

Optimal hand locations for safe scaffold-end-frame disassembly

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Abstract

Overexertion and fall injuries comprise the largest category of injuries among scaffold workers. A significant portion of these injuries is associated with scaffold-end-frame dismantling tasks, which require both muscle strength and postural balance skills. The commonly used tubular scaffold end frame is 1.52-m wide × 2-m high and weighs 23 kg. Previous studies have indicated that a great muscle strength can be generated when scaffold workers placed their hands symmetrically at knuckle height. However, adequate postural stability can only be reached when the workers placed their hands at the chest or shoulder height, which is near to the height of scaffold-end-frame center-of-mass. A reasonable approach to solve this dilemma is to develop an assistive lifting device, such as a light-weight clip-and-lift bar, that allows workers to place their hands at the height of the center-of-mass of end frames and concurrently allows an optimal hand separation for them to generate an adequate maximum isometric muscle force to safely accomplish the task.

This study was conducted to determine the optimal hand location for a conceptual assistive lifting device to mitigate potential postural imbalance while reducing overexertion hazards during scaffold disassembly. This location would be within a window defined by a vertical hand placement between shoulder height and knuckle height and by a horizontal hand separation distance of shoulder width to end-frame width. The whole-body maximum isometric strength of 54 construction workers was measured in nine symmetric scaffold-end-frame disassembly postures, defined by a combination of three vertical hand placements by three horizontal hand separation distances within the aforementioned window. The study apparatus include a computer-controlled data-acquisition system, a custom-fabricated scaffold fixture, and two Bertec force platforms.

An analysis of variance showed that the interaction effect of vertical hand placement and hand separation on workers' maximum isometric strength was significant ($p < 0.004$). A hand location between elbow height and chest height with a hand separation distance of 46 cm (a conceptual, light-weight assistive bar) would allow workers to generate sufficient isometric strength (about twice that of the scaffold weight) to disassemble the typical 23 kg scaffolds while concurrently allowing them to mitigate the likelihood of postural imbalance. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Isometric strength; Scaffold; Overexertion; Postural stability

1. Introduction

Dismantling of frame scaffolds has been identified as one of the most hazardous tasks for the carpenter trade in the construction industry due to overexertion and fall hazards (National Constructors Association, 1985). The overexertion hazards are associated with muscular force insufficiency for scaffolding work, and job designs, which are incompatible with workers' performance. The fall hazards are associated with scaffolding task design, environmental conditions, and personal factors; losing

balance while handling scaffold end frames is one of the major intrinsic factors for fall incidents during scaffolding work.

A previous study that investigated the maximum isometric strength of construction workers in typical scaffold disassembly postures found that a symmetric front lifting method with hand locations at knuckle height (Fig. 1a) would be the most favorable posture to reduce the risk of overexertion (Cutlip et al., 2000). However, the risk of worker fall is relatively high when this dismantling method is employed. The commonly used tubular scaffold end frame is 1.52-m wide × 2-m high and weighs 23 kg. The center-of-mass of the end frame is typically at the workers' chest or shoulder

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Fig. 1. A great muscle strength can be generated when scaffold workers placed their hands at knuckle height (a). However, once an end frame is lifted out of the lower frame using the method, a fractional force at the anterior–posterior direction plus 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 (b).

Table 1
Anthropometric data of the subject population

Variable	Mean	Standard deviation	Range
Age (year)	35.4	8.2	18–49
Height (cm)	178.3	5.3	165.1–190.7
Body mass (kg)	92.2	16.9	65.9–140.0
Acromial height (cm)	147.6	5.2	137.6–160.9
Acromial width (cm)	41.4	2.4	36.0–48.6
Chest height (cm)	131.6	4.7	122.3–141.0
Elbow height (cm)	111.3	4.6	102.6–122.3
Knuckle height (cm)	80.6 ^a	4.0	73.4–89.5

^aThe mean knuckle height was 100.1 cm when workers were lifting scaffold end frames. It was 80.6 cm when the hands were resting at a standard standing posture.

