Improving Productivity and Ergonomics in HVAC Installation

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Mechanical installation workers experience high rates of work-related musculoskeletal disorders (WMSDs). This study investigated ways to reduce the ergonomic loads and improve the productivity of workers performing duct installation of heating, ventilation and air-conditioning (HVAC) systems. The study focused on installation of rectangular ductwork components using ladders, and analyzed five operations by two mechanical contractors. The videotaped operations were analyzed for production and ergonomics using continuous time observational assessment. The ergonomic analysis examined four body regions: neck, shoulders, back, and knees for moderate and extreme loads. The findings identify the tasks with extensive extreme postures, and the task characteristics that generate extreme postures. Addressing the identified factors can improve productivity and reduce ergonomic demands.

Key Words: Mechanical workers, WMSD, Duct installation, Ergonomics, Productivity.

Introduction

Work related musculoskeletal disorders (WMSD) are injuries or disorders of the muscles, nerves, tendons, joints, cartilage, and spinal discs, in which the work environment and performance of work contribute significantly to the condition; and/or the condition is made worse or persists longer due to work conditions (Centers for Disease Control 2011). WMSDs include sprains, strains, and tears, back pain, carpal tunnel syndrome, hernia, etc. (NIOSH 2004). WMSDs are recognized as a serious physical problem due to the large number of workers affected, the impact on the workers' quality of life, and the high costs to employers due to absenteeism, lost productivity, and increased health care, disability, and worker's compensation costs (Chaffin & Andersson 1991; Institute of Medicine 2001; NIOSH 2004).

In the construction sector, the rate of WMSDs is higher than other industries (Schneider 2001, CPWR 2008). As construction workers are exposed to multiple physical risk factors associated with WMSDs, such as physical force and repetitive motion, awkward or static body postures, heavy lifting of materials, contact stress, vibration, or extreme temperatures (Bernard 1997, Hoogendoorn et al. 1999, Marras et al. 1995, NIOSH 1997, IOM 2001, CPWR 2008). According to Meerding et al. (2005), 59% percent of construction workers had musculoskeletal complaints in the preceding six months, and 21% during the previous day. Forty-one percent had low back complaints in the preceding six months, with 16% of low back complaints requiring sick leave.

Among the construction trades, mechanical installation workers experience serious overexertion injuries at rates exceeding the national average for all industries and all construction workers (Welch et al. 1995, Fredericks et al. 2002, Albers et al. 2005). Between 1992 and 1998, 26% of all mechanical installation workers injuries and illnesses resulting in days away from work, were due to overexertion or repetitive motion (Albers et al 2005). Welch et al. (1995) found that symptoms of neck, arm, and hand pain are common in sheet metal workers who are actively working, and that shoulder pain or shoulder injuries are associated with work overhead (hanging duct). Working with the arms elevated, especially with the hands or elbows above shoulder level, is frequent in the construction industry and has been associated to the development of neck and shoulder disorders (Engholm and Holmström, 2005; Moriguchi et al. 2012).

Previous studies have identified mechanical installation tasks that involve significant ergonomic risks. With regards to sheet metal work, Albers et al. (2005) identified the following high risk tasks: Drill holes, Screw/shoot into ceiling; Place hangers; Position and connect duct pieces together; Connect duct to hanger/ceiling; Assemble duct pieces in the field; Cut and trim duct joints; Weld; Move heavy equipment (rigging); and Cut and remove duct sections during demolition. This study investigated opportunities to reduce the ergonomic risks and improve the productivity of duct installation.

Objectives

The main goal of this study was to identify opportunities to reduce the ergonomic loads on HVAC workers. The study had the following objectives:

1. Quantify the ergonomic demands of HVAC duct installation. The metric used was the percent of activity's duration under extreme posture. The study measured the duration and severity of the workers' postures for four body regions—neck, shoulders, back, and legs, and measured the workers' loads with regards to lifting, and pushing/pulling.

2. Identify the tasks and factors that increase the ergonomic demands. The goal was to identify the tasks where extreme postures and loads occurred, and the work elements that strongly influenced the extreme postures and their duration. Work elements examined included design requirements—such as component design, location of installation, fastening requirements, etc.; work methods—that is, the tools and equipment used; and task duration which influences the duration of ergonomic exposure.

3. Identify potential interventions to reduce the ergonomic demands. The aim was to identify changes in the operation that would reduce physical stress while at the same time increase productivity. These tasks are the first priorities for improvement.

