

Demonstration of Work Performance Metrics in Ironworkers Using the ERGOS Sapphire TM Work Simulation System

Zahra Jabbarani Torghabeh, M.Sc., and Terry L. Stentz, Ph.D., MPH, CPE,CPC, and Kelli Herstein, Ph.D.
College of Engineering, University of Nebraska- Lincoln
Nebraska, Lincoln

Ironworkers perform heavy physical work at high elevations often with awkward postures, heavy loads, and high force applications. Ironworkers are at higher risk for falls and other injuries compared to other trades. This demonstration study, which was conducted at the Durham School of Architectural Engineering and Construction, Lincoln, Nebraska, utilized the ERGOS Sapphire TM Work Simulation Test Apparatus to measure the physical performance metrics of one (1) male experienced ironworker and ten (10) convenience sample inexperienced male college students. The work measurement protocol was based on the expert knowledge of the ironworker. Metrics included 2-handed touch panel, overhead push-pull, static lift, dynamic lift and carry, lateral pinch, 3-point pinch, and hand grip. Metrics were taken on the subject sample with and without Personal Protective Equipment (PPE) including full tool belt, hard hat, body harness, safety shoes, gloves, and safety glasses. The ERGOS Sapphire TM System was able to delineate physical performance differences in the subject sample. The experienced ironworker scored higher in most metrics compared to the subject sample. Significant differences between the ironworker and inexperienced subjects were noted in some metrics for no PPE and PPE, simulated work task, and symmetrical and non-symmetrical tool belt loading. Most inexperienced subjects found the PPE and asymmetrical tool loading noticeably uncomfortable.

Key Words: ERGOS Sapphire TM Work Simulation, Ironworker, PPE, Physical Work Performance

Introduction

The construction industry has higher rates of musculoskeletal disorders and injuries compared to other industries. Construction workers are at a high risk of exposure to Work-Related Musculoskeletal Disorders (WRMSDs) because of risk factors on the construction site (Forde & Buchholz, 2004). The incidence rate of nonfatal injuries among construction workers resulting in days away from work (DAFW) is one of the highest at 143.4 per 10,000 full-time workers compared to 102.3 per 10,000 full-time workers for total private industry (U.S. Bureau of Labor Statistics, 2012). Construction Ironwork duties force them to lift, carry, and manipulate heavy loads; work in severely cramped spaces or sustained awkward postures; work with their arms overhead; use heavy, vibrating pneumatic tools to which they must apply large forces while holding in static positions. Non-neutral postures of the trunk, arms, and legs were the most evident ergonomic hazard regarding all CI tasks (Forde & Buchholz, 2004; O*NET, 2014). Pre-employment screening is an option to have better results at the work site (Snashall, 1997). Increased weight of the load, horizontal location of hands, vertical location of hands (lifting load near the floor or above shoulder), distance of lift, asymmetric lifting, and hand couplings can affect a subject's musculoskeletal health during lifting and lowering of loads. High forces on the spine, high strength requirements, risk of slipping and falling, and body posture are concerns related to pushing and pulling objects. Carrying of an object by humans should be used only as a last option. If human carriage is unavoidable, the momentum of the load on the spine must be minimized and job rotation should be considered to reduce pressure on the workers (Nordin, Andersson, & Pope, 1997; Sanders & McCormick, 1993). ERGOS Sapphire TM is a computer-aided work assessment system, which is commonly used in clinical and rehabilitation section for measuring current or future employees' aptitude for a specific job. The aim of this demonstration is to use this system in construction domain.

Methodology

This demonstration study utilized the ERGOS Sapphire ™ Work Simulation Test Apparatus manufactured by Simwork Systems to measure the physical performance metrics of one (1) male experienced ironworker and ten (10) inexperienced male college students. Subjects completed two (2) separate trials of the ERGOS Sapphire ™ protocol while wearing personal protective equipment (PPE) required for ironworkers. The two trials considered symmetric and asymmetric equipment loading. Tools were loaded on the subject's tool belt such that the body was equally loaded on their left and right sides for symmetric loading (Figure 1a). All test subjects were right-hand dominant; therefore all tools were loaded on right side of the body during the asymmetric loading situation (Figure 1b).

