Towards Standard Exoskeleton Test Methods for Load Handling

Roger Bostelman, Ya-Shian Li-Baboud, Ann Virts, Soocheol Yoon, Mili Shah

***Abstract*— Exoskeletons are now being marketed by several manufacturers and yet there are currently no standard test methods to help match exoskeletons[1] to desired tasks. The National Institute of Standards and Technology (NIST) has been a key contributor to the formation of a new ASTM F48 standards committee on exoskeletons and has a project to research measurement science and test methods in support of exoskeleton standards. This paper describes the NIST exoskeleton project efforts for one of several ongoing research areas that target typical industrial tasks - i.e., load handling. The paper will describe the design of the NIST Position and Load Test Apparatus for Exoskeletons (PoLoTAE), a reconfigurable testbed and its use within a NIST human subject's study. Experimental results from the first load handling test are described and future tests are outlined.**

I. Introduction

Exoskeletons can be passive, with only springs and/or counterweight augmentation of human motion, or active, with motor augmentation - sometimes called wearable robots, or a combination of passive and active. In the early 2000's, the U.S. Defense Advanced Research Project Agency (DARPA) began development and demonstration of "… critical technologies such as power, control, and actuation that will lead to a self-powered external structure to enable a Soldier to effortlessly carry over 45 kg (100 lbs) of additional weight [1]." Exoskeletons were recognized as potentially beneficial to many other domains: as of December 2016, [2] identified 58 commercial and/or non-profit organizations that have developed or were developing exoskeletons or wearable robotics. Today, there are roughly 80 commercial systems on the market.

Several events laying the foundation for standards have occurred since the DARPA developments, including a Round Table and several Technical Interchange Meetings, fostered by U.S. government organizations and with invitees from international government, industry, and academia [3]. One common theme that was discussed was the need for standard test methods for exoskeletons. To this end, an exploratory project within the National Institute of Standards and Technology (NIST) Engineering Laboratory (EL), began in September 2017 and cumulated into the ASTM International Committee F48 Exoskeletons and Exosuits (ASTM F48) [4]. Six F48 subcommittees were established: F48.01 Design and Manufacturing, F48.02 Human Factors and Ergonomics, F48.03 Task Performance and Environmental Considerations, F48.04 Maintenance and Disposal, F48.05 Security and Information Technology, and F48.91 Terminology. An exoskeleton is currently defined by ASTM F48.91 as a "wearable device that augments, enables, assists, and/or enhances physical activity." Two notes support the definition with 1) "an exoskeleton may include rigid and/or soft components (see exosuit)" and 2) "physical activity may be static or dynamic".

The NIST EL project also includes developments in two areas that have continued into a longer-term project beginning in fiscal year 2019: 1) measurement science towards development of new methods to measure the exoskeleton fit and movement of the exoskeleton to the user, and 2) the impact that wearing an exoskeleton has on the performance of users executing tasks that are representative of activities in industrial settings. Based on the United States Bureau of Labor statistics, in 2014 there were about 12 188 300 manufacturing jobs in the United States [5]. Approximately 5 086 905 of manufacturing employees belong to small and medium enterprises according to the US Census Bureau for 2012 [6]. With so many manufacturing jobs performed, including nearly half in the small and medium size organizations, even a small percentage of these jobs could benefit from using exoskeletons if they are safe and effective. As a result, exoskeleton standards are necessary.

Initial NIST EL efforts to support exoskeleton standards include developing test methods from previous research areas such as response robots and autonomous industrial vehicles [7]. A NIST study, which began in June 2018 [8], is researching the two EL project areas described above. The results of the study will inform future test method development at NIST and at other organizations, all under the purview of ASTM F48. Area 1 has been completed for exoskeleton fit to the leg and analysis is underway. Within area 2, the focus of this paper, a reconfigurable Position and Load Test Apparatus for Exoskeletons (PoLoTAE) [9] was designed. Six test methods were designed to target industrial tasks where the first load positioning task will be the focus experiment and findings described in this paper. The outcome of the load handling tasks is also expected to provide support for development of ASTM

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[1] Disclaimer: Commercial equipment, software, and materials are identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials, equipment, or software are necessarily the best available for the purpose.

subcommittee F48.03 work item WK65295 - Load Handling When Using an Exoskeleton.