This study focused on installation of rectangular sheet metal duct and components using ladders. This activity and installation method was selected because it is the most common method for HVAC installation: (1) Duct installation is the activity that takes the greatest portion of labor time. It is the primary "value-adding activity" of the HVAC installers as it installs the final product. (2) The use of ladders is the most common method for installing HVAC duct in "typical" buildings with 11-12 foot ceiling. For building with high ceilings, typically a scissor lift is used. (3) The rectangular duct was selected as it is a very common design choice. (4) According to Albers (2005) it is considered to be an activity with high ergonomic risk.

Methodology

The research method included the following activities:

1. Field data collection. The researchers observed, videotaped and analyzed five operations as shown in Table 1. For each operation, the researchers discussed the activity with the supervisors and workers. Discussions addressed questions regarding the steps of the operation, the type of material, the tools and equipment, the installation area and difficulties, workers experience, etc.

The installation of rectangular sheet metal duct and components requires the following tasks:

- Lifting the duct in place. Small components were often raised by hand. For larger heavier duct, lifting equipment (super lift) was used.

- Getting in position on the ladder(s). The installer(s) positioned and climbed the ladder.

- Aligning the ducts. This involved adjusting the position of the duct so that the metal flanges align and then using horse nippers or a duct puller to hold the two pieces together.

- Connecting the duct pieces by inserting two slip drives (aka S-drive) either at the top and bottom of the duct or at the right and left sides, and fastening them with screws.

- Connecting the duct to the hangers.

2. Productivity analysis. Productivity was analyzed using a continuous time analysis of the production tasks, and developing the Crew Balance Chart (CBC) for each worker observed (Oglesby et al 1989). The CBC indicated the tasks performed, and their durations. The productivity of the operations was evaluated with respect to the percentage of productive time, support time and non value-adding time.

Table 1. Operations analyzed

	Operation 1	**Operation 2**	**Operation 3**	**Operation 4**	**Operation 5**
Company	A (union)	A (union)	A (union)	B (non union)	B (non union)
Duct type & size	12”x12”x12’ rectangular duct	12"x12"x12' rectangular duct	12”x24”x3’ VAV box	12"x24"x10' rectangular duct	12"x24"x10' rectangular duct
Height (bottom of duct)	9’-6”	9’-6”	9’-6”	9'-8"	9'-8"
Crew	1 Journeyman 1 Apprentice	1 Journeyman 1 Apprentice	1 Journeyman 1 Apprentice	1 Leadman 1 Worker	1 Leadman 1 Worker
Equipment	8’ alum ladder & super lift	8’ and 12' ladders & super lift	8’ and 10’ alum ladders	Two 10' ladders & one super lift	Two 10' ladders & one super lift
Duration	3 min 45 sec	4 min 47 sec	4 min 2 sec	7 min - 40 sec	8 min- 21 sec
Workers analyzed	Journeyman	Journeyman & Apprentice	Journeyman & Apprentice	Leadman & worker	Leadman & worker

3. Ergonomic analysis. The study deployed an observational assessment method. To assess the severity of postures for the selected body regions, the study used the flexion and extension angles that RULA, and REBA have established for the four body regions of interest (neck, arms/shoulders, back and legs). RULA (Rapid Upper Limb Assessment; McAtamney & Corlett 1993) and REBA (Rapid Entire Body Assessment; Hignett & McAtamney 2000), are observational assessment techniques that can quickly assess targeted areas of the body, such as upper arms, lower arms, wrists, neck, trunk and legs. With regards to the loads, the NIOSH lifting guide was used. Table 2 shows the postural guide used. Figure 1 provides visual illustration of extreme postures for arms/shoulders, back flexion and neck extension.

Table 2. Postural analysis guide for selected body regions.

Body region	Criterion	Neutral	Minimal	Moderate	Extreme	Source
Arms/Shoulders	Flexion	-	0-45°	45°-90°	> 90°	RULA/ REBA
Back	Flexion	-	0-20°	20°-60°	> 60°	REBA
	Extension	-	-	0-20°	> 20°	
	Twisting	-	-	45°-60°	> 60°	
Neck	Flexion	-	0-20°	> 20°	-	RULA/ REBA
	Extension	-	0-20°	> 20°	-	
	Twisted	-	-	-	all movement	
Legs	Standing, walking, sitting	< 30°	30°-60°	-	-	REBA
	Unstable	-	-	30°-60°	> 60°	
	Squatting	-	-	stable	unstable	

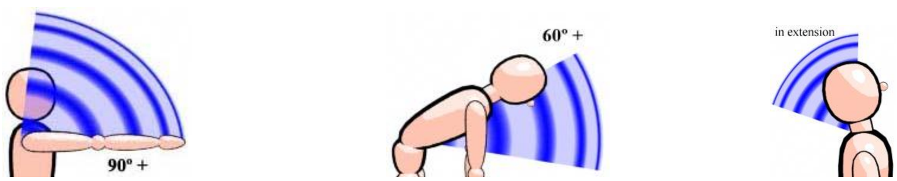

Figure 1. Illustration of extreme postures for arm, back flexion, and neck extension.