1a-Symmetric Tool Belt Loading

1b-Asymmetric Tool Belt Loading

Figure 1: Symmetric and Asymmetric Tool Belt Loading

Human Subjects

Two (2) groups of male human subjects participated in this experiment including one (1) experienced ironworker and ten (10) convenience sample inexperienced male college students. Inexperienced workers were those who do not have a prior experience in ironworking while the experienced subject was professional ironworker with more than 15 years of full-time work experience. Table 1 shows the details of the human subject characteristics. The experienced worker was 37 years old, 70 inches, and 210 pounds with a body mass index (BMI) of 30.06 (grade 2 obese). The inexperienced workers were a median age of 25.5 (21, 47), an average of 71.7 inches tall, and a mean weight of 193 pounds (159, 260) with a mean BMI of 26.35 (21.81, 34.46) (grade 1 obese). Body mass index in last column is interpreted as follows: desirable weight 20-25, grade 1 obesity 25-29.9, grade 2 obesity 30-40, morbid obesity >40 (Morrow, Jacson, Disch, & Mood, 2000).

Table 1

Human Subject Characteristics

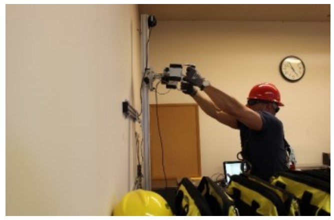
Test Subject	Subject Age	Subject Height (in)	Subject Weight (lbs.)	Body Mass Index (BMI)
1*	25	72	200	27.09
2*	47	72	215	29.12
3*	26	72	161	21.81
4*	28	72	190	25.73
5*	34	69	185	27.40
6*	22	73	260	34.46
7*	34	68	159	24.10
8*	21	70	190	27.20
9*	25	70	165	23.62
10*	24	79	205	23.02
11**	37	70	210	30.06

* Inexperienced, ** Experienced

Test Equipment

Performance of test subjects was investigated using the ERGOS Sapphire ™ Work Assessment System. Other studies were found that had used the ERGOS™ Work Simulator to investigate the performance of test subjects, but not in construction, so this demonstration's aim is to use this system in construction domain (Dusik, Menard, Cooke, Fairburn, Beach, 1993; Cooke, Dusik, Menard, Fairburn, & Beach, 1994; Frings-Dresen & Sluiter, 2003; Boadella, Sluiter, & Frings-Dresen, 2003).The wall mounted version of the ERGOS Sapphire™ work simulator measures 29 physical demands including lifting strength, push/pull strength, carrying, stooping, kneeling, crouching, forward reach, overhead reach, standing postures (Simwork Systems Inc., 2014). Figure 2 shows tests that were performed in this demonstration.


2a-Touch Panel


2b-Overhead Pull


2c-Overhead Push


2d-Dynamic Lifting


2e-Dynamic Carrying

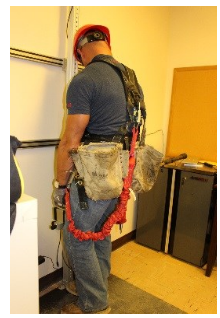
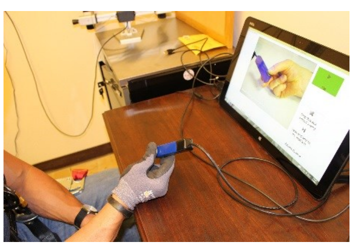

2f-Static Lifting

Figure 2: The Wall Mounted Version of the ERGOS Sapphire ™ Work Simulator

The ERGOS Sapphire™ Portable Upper Extremity Testing (UET) was used for testing the upper extremity work performance abilities of the subjects. The Sapphire software tests and records the isometric wrist flexion and extension strength, forearm pronation and supination strength, functional hand grip and finger pinch strength. (Simwork Systems Inc., 2014). However, for this demonstration only the tests shown in Figure 3 were conducted and recorded for the ironworker job description test protocol.