height. Once an end frame is lifted out of a lower frame using the aforementioned method, the weight and the momentum of the top portion of the end frame will pull the workers forward or backward (due to the long moment arm between the hand locations and the center-of-mass of the scaffold end frame plus a fractional force in the anterior–posterior direction at the hand locations after the end frame is lifted), causing them to become unbalanced and thus increasing their risk of a fall (Fig. 1b). To solve the dilemma for the construction population, a lifting strategy which would mitigate postural imbalance while allowing the generation of sufficient isometric forces to reduce overexertion hazards would be needed. A logical “lifting strategy” is to use an assistive lifting bar (or device) that allows workers to place their hands close to the level of height of the scaffold-end-frame center-of-mass and concurrently allows an optimal hand separation for them to generate sufficient isometric force to safely accomplish the task. In this case, the optimal hand locations in relation to the scaffold-end-frame center-of-mass would be within the window defined by a vertical hand placement between acromial height (shoulder) and knuckle height and by a horizontal hand separation distance of shoulder width up to end-frame width.

The objective of this study was to determine the optimal hand location for a conceptual assistive lifting device to mitigate potential postural imbalance while reducing overexertion hazards during scaffold disassembly. Nine different postures within the aforementioned window, defined by a combination of three vertical hand placements by three horizontal hand separation distances, were evaluated by measuring workers’ maximum isometric strength.

2. Methods

2.1. Subjects

Fifty-four male subjects who were experienced in scaffold disassembly were recruited from the local construction industry in Morgantown, West Virginia. They ranged in age from 18 to 49 years. The average height and mass of the subjects were 178.7 cm (SD = 5.5 cm) and 92.2 kg (SD = 16.9 kg), respectively (Table 1). Individuals who volunteered for the study were allowed to participate after passing a physical exam administered by a physician with the National Institute for Occupational Safety and Health (NIOSH).

2.2. Apparatus and procedure

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, two Bertec force platforms, and a custom-fabricated fixture and scaffold end frame. 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 with time on the biofeedback screen while the subject performed an isometric exertion (to help subjects maintain a steady-state

maximal exertion). The isometric force was calculated in real time by the data-acquisition algorithm by adding the real time vertical forces from each force plate and then subtracting the subject's total body weight. 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 s of the exertion (Caldwell et al., 1974). 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% (Chaffin et al., 1978).

2.3. Experimental design

The experimental design was a randomized design with two factors: hand separation distance and vertical hand placement. Both hand separation distance and vertical hand placement had three levels (46, 86.4, and 116.8 cm separations; acromial, elbow, and knuckle heights) which resulted in nine combinations (Fig. 2).

Each of the combinations had six subjects. Each subject performed three successful isometric exertions in an assigned posture as well as three successful isometric exertions in a baseline posture (symmetric lift at elbow height, 46 cm hand separation distance, 90° elbow flexion). Exertions were performed for a duration of 5 s each at 2 min intervals and the subjects were instructed to perform the exertions in a comfortable posture with the legs straight (little knee flexion) to mimic the scaffold dismantling task in the construction field.

3. Data analysis

Data analyses were performed by the SAS general linear model (GLM) procedure (SAS, 1991). To estimate the effects of experimental conditions and their interactions, a univariate analysis of variance (ANOVA) (Winer, 1971) was performed. Whole-body maximum static isometric strength (force) was the dependent variable; hand vertical placement and horizontal separation were the independent variables. Newman–Keuls (Zar, 1996) multiple comparison procedures were