4. Simultaneous analysis of productivity and ergonomic. The analysis of extreme postures in relation to the production tasks identified the percentage of the task duration the workers were in extreme ergonomic postures as well as the tasks where extreme postures occurred, and the task variables that determined the intensity and duration of extreme postures. Table 3 illustrates the duration of extreme postures during the different tasks performed by the journeyman.

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Table 3. Tasks with extreme postures for journeyman in operation 3.

Journeyman tasks	Task duration[1]	Duration of extreme postures[2]			
		Shoulders	Back	Neck	Legs
Align the duct	23%	17%	22%	23%	
Insert right S drive	5%		5%	4%	
Ascend/ descend ladder	15%	2%		8%	15%
Fasten hangers	15%	6%			4%
Total		**25%**	**27%**	**35%**	**19%**

[1] Task duration is expressed as percent of the total operation time.
[2] Duration of extreme postures is expressed as percent of the total operation time.

Operation Observations

Operation 1

In operation 1, a journeyman and an apprentice installed a rectangular 12-foot duct. The apprentice was on the ground operating the super lift, and the journeyman was on the ladder making the connection. In this case, only the journeyman was videotaped and analyzed. Aligning the duct took about 53% of the total activity duration. The actual time to make the connection (the productive time) was only 7% of the overall duration. Aligning the duct was the task in which most of the extreme postures occurred. Extreme back posture occurred only when the worker was setting the horse nippers on the ducts. Extreme neck posture occurred as he was turning his head to check the duct alignment. Extreme leg posture was caused by stepping up and down the ladder.

Operation 1 showed the lowest extreme postures across all cases. This was largely due to the journeyman's positioning of the ladder. The journeyman positioned his ladder twice during the operation because he made connections on both sides of the duct. He positioned the ladder at about 30-40 degrees angle to the duct run. This minimized the twisting of his back and his neck. He also climbed up high enough so that he did not have to flex his shoulders more than 90 degrees.

Operation 2

In operation 2, a very experienced journeyman (27 years of experience) and a very new apprentice (1 year of experience), installed a 12-foot long, 12 inch x 12 inch rectangular duct. The journeyman raised the duct using the super lift and gave instructions to the apprentice who was on the ladder and installed the duct. The journeyman climbed his ladder briefly to assist the apprentice by putting horse nippers on the duct. The journeyman had significant extreme postures for neck (27%), and low extreme postures for shoulders (3%) and legs (5%).
The apprentice performed productive work for 17% of the time. Neck twisting was the most significant extreme posture (40% of the time), and this extreme posture occurred primarily during duct alignment.

The position of the ladder contributed significantly to the extreme postures. The ladder was positioned perpendicular to the duct with the top of the ladder 1-2 feet away from the duct. The ladder was positioned this way because it was higher (12') than the bottom of the duct (9'-6"). As a result, the worker had to turn his head to check the duct alignment much more than the worker in operation 1.

Operation 3

During this operation, one journeyman and one apprentice installed a 3-foot long, 12 inch x 12 inch rectangular duct component (VAV box). The installation requirements and method for the VAV box were exactly the same as the requirements for the duct. The journeyman carried the VAV box manually up the ladder, and with the help of the apprentice who was on the second ladder, aligned the box with the duct. The journeyman inserted the S-drive on the right side of the box, and then the apprentice inserted the S-drive on the left side.

Aligning the duct was the task that took the longest portion of time and involved the most extreme postures. For both the journeyman and the apprentice, multiple extreme postures occurred at the same time as a combination of the box being lifted manually and the position of the ladders. The journeyman positioned his ladder parallel to the duct so he could better hold the VAV box at the proper location. However, this caused him to twist and turn his body to see and work on the duct. The apprentice's position was too close to the duct and caused extreme postures in the shoulder, back and neck due to more neck and back twisting. Due to his position on the ladder, the apprentice also had extreme postures while inserting the S-drive.

Operation 4

In operation 4, two non-union workers installed a 10-foot long, 12 inches x 24 inches rectangular duct. The workers used a super lift to lift the duct to elevation, and they both worked on their ladders to align the duct and make the connection. The top of the duct was only one or two inches from the ceiling. This made it very difficult to align the duct and install the S-drive on the top of the duct. Tables 7 and 8 summarize the extreme postures for the lead man and the worker.