II. Test Method Design

Repeatable test methods can help exoskeleton manufacturers and users highlight capabilities of their systems, compare exoskeletons to their motion tasks, show design flaws or enhancements, and help with procurement requirements. Ideally, these test methods are not only repeatable, but also standardized, such that both manufacturers and users can simply select a document that describes how to perform the test method no matter which exoskeleton they make or use. Although NIST has been focusing on industrial test methods, there is overlap with military, medical, response, and perhaps commercial exoskeletons. For example, military logistics personnel carry relatively heavy loads and, for example, mount wheels on military equipment. Example cross-industry/medical use of exoskeletons may be for nurses and orderly staff to pick-up and maneuver patients. Movement of an elderly person at home with the help of an exoskeleton device would not be considered a medical application if the device is not prescribed by a medical doctor.

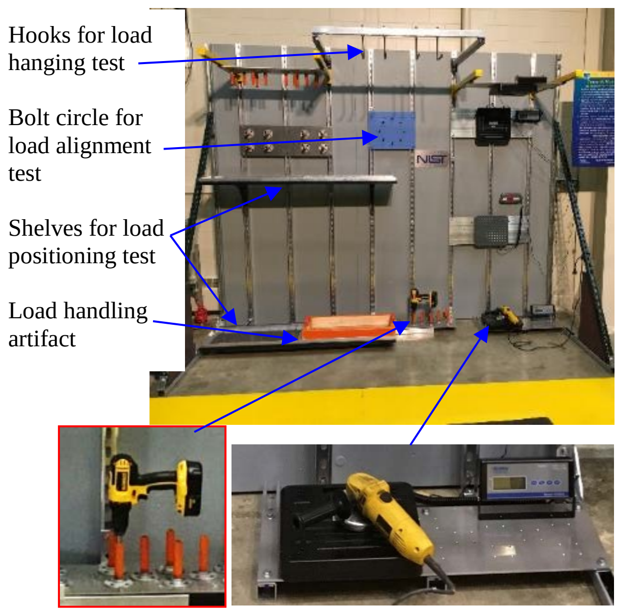


Figure 1. PoLoTAE showing inserts of the force plate with tool (top) and drill with bit in a pipe for peg-in-hole tests.

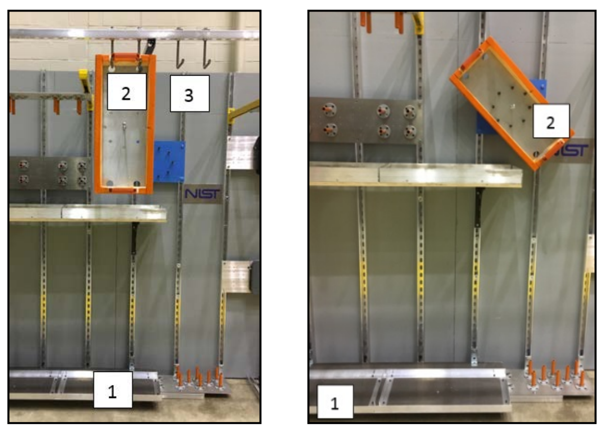
In addition to supporting the development of ASTM F48, which includes all of the above applications, NIST began designing test methods that are representative of industrial tasks including: applying forces (e.g., grinding, sawing, drilling, pushing, etc.), inserting pegs (e.g., screw, drill bit, etc.) into holes, non-contact alignment (e.g., laser pointing, siting, etc.), and load handling (e.g., holding a load and aligning to a fixture, hanging a load on hooks, and placing/positioning loads). All of these tests are planned for the experiments within the NIST study. In this paper, we describe the study of the first of the six planned tasks – i.e., load positioning.