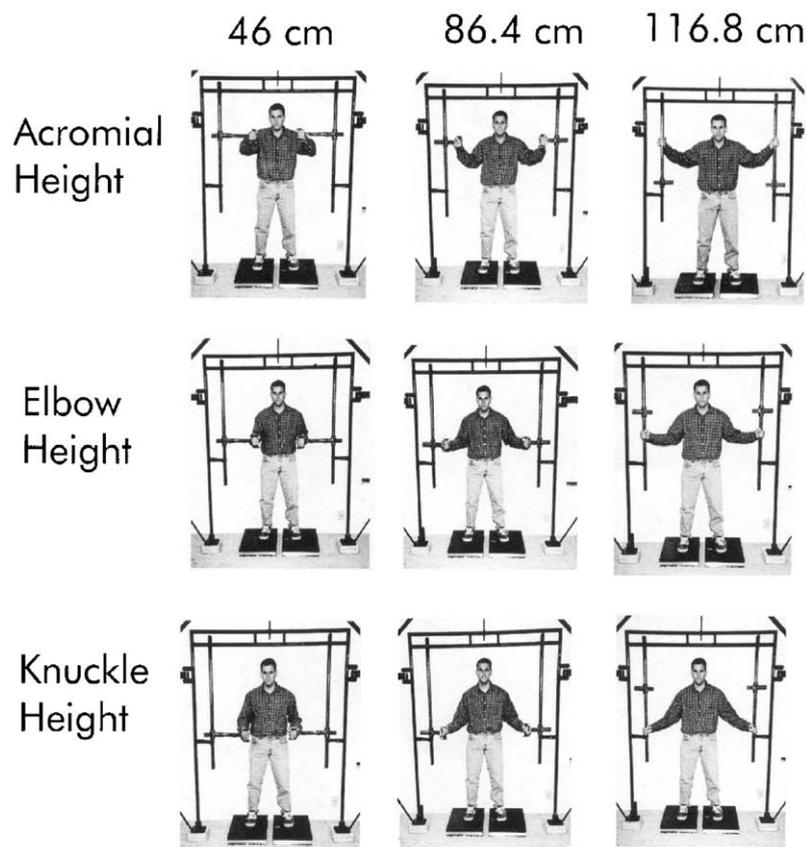


Fig. 2. Test postures.

performed to investigate pair-wise differences between postures (i.e., hand locations).

For each posture level, the estimated percentages of the male construction worker population that have maximum isometric strength >223 and 445 N were also estimated based on 95% two-sided normal distribution tolerance bounds (Hahn and Meeker, 1991). The 223 N value is equivalent to the weight of a scaffold end frame (23 kg) while the 445 N value is equivalent to a safety ratio of 2 for lifting the 223 N scaffold. The standard deviation used to construct all tolerance bounds was pooled from the nine postures.

To investigate the assumption of approximate normality for the tolerance bounds, the skewness and kurtosis were calculated at all posture levels. To investigate the assumption of approximate normality for the ANOVA residuals, the residual's skewness and kurtosis were calculated. The homoscedasticity assumption was investigated through calculation of the standard deviation at all posture levels.

4. Results

4.1. Isometric force as a function of hand separation distance and vertical hand placement

ANOVA results indicate that there are no significant differences in baseline isometric strength between subject groups. Therefore, no covariance analysis is necessary for the whole-body isometric strength in evaluating the difference among the nine postures. An ANOVA showed that the interaction effect of vertical hand placement and hand separation on workers' isometric strength was significant ($p < 0.004$). As horizontal hand separation distance increased from 46 to

116.8 cm, isometric forces increased using hand placements at elbow and knuckle height; in contrast, isometric force decreased as horizontal hand separation distance increased from 46 to 116.8 cm using hand placement at acromial height (Fig. 3). As vertical hand placement increased from knuckle to acromial height (100.1–147.6 cm), the isometric forces generated at a hand separation distance of 46 cm were equivalent (Fig. 4). Isometric forces decreased with increasing vertical hand placement (100.1–147.6 cm) at hand separation distances of 86.4 and 116.8 cm. The decrease in force was much more pronounced at a hand separation distance of 116.8 cm. At the height of about 126–130 cm (the height of mass center of the scaffold end frame), a hand separation of 46 cm would produce the greatest muscle strength as compared to the other two hand separations.

4.2. Strength tolerance intervals

The results show that at least 77%, 91%, 95%, 95%, and 97% of the male construction worker population have isometric strength above 223 N when using postures A116.8 (stands for acromial height and 116.8 cm hand separation), A86.4, A46, E46 (stands for elbow height and 46 cm hand separation), E86.4, and K46 (stands for knuckle height and 46 cm hand separation), respectively. At least 99% of the male construction worker population have isometric strength values above 223 N when using postures K86.4, E116.8, and K116.8 (Table 2). The results also showed that $<50\%$ of the male construction worker population have isometric strength above 445 N when using postures A116.8, A86.4, A46, and E46. At least 51%, 58%, 69%, 73%, and 92% of the male construction worker population have isometric strength above 445 N when

