), to estimate the biomechanical stresses on a worker's body parts. Fig. 2 depicts the procedure used to analyze the scaffold-handling techniques. The 3DSSPP allows analysts to manipulate human work postures to obtain postures that match those identified in the videotapes. With the posture information and other inputs, such as the weight of objects being handled and worker anthropometry, the program calculates the biomechanical stresses on body segments for each simulation. The biomechanical information was then used (a) to determine the estimated magnitude of overexertion problems associated with scaffolding handling tasks, (b) to identify less stressful work methods, and (c) to suggest overexertion injury prevention strategies.

3. Results

The task components involved with the erection and dismantling of frame scaffolds include (1) preparing foundation, (2) carrying scaffold parts, (3)

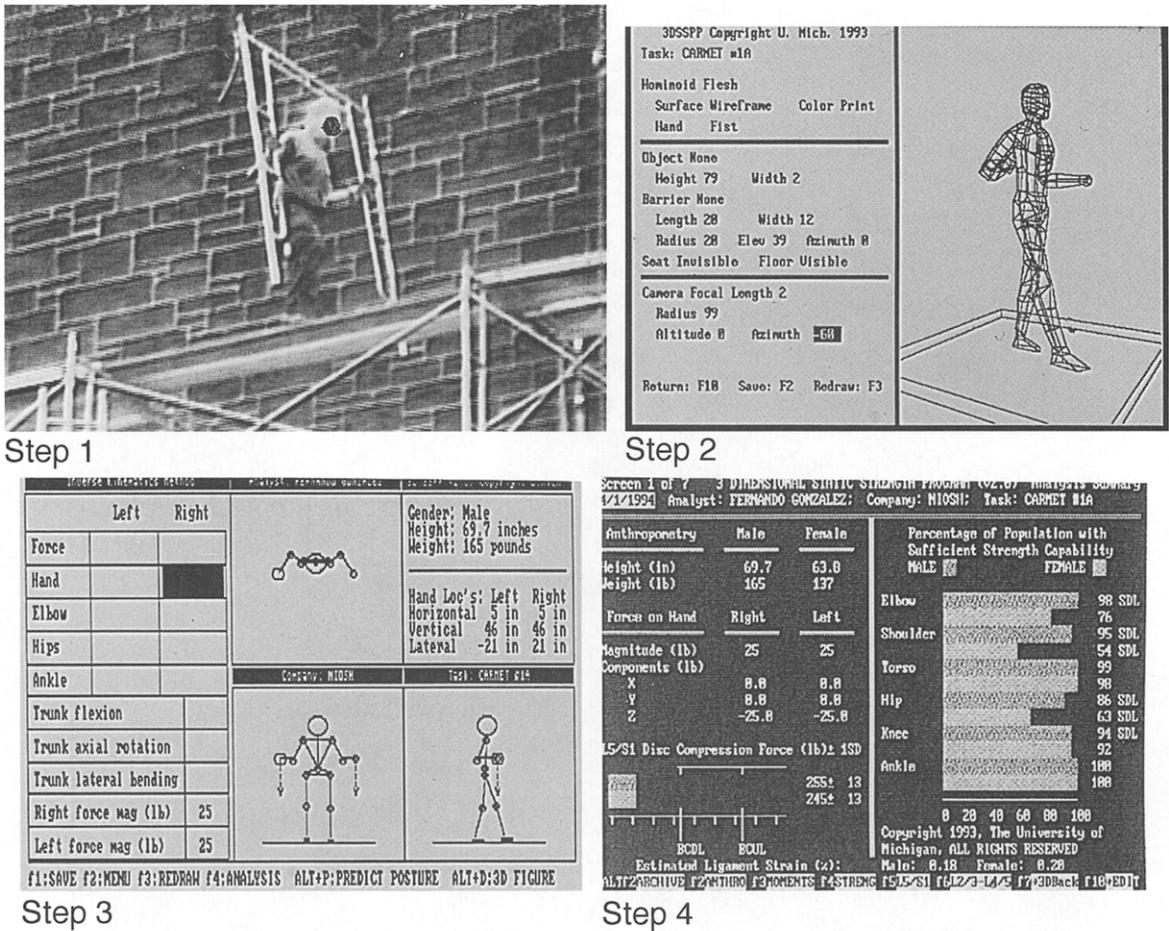


Fig. 2. Steps of study procedure to analyze scaffold handling techniques. Step 1: Use video analysis to characterize scaffold-handling techniques; Step 2: Use computer to reconstruct/simulate current scaffold-handling techniques; Step 3: Input other simulation information for biomechanical analysis; Step 4: Identify the magnitude of potential musculoskeletal problems associated with the simulated tasks.