Towards a standardized approach to a replicable apparatus that can be used by the exoskeleton manufacturers, users, and researchers, NIST designed the PoLoTAE and will provide the PoLoTAE design in a future NIST internal report [8]. The PoLoTAE, shown in Figure 1, was designed to be reconfigurable, minimal cost, and expandable to larger dimensions or to focus more specifically on the required exoskeleton tasks. Variability in generic loads/tools, positioning heights, defined motion spaces, etc. can also be added to the PoLoTAE to help exoskeleton designers fit the tasks to the potentially wide variety of exoskeleton wearers.

Loads can vary dramatically depending on the application. However, load handling includes not only picking up but also placing loads, sometimes with relative precision (e.g., installing a wheel on a vehicle axle bolt- circle). Ideally, a single, replicable artifact (e.g., the load artifact shown in Figure 1) is used for picking, placing, aligning, and hanging loads.

Figure 2 a, b, and c show the series of load handling tasks that are planned for experimentation on at least 30 subjects each. Figure 2 a and b show load hanging and load alignment tests planned for future experiments within the study and will not be further explained in this paper. Figure 2 c shows the load positioning test design setup which is the focus of the remainder of this paper.

Figure 2 d shows the 6.8 kg (15 lbs) load artifact designed for use in all three load handling tests. For load positioning, the artifact base was approximately 3 mm smaller on all four sides than the tray-surround on each shelf. The surround ensures that the subject being tested must not only place the artifact in the correct location but must also position and seat the artifact correctly within the surround. Handles or other grasp methods can also be incorporated into the artifact.



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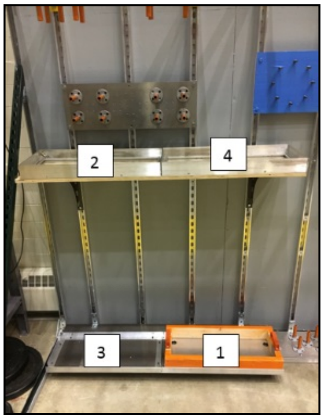

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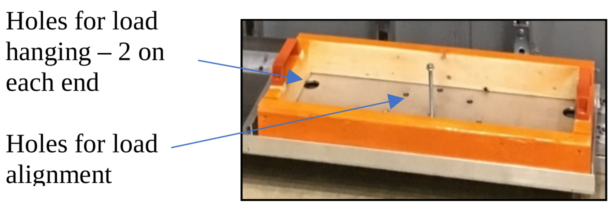

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Figure 2. PoLoTAE a) load hanging, b) load alignment, and c) load positioning test designs setup and numbered order of subject movements planned within the NIST study. d) Artifact used for all three load handling tasks.

III. Load Positioning Experiment

NIST currently owns a full-body, passively-mechanized exoskeleton which uses springs internal to the frame. This exoskeleton will allow for the initial development of study procedures with the expectation that additional models will be procured or borrowed to validate and expand the tests on a variety of exoskeletons. The test methods described below are designed to exercise all aspects of a full-body exoskeleton through timed video recording, so that the sub-tasks (e.g., lifting, placing, bending, etc.) can be separated out for individual review.

Subject recruitment included posting brochures requesting NIST federal employee volunteers that fit the profile required of the test and the exoskeleton to be used. In a similar test method development, EL researchers worked with the NIST Statistical Engineering Division to determine the number of tests to perform for statistical significance. The statisticians determined that for 85 % confidence, 30 repetitions were required. At least 30 subjects, each performing one of six tests, requires nearly 200 subjects. Also, the same subject can return for another future test. From a pilot study on a subject having average physicality, 30 repetitions of a task appeared to be a good limit to test fatigue without strain caused by the task motions.

The recruited subjects were:

- At least 18 years of age
- Physically fit to complete the test which relied on the subjects perspective of their own capability.
- Willing to participate for up to 1 ½ hours.
- Able to wear an exoskeleton that weighs approx. 13.7 kg (30.3 lbs).
- Able to perform knee bends, position tools, and apply forces 30 times twice (60 total) using tools (up to the approx. weight of 13.7 kg (30.3 lbs)).
- Able to fit within the exoskeleton manufacturers specification for height 1.5 m to 1.9 m (5’ 0” to 6’ 1”) and weight 49 kg to 102 kg (108 lbs to 225 lbs).