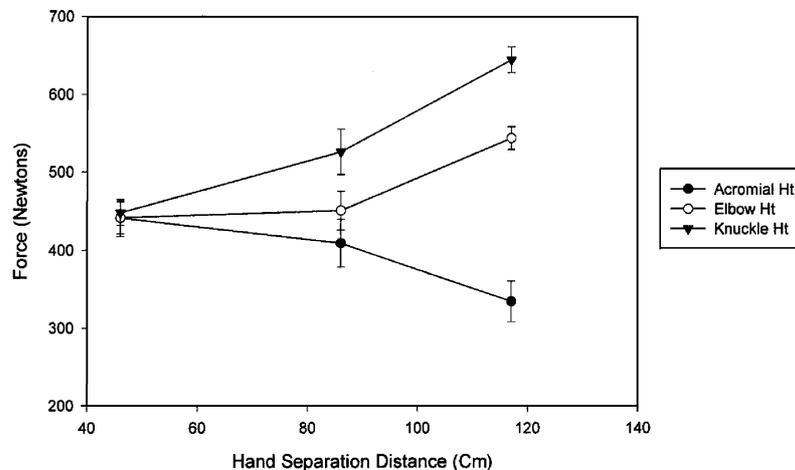


Fig. 3. Isometric force versus hand separation distance. Data are presented as mean values \pm standard error.

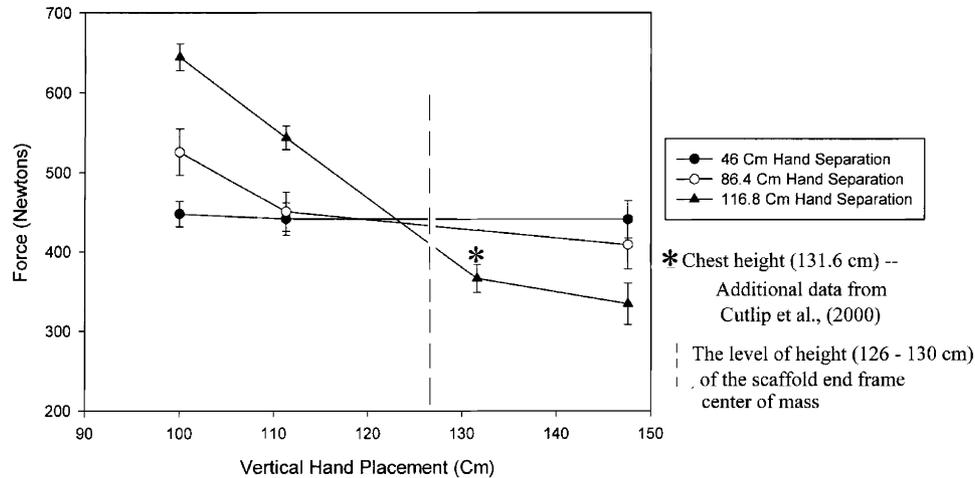


Fig. 4. Isometric force versus vertical hand placement. Data are presented as mean values \pm standard error.

using postures E86.4, K46, K86.4, E116.8, and K116.8, respectively.

4.3. Diagnostics

For force measurements at all posture levels, the skewness, kurtosis, and standard deviation values ranged from -1.11 to 1.21 , -1.54 to 1.02 , and 62.73 to 130.03 , respectively (Table 2). The skewness and kurtosis for the ANOVA residuals were 0.44 and -0.40 , respectively. Based on these statistics, it was concluded that the deviation from homoscedasticity and/or normality was not severe enough to significantly alter the power and/or significance level of the tolerance bounds and ANOVA F tests.

5. Discussion

The mass center of the scaffold end frame depicted in this study is ≈ 126 – 130 cm. If scaffold workers select a grip height at this range or at acromium height (146 cm), the possibility of postural imbalance is mitigated. However, only 71 – 73% of the population can generate forces in excess of 223 N (i.e., scaffold weight) when using this posture. To solve both fall and overexertion risks, a logical strategy is to put the hand location slightly above the elbow height, which is near the height level of the center-of-mass of scaffolds. At this level, a hand separation of 46 cm yielded the greatest muscle strength as compared to the other conditions. About 95 – 97% of the construction population could generate forces in excess of 223 N when using this posture. This would allow construction workers to mitigate the possibility of postural imbalance while generating adequate isometric strength during this task.