erecting/removing end frames, (4) erecting/removing cross braces, (5) installing/removing access ladders, (6) installing/removing planks, (7) installing/removing guardrails, and (8) securing/removing scaffold tiebacks. These components are shown in Fig. 3. The investigation identified lifting scaffold end frames, carrying end frames, handling scaffold planks, removing cross braces, and removing guardrails as activities that increase biomechanical stresses to the worker and thus increase the risk of overexertion injuries. These activities involve handling bulky materials, awkward working postures, restricted work spaces, or elevated work surfaces.

Fig. 4 presents the end-frame handling methods. Video analyses showed that six lifting and five carrying methods for end frames were commonly used. The methods used were different at the ten construction sites (Table 1). Computer simulations of these work techniques show that considerable biomechanical stress occurs to most of the workers at their shoulders, elbows, and hip. The simulation results of all work techniques are summarized in Table 2.

Lifting methods 1 and 2 were the most commonly used end-frame lifting techniques among the subjects studied (Table 1). Biomechanical analyses indicate that both methods put scaffold workers at an in-

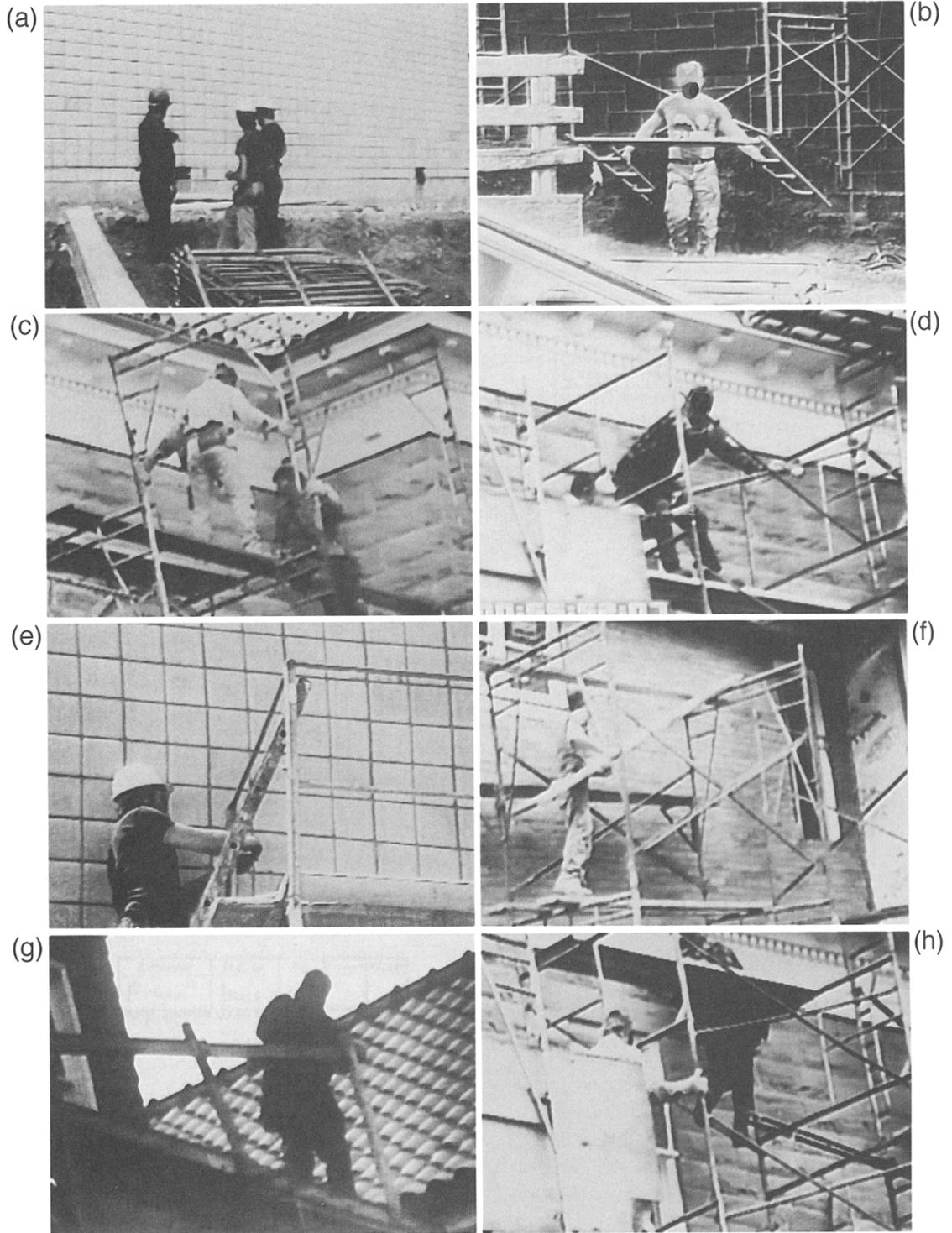


Table 1
Frequency analysis of end-frame lifting and carrying strategies at 10 different construction sites^a

Sites	End-frame lifting (see Fig. 4 for pictures of the lifting methods)						Total
	Method 1	Method 2	Method 3	Method 4	Method 5	Method 6	
Site 1	6	1	1	2	0	0	10
Site 2	3	0	1	0	0	3	7
Site 3	2	1	1	8	0	0	12
Site 4	1	0	0	3	0	4	8
Site 5	10	1	1	0	0	0	12
Site 6	20	32	0	0	0	0	52
Site 7	18	20	0	0	0	0	38
Site 8	15	8	2	0	3	0	28
Site 9	13	0	0	0	0	0	13
Site 10	6	0	0	3	0	0	9
Total	94	63	6	16	3	7	189

Sites	End-frame carrying (see Fig. 4 for pictures of the carrying methods)					Total