3a-Three Point Pinch


3b-Lateral Pinch Strength


3c-Grip Strength

Figure 3: The ERGOS Sapphire ™ Portable Upper Extremity Testing (UET)

Protocol

The O*NET job description for ironworkers and the knowledge and expertise of the experienced ironworker were used to define the test protocol (O*Net, 2014). Steps one through five of the test protocol was performed using the wall-mounted ERGOS Sapphire™ work simulator in three different situations. First, subjects were asked to take part in the experiment without personal protective equipment. Second, subjects were outfitted with personal protective equipment loaded symmetrically. Third, subjects were loaded with personal protective equipment loaded asymmetrically. Personal protective equipment consists of a full body harness, hardhat, gloves, safety shoes and safety glasses. The full body harness was loaded with two wrenches, a positioning tool, and mallet. For steps six through eight of the test protocol, test subjects were asked to perform the tests twice, with and without using gloves.

Standard positioning for grip strength was taken from the American Society of Hand Therapists (ASHT) clinical protocol descriptions that included: “the patient should be seated with his shoulder adducted and naturally rotated, elbow flexed at 90° and the forearm and wrist in neutral position”. ASHT also recommended that the mean of three successive trials be used as the measure of strength (Fess & Moran, 1981 as cited in Mathiowetz et al., 1986). In three-point pinch meter was grasped with the index finger, middle finger and thumb. For lateral grasping the pinch gauge was positioned between the pad of thumb and the radial side of the index finger (Mathiowetz et al., 1984; Mathiowetz et al., 1986; Nilsen et al., 2012). The following tests were performed in order:

1. Touch Panel (2-handed, Figure 2a): Overhead, tilted at a fixed Height (64" from the floor to the center of the board)
2. Static Strength (2-handed , Figure 2b and 2c): Overhead Push and Overhead Pull 72" from the floor – 3 repetitions,
3. Static Strength (2-handed, Figure 2f): Lifting Load 32" From Floor - 3 repetitions,
4. Dynamic Lift (2-handed , Figure 2d): 25 lbs. (43", 5 repetitions) and 50lbs (43", 4 repetitions),
5. Dynamic Carry (2-handed, “L” pattern to a designated point and returning to the start location. The first leg of the pattern was 36" and the second leg was 98", Figure 2e): 25 lbs. (3 repetitions) and 50 lbs. (2 repetitions),
6. Lateral Pinch (Right and Left, Figure 3b) - 3 repetitions each,
7. Three Point Pinch (Right and Left , Figure 3a) - 3 repetitions each,
8. Grip Strength (Right and Left, Figure 3c) - 3 repetitions each.

The test subjects were given instructions by the ERGOS Sapphire ™ work simulator via pre-recorded voice commands and photographs for each test. After completing each activity, test subjects were asked to mention their fatigue or discomfort level by choosing the affected body part(s) on the screen and assigning a score on a scale of one-to-ten with ten being the greatest possible discomfort or fatigue (Figure 4).

Figure 4: Selecting Fatigue and Discomfort Level Requested After Each Activity

Results

MTM-II Performance and Physical Demand Level

Table 2 shows the results of test subjects for performing tasks in different situations. The ERGOS Sapphire ™ software reports the results of pushing, pulling, static lifting, grip and pinch tests and also the maximum effort of test subjects in pounds. Results for the dynamic lift test show the lifting velocity and replacing velocity in terms of inches per second. Results for the overhead reach test and dynamic carry test were given in terms of MTM-II (Method Time Measurement). “MTM is a procedure which analyzes any manual operation or method into the basic motions required to perform it and assign to each motion a predetermined time standard which is determined by the nature of the motion and the conditions under which it is made” (Maynard, Stegemerten, & Schwab, 1948). The ERGOS Sapphire ™ software summarizes and categorizes tests subjects based on their performance. MTM-II performance categories divide the competitiveness of test subjects into four levels: below competitive (<70%), entry (70-80%), competitive (80-100%), and above competitive (>100%). Physical demand level of test subjects includes sedentary work, light work, medium work, heavy work, and very heavy work (Dictionary of Occupational Titles, 1986). The experienced ironworker placed in the above competitive category for MTM-II performance and in the heavy and very heavy categories for physical demand level. Results of inexperienced ironworkers placed them in the competitive and above competitive categories for MTM-II performance and in heavy and very heavy categories for physical demand level except for grip strength, 3-point pinch, push and pull that some of test subjects were placed in medium and light categories (Table 3).