The lead man had his ladder positioned in a way that he did not need to twist his back or neck to extreme posture. Some extreme neck posture occurred as the lead man was looking at his tool belt (down and sideways) to find the tools he needed. In addition to being very close to the ceiling, this duct was installed next to an existing open web floor truss. The lead man was working from the side of the truss and this condition affected his shoulder posture.
For the worker, aligning the duct was the longest task with the most extreme postures. The position of the duct close

to the ceiling prevented the worker from standing higher on the ladder, causing extreme shoulder posture while aligning the top of the ducts. Moreover, the angle of the ladder caused the worker to twist his back for most of the time.

Operation 5

In this case, the HVAC duct was also close to the ceiling, parallel to a truss. Moreover, the duct had to be installed over an existing sprinkler line that was running perpendicular to the duct run, at about one foot lower than the bottom of the duct, and about one foot from the duct connection. The lead man performed productive work 8% of the time, support work 60% of the time and was idle for 32% of the time. He moved his ladder six times throughout the operation, making small adjustments for better positioning.

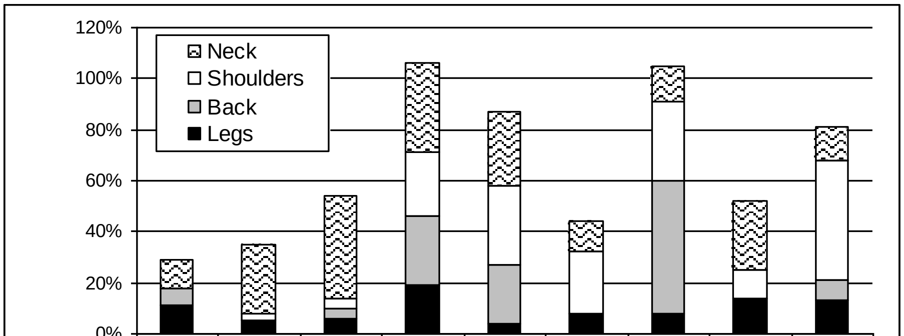
Duct alignment took 21% of his time. It occupied both crew members adjusting the super lift and making small adjustments to the duct. Most of the extreme postures for the lead man occurred during this task. The worker was working primarily on the top of the duct. He was also standing on a lower step of the ladder in a way that his arms were stretched upwards. In this operation, the worker changed the position of his ladder, and reduced the amount of back twisting compared to operation 4.

Results

Figure 2 summarizes the results of the postural analysis. A worker's exposure to an extreme posture (i.e., the duration of extreme posture) is indicated as a percentage of the total operation time. This approach normalizes the exposure across operation of different durations. Extreme postures for different body regions often occurred simultaneously. For example, when a worker was looking up and reaching overhead, extreme postures could occur for neck and shoulders at the same time. Thus, it is possible for the cumulative extreme postures to exceed 100%.

Extreme neck posture (neck twisted) varied from 11% to 40% of the operations' duration, with an average value of 23%. Extreme shoulder posture (arm flexion > 900) had an average value of 20% but showed significant variations between activities ranging from 0% in operation 1 to 47% in operation 5. Extreme back posture ranged from 0% to 52% of the operations' duration, with an average value of 13%. Extreme leg posture varied from 5% to 19% of the task duration, with an average value of 10%. No lifting of heavy loads was observed. Moderate loads were lifted on average 6% of the time. No heavy pushing/pulling was observed; moderate pushing/pulling was observed on average of 13% of the time.

The analysis of the five operations resulted in the following observations regarding the productivity of the operations, and the task parameters that influence the extreme postures.



	Case 1 J'man	Case 2 J'man	Case 2 Apprent.	Case 3 J'man	Case 3 Apprent.	Case 4 Leadman	Case 4 Worker	Case 5 Leadman	Case 5 Worker
Neck	11%	27%	40%	35%	29%	12%	14%	27%	13%
Shoulders	0%	3%	4%	25%	31%	24%	31%	11%	47%
Back	7%	0%	4%	27%	23%	0%	52%	0%	8%
Legs	11%	5%	6%	19%	4%	8%	8%	14%	13%

Figure 2. Duration of extreme postures as percent of activity duration.