	Method 1	Method 2	Method 3	Method 4	Method 5	
Site 1	2	4	0	0	0	6
Site 2	3	2	2	0	0	7
Site 3	0	10	0	2	0	12
Site 4	1	2	2	0	0	5
Site 5	6	2	1	0	1	10
Site 6	9	34	14	0	0	57
Site 7	9	12	0	0	0	21
Site 8	1	0	0	7	7	15
Site 9	13	5	11	0	0	29
Site 10	8	3	7	0	0	18
Total	52	74	37	9	8	180

^a Average duration of the observations at each site was 73 minutes with 33 minutes standard deviation.

creased risk of overexertion at the elbows and shoulders (Table 2). It is estimated that: (a) 58% of the female and 96% of the male population have sufficient shoulder strength capacity to perform lifting method 1; and (b) 1% of the female and 47% of the male population have sufficient elbow strength capacity to perform lifting method 2. Lifting methods 3, 4, and 5 require awkward upper extremity extension, torso flexion, or torso twisting which can contribute to increased biomechanical stress to these

body parts (Fig. 4 and Table 2). Method 6 involves two workers, yet it is not necessarily the least stressful. The posture that workers have to assume to lift the end frame puts significant biomechanical stress on their shoulders, torsos, and hips. In addition, method 6 can be performed only on the ground and is not practical at elevated levels.

Carrying methods 1, 2, and 3 appear to be the most common end-frame carrying methods. Biomechanical analyses indicate that these three methods

Fig. 3. Task components of erection and dismantling of frame scaffolds. (a) Prepare foundation; (b) Carry scaffold parts; (c) Erect/remove end frames; (d) Erect/remove cross braces; (e) Install/remove access ladders; (f) Install/remove planks; (g) Install/remove guardrails; (h) Secure/remove scaffold ties.

put scaffold workers at an increased potential of overexertion at the elbows, shoulders, and hips (Table 2).

Carrying methods 4 and 5 also increase the biomechanical stress on the workers' elbows and

hips because of asymmetric loading and awkward postures (Table 2).