Table 2

Subject Sample Sapphire ™ Physical Performance Values Without PPE and With PPE/Tool Loading Symmetry

Tasks	n	Unit	Without Using PPE			PPE/ Symmetric Load			PPE/Asymmetric Load		
			Min	Max	SD	Min	Max	SD	Min	Max	SD
Overhead reach	11	%	94.90	128.10	11.17	98.20	152.20	15.75	92.00	160.10	21.06
Pushing	11	lbs	13.45	37.74	8.11	17.22	50.55	11.67	19.83	51.67	11.27
Pulling	11	lbs	14.24	33.64	6.30	18.22	37.84	6.69	18.83	37.21	5.38
Static lifting	11	lbs	54.33	191.59	43.05	52.66	187.54	38.86	55.08	171.97	37.28
Dynamic LV(25lbs)	11	in/sec	6.70	9.00	0.73	5.80	8.90	1.10	7.00	9.60	0.83
Dynamic RV(25lbs)	11	in/sec	7.50	9.00	0.42	7.70	9.20	0.59	7.90	9.70	0.61
Dynamic LV	11	in/sec	7.20	8.90	0.59	7.40	8.90	0.57	7.00	9.60	0.88
Dynamic RV(50lbs)	11	in/sec	7.50	8.90	0.48	7.10	10.00	0.79	7.30	11.00	1.02
Carrying(25 lbs)	11	%	103.83	156.70	18.02	93.43	195.20	27.21	97.30	213.95	31.24
Carrying(50 lbs)	11	%	112.85	234.70	34.50	113.80	213.00	29.89	114.90	234.80	33.71
			No Gloves			Gloves					
			Min	Max	SD	Min	Max	SD			
Lateral pinch (RH)	11	lbs	14.30	28.17	4.67	14.64	24.08	3.48			
Lateral pinch (LH)	11	lbs	12.71	28.55	4.72	14.49	25.30	3.60			
Three-Point-Pinch	11	lbs	11.85	26.58	4.68	12.53	23.30	4.21			
Three-Point-Pinch	11	lbs	12.29	26.89	4.20	12.16	23.43	3.59			
Grip Strength(RH)	11	lbs	14.64	89.25	19.20	18.82	86.24	22.83			
Grip Strength(LH)	11	lbs	29.63	96.23	19.86	21.67	72.68	19.34			

LV: Lifting Velocity, RV: Replacing Velocity, RH: Right Hand, LH: Left Hand

Table 3

Physical Demand Level Category Counts for Test Subject

Tasks	Without Using PPE						PPE/ Symmetric Load					PPE/Asymmetric Load				
	V	H	M	L	A	C	V	H	M	A	C	V	H	M	A	C
Overhead reach					8	3				10	1				9	2
Pushing	4	6	1				4	7				3	8			
Pulling	1	8	2				5	6				5	6			
Static lifting	11						11					11				
Dynamic Lifting (25lbs)		11						11					11			
Dynamic Lifting (50lbs)	11						11					11				
Carrying (25lbs)					11					10	1				10	1
Carrying (50lbs)					11					11					11	

Tasks	No Gloves						Gloves					
	V	H	M	L	A	C	V	H	M	L	A	C
Lateral pinch (Right Hand)	5	6					1	10				
Lateral pinch (Left Hand)	2	9					1	10				
Three-Point-Pinch	2	8	1					11				
Three-Point-Pinch	2	8	1					10	1			
Grip Strength (Right Hand)		8	2	1				7	4			
Grip Strength (Left Hand)	1	7	3					9	2			

V: Very Heavy, H: Heavy, M: Medium, L: Light, A: Above Competitive, C: Competitive

Note: Test subject count numbers are shown for each physical capacity category.

The experienced ironworker had no complaints about fatigue or body discomfort during the test period showing that the ironworker was used to doing the heavy work and repetitive jobs while wearing required PPE. In contrast, inexperienced test subjects mentioned different levels of fatigue and discomfort during the test; they had the greatest number of complaints during the overhead reach, static strength, dynamic lifting, and dynamic carrying tests. The number and level of fatigue or discomfort increased after using full body harness especially in test subjects' back, shoulder and neck. These complaints can be either associated with the new type of full body harness that is not convenient or inexperienced test subjects who were not used to performing these tasks; however using gloves and safety shoes increased the level of comfort of the test subjects. Test subjects complained more about discomfort and fatigue on their right side of their body when the loads were transferred to that side.