Small portion of productive work

The study found that the productive tasks (connecting the new duct component to the existing duct and to the hangers) comprised only a small portion of the operations' time (10-20%). This indicates that these operations have significant potential for productivity improvement. In order to improve both productivity and ergonomics, it is critical to shorten or eliminate tasks with significant portion of extreme postures. If we reduce the duration of tasks with small portion of extreme postures, we would improve productivity (due to reduced cycle time) but we would increase the percent of time with extreme postures. Furthermore, the loss of tasks with low ergonomic loads in the long run may increase fatigue which can mitigate the productivity gains from shorter cycle time.

Duct alignment difficulties

Duct alignment was consistently found to be the task that took the longest time and generated the majority of extreme postures. This is the most difficult task and it should be a focus area for improvement. Improvements in this task will reduce both the task duration (thus increasing productivity), and the exposure to extreme postures. Improvements may come from better tools, equipment or redesigning the flange connection.

Ladder position

Duct installation tasks performed on the ladder (aligning the ducts, holding them together, and inserting the slip drives, and fastening) require a wide range of movement. Ladders however, provided limited freedom of movement. The observation of the operations indicated that the position of the ladder can significantly affect the extreme postures of back (bending and twisting), neck (twisting) and shoulders (flexion > 90).

- The ladder's distance from the duct can cause the worker to reach (if the duct is far as in case 2) or to lean backwards or twist if it is too close.

- The ladder's angle with the duct can cause workers to twist their back or neck (as in operation 4). Positioning the ladder parallel to the duct increases back and neck twisting. If the ladder is taller than the bottom of the duct, it has to placed either parallel or further from the duct (operation 2).

- The worker's height on the ladder affects shoulder flexion. Standing with the shoulders higher than the duct reduces extreme shoulder posture (operation 1). In operations 4 and 5, the low ceiling clearance prevented workers from standing higher and resulted in high shoulder flexion.

The ladder position with the lowest extreme postures (in operation 1) was at an angle of about 30^0 with the non-working hand (left hand for right-handed) close to the duct. However, one position may not be the optimum for all tasks the worker performs on the ladder. One approach would be to find the optimum ladder position that best supports most tasks without repositioning the ladder. A second approach would be to find the optimum ladder position for each task. The trade-off is that a worker would need more time to reposition the ladder and climb up and down (which creates extreme postures on legs). On the other hand, this may also reduce the risk of falling off the ladder. A third approach would be to change the tasks in order to reduce the movement required by the workers while on a ladder. Overall, ladder positioning is an area where training guidelines need to be developed.

Climbing up and down the ladder

In the operations analyzed, extreme leg postures occurred only when the workers were climbing up and down the ladders. Although it is a necessary support task, it is not a productive task. Hence, reducing the number of times that workers climb up and down the ladder would reduce the extreme postures as well as the overall activity duration. Common reasons to climb up and down include getting tools, adjusting the super lift, or adjusting the position of the ladder.

Work area constrains

In operations 4 and 5, the characteristics of the work area (the position of the duct close to the ceiling, and along the truss, and the existence of sprinkler line) increased the workers' extreme postures. Tenant improvement projects create restricted work areas for duct installers as pipes, vents and trusses hinder mobility.

Conclusions and Recommendations

This study makes two contributions towards reducing the ergonomic risks of mechanical workers: First, it quantified the severity and duration of ergonomic postures and loads during duct installation operations. The main finding from this small sample of activities is that there is significant variation in the duration of extreme postures. Second, the analysis of these variations identified tasks and task parameters where improvements can increase productivity and at the same time reduce extreme postures:

- Duct alignment is the task with the longest duration and highest extreme postures. Improving this task is a priority.
- Ladder position in terms of distance and angle to the duct run, has a significant effect on extreme postures.
- The location of the duct in relation to the ceiling and the other components on the ceiling (pipes, trusses, etc.) can have a significant effect on extreme postures.
- Tool availability and easy access to tools can further reduce ergonomic loads.

Based on the findings, the recommendations for industry are the following:

- Investigate or develop better techniques to perform duct alignment.
- Develop guidelines and training for better ladder positioning.
- Develop design guidelines that can reduce ergonomic stresses on HVAC installers. For example, the positioning of the duct or the use of round duct could reduce some of the difficulties involved in installation of rectangular duct.

To reduce the ergonomic risks of HVAC installation workers, further research is recommended in the following directions:

- Address the areas that need improvement, specifically ladder positioning and new improved ways to perform duct alignment.
- Further investigate the effect of design choices (and specifically duct location) on ergonomic stresses.
- Investigate the effect of different methods on extreme postures, such as the use of scissor lifts instead of ladders.
- Expand the research to other HVAC installation activities, such as layout, duct assembly on site, and other methods.

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