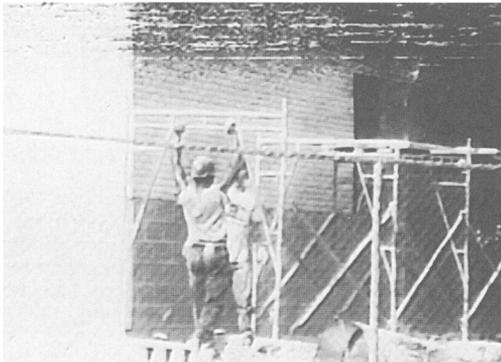
In summary, lifting method 1 and carrying method 2 are the least stressful end-frame handling techniques for a single-person operation. However, nei-



Lifting method 1



Lifting method 2



Lifting method 3



Lifting method 4



Lifting method 5



Lifting method 6

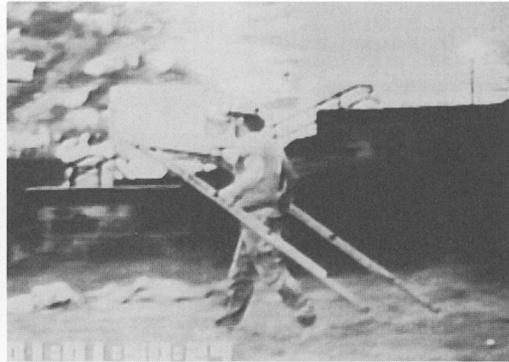
Fig. 4. Typical end-frame lifting and carrying techniques.

ther of these two techniques is considered physically acceptable to the general work population. An increased risk of injury and fatigue may exist for some individuals if they are not carefully trained for the lifting and carrying tasks and the scaffolding task is

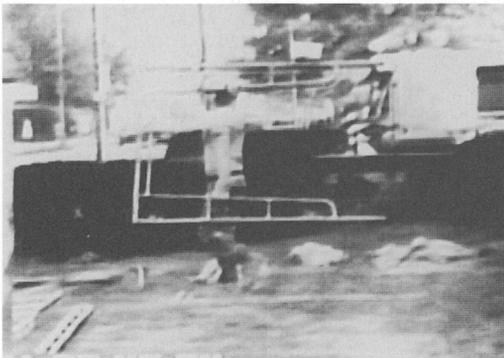
not modified. Approximately 4% of the male workers and 37% to 42% of the female workers will exceed recognizably safe biomechanical stresses while performing these tasks. The methods currently being used to lift and carry end frames are putting



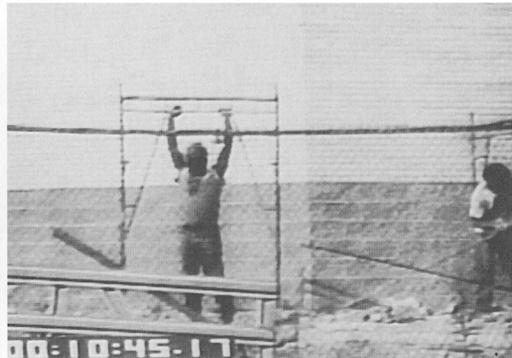
Carrying method 1



Carrying method 2



Carrying method 3



Carrying method 4



Carrying method 5

Fig. 4 (continued).

Table 2

Summary of percentage of population with sufficient strength capability to lift and carry end frames using different end-frame lifting and carrying methods (as estimated by the University of Michigan 3DSSPP)

Body part	Lifting					
	Method 1	Method 2	Method 3	Method 4	Method 5	Method 6
Elbow (M) ^a	98	47	86	94	99	99
Elbow (F) ^a	74	1	18	33	85	90
Shoulder (M)	96	98	99	69	84	97
Shoulder (F)	58	78	99	3	15	69
Torso (M)	99	98	99	97	96	96
Torso (F)	98	96	99	94	90	88
Hip (M)	98	96	99	63	88	73
Hip (F)	98	93	99	19	64	28
Knee (M)	99	99	98	96	99	96
Knee (F)	99	99	97	96	94	84
Ankle (M)	99	99	99	56	98	99
Ankle (F)	99	99	99	14	97	99