Comparison of the Experienced Ironworker to the Inexperienced Test Subjects

Analysis of collected data through the ERGOS Sapphire ™ software was performed using Statistical Package for Social Science 18.0 (SPSS) software and Microsoft Office Excel. The performance of the inexperienced subjects were lower than the experienced ironworker except for lifting velocity for 25 lbs. and left hand grip strength when not wearing PPE, lateral pinch strength for left hand when wearing PPE with symmetric loading, and overhead reach wearing asymmetric loaded PPE. Considering a one-tailed single t-test with alpha level of 0.05 and df=9, wearing PPE and not wearing PPE, loading the tool belt symmetrically and asymmetrically, showed some significant differences in work performance metrics of experienced ironworker and inexperienced test subjects. Table 4 summarizes the outcomes.

Table 4

Comparison of The Experienced Ironworker to the Inexperienced Test Subjects

Task	Testing Without PPE	Testing With PPE Symmetric Loadings	Testing With PPE Asymmetric Loadings
Overhead reach	$t(9)=-1.097; p>0.05$	$t(9)=-0.494; p>0.05$	$t(9)=1.012; p>0.05$
Pushing	$t(9)=-5.048; p<0.05$	$t(9)=-6.043; p<0.05$	$t(9)=-5.863; p<0.05$
Pulling	$t(9)=-1.812; p>0.05$	$t(9)=-3.466; p<0.05$	$t(9)=-3.421; p<0.05$
Static lifting	$t(9)=-5.861; p<0.05$	$t(9)=-4.679; p<0.05$	$t(9)=-6.795; p<0.05$
Dynamic lifting/Lifting velocity (25 lbs.)	$t(9)=0.785; p>0.05$	$t(9)=-1.967; p<0.05$	$t(9)=-5.991; p<0.05$
Dynamic lifting/Replacing velocity (25 lbs.)	$t(9)=-0.431; p>0.05$	$t(9)=-1.238; p>0.05$	$t(9)=-6.893; p<0.05$
Dynamic lifting/Lifting velocity (50 lbs.)	$t(9)=-0.875; p>0.05$	$t(9)=-3.878; p<0.05$	$t(9)=-4.353; p<0.05$
Dynamic lifting/Replacing velocity (50 lbs.)	$t(9)=-2.030; p<0.05$	$t(9)=-2.934; p<0.05$	$t(9)=-3.028; p<0.05$
Dynamic carrying (25 lbs.)	$t(9)=-0.069; p>0.05$	$t(9)=-8.776; p<0.05$	$t(9)=-12.632; p<0.05$
Dynamic carrying (50 lbs.)	$t(9)=-13.434; p<0.05$	$t(9)=-10.696; p<0.05$	$t(9)=-14.298; p<0.05$
	Testing Without Gloves	Testing With Gloves	
Lateral pinch strength (RH)	$t(9)=-2.38; p<0.05$	$t(9)=-3.958; p<0.05$	
Lateral pinch strength (LH)	$t(9)=-0.624; p>0.05$	$t(9)=2.370; p<0.05$	
Three-Point-Pinch strength (RH)	$t(9)=-4.153; p<0.05$	$t(9)=-4.760; p<0.05$	
Three-Point-Pinch strength (LH)	$t(9)=-3.307; p<0.05$	$t(9)=-4.438; p<0.05$	
Grip (RH)	$t(9)=-2.265; p<0.05$	$t(9)=-4.411; p<0.05$	
Grip (LH)	$t(9)= 1.021; p>0.05$	$t(9)=-0.545; p>0.05$	

RH: Right Hand, LH: Left Hand

Comparison between Different Work Situations (Without Using PPE, Using PPE and Symmetric Loading, Using PPE and Asymmetric Loading):

A paired t-test with an alpha level of 0.05 and df= 10, was performed to compare the performance of the test subjects in three different test conditions including performing test without using PPE, using PPE with symmetric equipment loadings and using PPE with asymmetric equipment loadings.