The research study procedure included the following:

- the subject reviewed a training video [11] and signed a consent form,
- the subject wore (one or two) wrist heart rate (HR) monitor(s) and the research team recorded the subject’s HR throughout the test,
- the subject first performed the baseline and then exoskeleton-use tasks, 30 times each, with help from the research team as needed to assist the subject with putting on/taking off the exoskeleton where the subject could stop the test at any time,
- the subject responded to a brief set of survey questions about the test upon its completion.

Repetition 1: The subject stepped one step forward from a start line to the load apparatus (refer to Figure 2c); the load apparatus was picked up from tray 1 (14 cm above the floor) and placed in tray 2 (138 cm above the floor); hands were released; The load apparatus was picked up from tray 2 and placed in tray 3; hands were released and the subject stepped back to the line. Repetition 2: The subject stepped from the line to the load apparatus; the load apparatus was picked up from tray 3 and placed in tray 4; hands were released; The load apparatus was picked up from tray 4 and placed in tray 1; hands were released, and the subject stepped back to the line. Repetition 1 and 2 are repeated 14 more times for a total of 30 repetitions.

IV. Subject Safety Protection

Subject safety - including physical safety as well as social safety - is a priority during the NIST exoskeleton research. All procedures during the study were approved by the NIST Institutional Review Board. The research team strictly followed the Human Subject Research protocol [8] to keep the subject socially safe. In addition, the subject is prevented from physical injury due to instability and raised heart rate through continuous monitoring.

To protect the subject’s personal information, the entire test area is surrounded with curtains. A pre-test survey is conducted to check whether the subject has potential risks (e.g., aches, pains, past broken bones, etc. that may affect their task completion). Many exoskeleton novices were unstable at first and were asked by the team to perform knee bends on soft safety mats to establish their stability. All wearable devices and parts were cleaned with sanitary wipes before and after the test, particularly for the components in contact with the body.

A. *Heart Rate Monitoring*

HR was monitored throughout the test. HR has been widely used as an indicator for response of heart to exercise since it is easy to measure and directly related to the autonomic nervous system [12]. The tests require activity and as a result HR was expected to increase during the tests. The American Heart Association [13] method of subtracting the subject age from 220 beats per minute (bpm) or a particular HR that the subject desired was set as the HR limit.

Wrist HR monitors, now widely used [14], were employed to measure and record HR. The monitors use optical sensors to measure HR which are verified to have 80 % to 91 % accuracy depending on make, application, test conductor, and subject response [15][16][19]. The actual accuracy of the HR monitor varies according to the subject's skin type, arm thickness, and shape. In addition, since the tasks require a wide range of motion, errors in HR measurement were primarily due to loss of steady attachment for durations up to 10 s.

To overcome this limitation, the procedure was revised during the experiment to include two steps to provide further corroboration of HR data. First, two HR monitors from different manufacturers were used. Both use optical sensors, but they have different sensor arrangements and straps. When they showed different HR values, the higher one was always accepted. Second, a hand grip monitoring bar, based on electrical conductance, was used to verify that the wrist HRs were working correctly. The bar uses electrodes to measure HR and was used as another technology method to help verify the optical HR monitoring method. Before the test, resting HR was measured, and the highest wrist HR was recorded after the test was verified with the HR bar.

Wrist HR was measured and recorded at 1 s time intervals using BlueTooth to offboard heart rate monitoring devices. Several HRs were marked at specific task repetitions such as prior to beginning, after 15, and after 30 repetitions. The research team frequently asked subjects their condition when their HR was elevated, e.g., above 150 beats per minute (bpm), and determined whether to continue the test, rest, or stop the test.

V. Data Collection System

The data collection system was comprised of four high definition (HD) camcorders mounted on tripods, a high definition multi-viewer, and an HD video capture device with external hard drive. The video was recorded at full HD 1080 pixel resolution. Figure 3 shows the output of the data collection system. Two videos of the output were recorded: the baseline test and the test when the subject wears the exoskeleton.

Figure 3. Snapshot of the data collection system display.