On the other hand, it is not surprising to see that workers compromised their fall risk to gain muscle strength for their long day of heavy work, given that assistive devices are not available for the scaffold dismantling jobs. Hsiao and Stanevich (1996) found from ten construction sites that 56% of the scaffold-end-frame lifts were performed using the symmetric posture with hand placements at knuckle or elbow height. Results from this study indicate that mean isometric forces of 644.7 N ($SD=71.1$ N) and 543.7 N ($SD=62.7$ N) were generated at knuckle height and elbow height, using a 116.8 cm hand separation. They correspond to 92% and 73% of the construction population being capable of generating forces in excess of 445 N (twice that of the scaffold-end-frame weight) and 99% being capable of generating forces in excess of 223 N. The muscle strength data as identified in this study echo workers' selections.

Finally, interpreting data from other studies that were not representative of scaffold tasks for determining scaffold disassembly strategies can be inadequate because muscle strength is significantly affected by hand orientation and posture (Chaffin et al., 1977; Pytel and Kamon, 1981). Garg and Badger (1986) found that maximum isometric strength for material handling decreased by $\approx 31\%$ when hand separation distance increased from 25 to 51 cm. Snook (1978) also found that the maximum acceptable weight of lift decreased by 23% when the box width increased from 36 to 75 cm. In contrast, the results from this study indicated that isometric strength increased with increasing hand separation distance using vertical hand placement at or below the elbow height. Apparently, the scaffolding work is quite different (at least the hand orientation) from the traditional box-lifting tasks and thus the resulting maximum isometric strengths are different.

Table 2
Summary statistics and tolerance bounds of maximum isometric strength (N)

Vertical hand displacement	Isometric strength (N)	Horizontal hand separation		
		46 cm	86.4 cm	116.8 cm
Acromial height	Mean	441.4	409.1	34.4
	SD	100.7	130.0	110.4
	Skewness	-1.11	0.83	1.21
	Kurtosis	1.02	-1.02	0.39
	Sample size	6	6	6
	% of forces > 445 N ^{a,b}	49%	42%	24%
	% of forces > 223 N ^{a,b}	95%	91%	77%
	Grouping	BC	BC	C
Elbow height	Mean	441.7	450.8	543.7
	SD	86.1	105.4	62.7
	Skewness	0.06	0.43	0.05
	Kurtosis	-1.33	-1.54	-1.12
	Sample size	6	6	6
	% of forces > 445 N ^{a,b}	49%	51%	73%
	% of forces > 223 N ^{a,b}	95%	95%	99%
	Grouping ^c	BC	BC	AB
Knuckle height	Mean	478.0	525.8	644.7
	SD	68.2	123.0	71.1
	Skewness	0.60	0.56	0.12
	Kurtosis	-1.24	-1.10	-1.23
	Sample size	6	6	6
	% of forces > 445 N ^{a,b}	58%	69%	92%
	% of forces > 223 N ^{a,b}	97%	99%	> 99%
	Grouping ^c	BC	AB	A

^a Values are based on normal distribution two-sided 95% tolerance bounds for the population of male construction workers.

^b Standard deviations were pooled for postures 1–9. Pooled SD = 9.81 with 53 degrees of freedom.

^c The same letters indicate no statistical difference among the groups.

6. Conclusion

Based on the location of scaffold-end-frames center-of-mass and the isometric strength data collected in this study, a hand separation of 46 cm at between the elbow and chest heights would be an optimal hand location for an assistive lifting device (e.g., a light-weight clip bar) for scaffold disassembly. It would mitigate the likelihood of postural imbalance while allowing for the generation of a mean maximum isometric force of about twice the weight of a scaffold end frame. At least 95% of the construction population would have isometric forces in excess of the weight of scaffold end frame. An alternative method without an assistive device would be a hand location slightly higher than the elbow height with a hand separation of 116.8 cm. This is a compromised situation that yields 2.4 times isometric strength of the scaffold weight with a little risk of postural imbalance.

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