Body part	Carrying				
	Method 1	Method 2	Method 3	Method 4	Method 5
Elbow (M)	98	99	79	97	91
Elbow (F)	76	87	10	47	26
Shoulder (M)	95	96	92	100	99
Shoulder (F)	54	63	38	99	93
Torso (M)	99	99	99	99	99
Torso (F)	98	98	97	99	98
Hip (M)	86	87	88	91	85
Hip (F)	63	66	73	78	65
Knee (M)	94	94	95	91	92
Knee (F)	92	91	95	87	89
Ankle (M)	100	100	88	100	97
Ankle (F)	100	100	55	100	95

^a (M): Male, (F): Female

scaffold workers at an increased risk of overexertion injury at their shoulders, elbows and hips because of the resulting biomechanical stresses.

4. Discussion

In this study, all of the lifting techniques were simulated with the assumption that the lifting motions were smooth. The open-type end frame weighs 22.7 kg (50 pounds) and thus the force at the hands was assumed to be 222 Newtons (50 pound force) in total for each simulation. In the workplace, however, the force that workers exert while lifting an end frame is usually higher than the weight of the end frame. The frame connections can clog with dirt,

cement, or rust, and thus require more external force to be coupled or uncoupled from an interconnecting frame section. A simulation was performed using lifting methods 1 and 2 to compare the stress generated by smooth lifting of 222 Newtons (50 pounds force) versus a jerk motion of 330 Newtons (74 pounds force). The results show significantly increased biomechanical stresses at the elbow, shoulder, and torso during the jerk motion. Only a limited percentage of the general adult population has sufficient strength capability to perform this task (male 73%, female 8% for method 1 and male 27%, female 1% for method 2). Therefore, the potential overexertion exposure is very high to scaffold workers who must dismantle end frame sections that are stuck together. In addition, because of the interaction of (a)

limited work space and (b) weight and bulky size of end frames, typically 1.52 meters wide by 2 meter height (5 feet by 6.6 feet), the scaffold erector's exposure to a fall is increased. Often, to be able to generate sufficient power to lift an end frame, workers will grasp the end frame at a location below elbow height. The center-of-mass of an open type end frame, however, is typically at or above the workers' shoulder height. Once an end frame is lifted out of a lower frame, the weight and the momentum of the top portion of the end frame will pull the workers forward or backward, causing them to become unbalanced and thus increasing their risk of a fall. The Scaffold Industry Association (1990) survey of fall incidences involving scaffold erectors during 1985 to 1989 confirms that loss of balance was the primary cause of scaffold-related fall injuries.

Detailed analyses of the plank-handling task are not presented in this paper; however, preliminary analyses indicate that four carrying and three lifting methods are commonly used while performing this task. Due to the heavy weight (36 kg typically) and bulky size (3.3 meters or 4 meters long) of scaffold planks, and the restricted work space inherent during erection and dismantling of scaffolds, construction workers are exposed to significant biomechanical stresses at the shoulders, elbows, and torso from plank handling. Redesign of planks utilizing lightweight materials and other fixtures is strongly recommended.

5. Conclusion

This investigation identified that lifting and carrying scaffold end frames are activities that generate high levels of biomechanical stress and therefore increase the risk of overexertion injuries occurring during erection and dismantling of frame scaffolds. The techniques used to handle end frames varied among construction workers performing scaffolding

tasks. Lifting method 1 and carrying method 2 (both shown in Fig. 4) appear to be the most common and the least stressful end-frame handling techniques from a biomechanical perspective for a single-worker operation. However, the likelihood of fatigue and injury exists for some individuals even when one of these methods is used, especially if scaffold end frame sections are stuck together. To reduce the risk of overexertion injuries during erection and dismantling of frame scaffolds, the following solutions are suggested: (1) design assistant devices to allow the scaffold erectors to assume better upper extremity posture and to require less exerting force during the scaffold dismantling phase, (2) redesign end frames utilizing lightweight materials, and (3) modify end frames by providing hand grips and changing the shape and center of mass of the frames. To reduce the risk of falls and fatigue, further laboratory evaluations to better understand how end frame lifting techniques affect physiological energy consumption, postural sway, motor response time, and center-of-body-mass shifting are needed.

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