- The results of the test showed no significant difference in the performance of the test subjects without using PPE and while using symmetrically equipment loaded PPE, except for the overhead reach (t=-3.19, P=0.01), pulling (t=-4.16, P= 0.002), and replacing velocity for dynamic lifting 25 lbs (t=-2.28, P = 0.045).

- The results of the test also indicated that performance of the test subjects was not significantly different in two different test conditions, performing the test without using PPE and Using PPE with asymmetric loading, except for pulling (t=-2.6, P= 0.026), replacing velocity for dynamic lifting 25 lbs (t=-2.69, P= 0.023) and replacing velocity for dynamic lifting 50 lbs (t=-2.58, P= 0.028)
- Performing the test with using PPE symmetrically loaded and using PPE asymmetrically loaded showed no significant difference between the performance of the test subjects except for replacing velocity for dynamic lifting 50 lbs (t=-2.38, P= 0.039).

Comparison of Left versus Right Hand, Push versus Pull, and Lifting Velocity versus Replacing Velocity

An independent sample t-test with alpha level of 0.05 and df =10 was chosen to detect any difference between left and right hand performance of the subjects, between push and pull performance, and lifting velocity versus replacing velocity in dynamic lifting activity. According to the results of the study no significant difference was detected (p>0.05) between left and right hand performance, push versus pull, and lifting velocity versus replacing velocity in the three different test work situations.

Conclusions and Recommendations

Only a small group of individuals were tested in this demonstration project not allowing a robust statistical analysis or the capability of making stronger conclusions and credible inferences. Subject classification was a weakness due to the fact that some of the inexperienced subject sample had no past or current experienced as an ironworker. In addition, constraint of a convenience sample did not allow for more accurate subject classification and recruitment of a larger sample size for use in the demonstration project. Another possible weakness is that while the ERGOS Sapphire TM System is a validated clinical test instrument for physical work evaluation related to worker disability status in clinical medicine it has not been validated for basic engineering and human factors research.

- The experienced ironworker scored higher in most metrics compared to inexperienced subjects. Significant differences between the ironworker and inexperienced subjects were noted in some metrics for no PPE and PPE, simulated work task, and symmetrical and non-symmetrical tool belt loading.
- Based on the ERGOS Sapphire TM analysis software, the experienced ironworker scored above competitive category" for MTM-II performance and heavy and very heavy category for physical demand level. Results of inexperienced subjects placed them in competitive and above competitive" categories for MTM-II performance and in very heavy, heavy, medium, and light in physical demand level categories.
- The test results showed no significant difference in performance with regard to different work conditions with the exception of overhead reach (p=0.01), pulling (P = 0.002) and replacing velocity for dynamic lifting 25 lbs (P = 0.045) when not using PPE and using PPE with symmetric tool loading; pulling (P= 0.026); replacing velocity for dynamic lifting 25 lbs (P= 0.023) and replacing velocity for dynamic lifting 50 lbs (P= 0.028) in performing the test without using PPE and Using PPE with asymmetric loadings; and pulling and dynamic lifting 50 lbs (P= 0.039) for performing the test with using PPE symmetrically loaded and using PPE asymmetrically loaded.
- No significant difference was detected (p>0.05) between left vs. right hand performance, push vs. pull, lifting velocity vs. replacing velocity in the three different test work situations.
- Most inexperienced subjects found the PPE and asymmetrical tool loading noticeably uncomfortable during the overhead reach test, static strength tests, dynamic lifting, and dynamic carrying test. The frequency and level of fatigue or discomfort reported by subjects increased after using the full body harness especially in the back, shoulder, and neck. However, using supplied gloves and safety shoes compared to no gloves and street shoes increased the level of comfort of the test subjects. Test subjects complained more about discomfort and fatigue on the right side of their body when the tools on the tool belt were transferred to that side for asymmetric loading.

The trial use of the ERGOS Sapphire TM Work Assessment System in this demonstration project revealed its potential to systematically and objectively measure physical work capacity in a broad range of construction tasks and job descriptions as provided in the O*Net Job Description Database necessary for detailed validation studies and future research in construction safety and ergonomics.

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