Frame A denotes (top) repetition number, (center) global positioning system time, temperature, date, and humidity, and (left) a timer. For the first load positioning task test and if time were a critical metric, video review could have been used to determine repetition-completion count within a set time. Figure 3 shows the more recent data collection system with repetition counter and timer added for the second task (e.g., peg-in-hole task currently underway). Frame B shows the output of two HR monitors (left and right) as described in section IV. Frames C and D are left and right views of the task being performed by the subject.

Digital photographs of the subject performing various portions of the task were also captured and added to the stored data. For example, the photos show snapshots of:

- the technique that the subject uses to pick-up and place the load artifact (e.g., bend at the hips or bend at the knees),
- the shelf height relative to the subject shoulder height (i.e., potentially critical for short subjects and less critical for tall subjects),
- and the change in the subject form from when first using the exoskeleton to final repetitions after the subject appears to be familiar with the exoskeleton.

VI. Results

A. Use of heart rate data

HR was monitored to protect the subject and also used to evaluate the physical demands of the task test on the subject with and without the exoskeleton. It is difficult to conclude whether a subject's HR response can be an indicator of an exoskeleton's effectiveness in augmenting or supporting humans with the physical demands of the task. However, combining HR with other test data obtained including video and a survey, additional information may be derived. Usually HR becomes high at the beginning when wearing an exoskeleton, and later it differs for each subject. For example, if a subject feels uncomfortable, HR gradually increases until the test is finished. Meanwhile, if a subject seems comfortable with using the exoskeleton, HR decreases or remains fairly constant. Even if a subject feels good, his/her HR can be higher than the reference. Thus, rather than the HR value itself, the HR value trend tells us much more about the test and performance.

B. Data for Load Positioning

The data set for load positioning included fit, HR, and survey data sets for 33 subjects who completed the Load Positioning task. Each subject completed the tasks in the following order, baseline 30 repetitions (without the exoskeleton), and 30 repetitions with the exoskeleton after a period of returning to a normal, resting heart rate. The uncertainty of the data sets are as follows:

1. The exoskeleton fit based on the anthropometry of the subject was estimated by asking the subject for rough height and waist measurements, which were typically given in inches, while the analysis was done in

centimeters. A rough estimate of the size uncertainty is around 3 cm, based on the 2.54 cm per inch conversion. Fit uncertainty is based on comfort of the user and visual verification of exoskeleton alignment to the subject's joints. In particular, the shin and femur adjustments are done based on alignment to the subject's heels, hips and knees, ensuring the exoskeleton is aligned to the center of the sagittal plane, where the inseam of the pants provide a sufficient visual indicator. The arms are based on a few inches above the elbow. The team received training as well as guidance from the exoskeleton manufacturer in fitting the suit to subjects.

2. The HR is estimated using two, and up to three devices, including both the use of optical wrist watches, and an electrical handheld device for corroboration. The HR recorded at the beginning of the task, while the subject is seated, and at the completion time of the task is based on the highest bpm of either of the optical devices. Of the optical devices, one was used predominantly for most of the Load Positioning subjects, and the other was only acquired later in the experiment. The electrical device is used only to verify the optical devices. If the steady heart rate is greater than 10 bpm compared to the optical wristwatch device(s), the electrical device reading was used. Issues that degrade the accuracy of the optical devices include the fit of the wristwatch, sensitivity to perspiration, and other factors that can impact the ability to maintain adequate skin contact for accurate readings. Studies have shown the optical wrist-worn monitors have a concordance correlation of 0.83 to 0.91 at a 95 % confidence interval [16].

3. The survey is based on a series of quantitative categories and free-form answers regarding pre-existing discomforts of the subject and the respective severity, comfort, range of motions, fit, discomfort to the subject caused by the exoskeleton or the task, and the subject's opinion on where the exoskeleton provided support during the task. While the full survey allowed users to enter 33 different regions of the body at 4 severity levels, *slight*, *moderate*, *severe*, and *extreme*, we based the initial analysis on just 10 areas that were indicated by the pool of initial subjects. The areas included head, neck, upper spine, mid-spine, back, lower spine, shoulders, waist, and hips. The free-form answers were also reviewed and categorized to ease analysis. For example, the responses to what the subject liked most about the exoskeleton included: (1) arm support, (2) back support, and (3) leg support. Similarly, the subjects least favorite attributes of the exoskeleton include: (1) heat dissipation, (2) knee motion, (3) range of motion, (4) fit, (5) stability, (6) arm motion/resistance, (7) impact on fine motor movements, and (8) exoskeleton weight. The survey also provided the ratings of perceived discomfort (RPDs) [10] based on Likert scales of 0 (uncomfortable) to 5 (very comfortable) as well as the actual regions of discomfort before, during, and after the test.

4. A quad video of the time and environmental conditions, HR monitors, and the left and right side of subject performing the task was also taken. Our current use of the video is limited to visual assessment of subject's skeletal joint positions. The video has also been used to corroborate with other data sources including HR, RPD, etc. We anticipate expanding the computational analysis by using the videos for quantitative assessment on skeletal joint angle variability.

C. *Analysis method*

An effective test methodology assesses the performance or exertion of the subject while wearing the exoskeleton and without the exoskeleton to complete the load positioning task. The intra-subject independent variable is the exoskeleton. The initial exploratory analysis is based on the Spearman's rank correlation coefficient, which assesses whether there is a monotonic relationship between two variables. Spearman's rank correlation can be used on both discrete ordinal (gender, exoskeleton fit sizes, survey agreement) and continuous (height, waist, heart rate differential) variables.

Various methods have been documented in applying heart rate to capture exercise intensity including the Karvonen method [17] and variants [18], both of which require age information. Because age was not available, the heart rate differential with and without the exoskeleton was used as a metric to capture the physical intensity of the task to the subject:

$$\Delta HR_{LP} = \left(Exo_{end} - Exo_{begin}\right) - \left(Baseline_{end} - Baseline_{begin}\right)$$

Equation 1

The final differential with and without the exoskeleton is recorded using the following equation:

$$\Delta HR_{Final} = \left(Exo_{end}\right) - \left(Baseline_{end}\right)$$

Equation 2

D. *Table of Results*

Tables 1 and 2 show a few trends above 95% level of significance with respect to gender, anthropometry, and fit. Based on [19], the r_{crit} value of the R coefficient, with 30 subjects is 0.306 at the 95 % confidence level. Females and those who indicated prior pains generally had lower heart rates in wearing the exoskeleton relative to the baseline. Shoulder width also indicated a correlation of broader shoulder width to an increase in the subject's physical exertion.

Table 1. Spearman rank correlation to final heart rate differential, $\Delta \mathrm{HR}_{\mathrm{Final}}$.

	R-Coefficient	P-Value
Gender	-0.36	0.04
Rigid Waist (exo fit)	0.35	0.05
Spine (exo fit)	-0.35	0.05
Shoulder (exo fit)	0.41	0.02

Table 2. Spearman rank correlation to task heart rate differential, ΔHR_{LP}.

	R-Coefficient	P-Value
Gender	-0.43	0.01
Prior Pain (any)	0.33	0.03

The findings do not necessarily indicate a causality, but potential avenues to explore. For example, if broader shoulders led to greater physical exertion, should the shoulders be sized for a more snug fit to reduce exertion or is the correlation due to the stature of the subject, where broader shoulders would lead to greater exertion?

We only had six females from the 33 subjects, which also leads to the need to further explore whether one of the performance criteria of the test method can be gender neutrality.

In the survey responses, subjects indicating shoulder chafing RPDs had an R coefficient of 0.33, with p-value of 0.06, relative to the HR differential, ΔHR_{Final}. Another interesting trend was the subjects who indicated what they least liked about the exoskeleton had an R coefficient of -0.33, with p-value of 0.07. The result is based on converting the free-form response into categories, where the lower values include heat dissipation, leg resistance, and range of motion. The trends indicate more in-depth investigation in how the characteristics of the exoskeleton may impact the physical demands on the subject.

In order to assess the subjects' opinion towards the exoskeleton and the subjects' HR response, a multiway analysis of variance (ANOVA) was computed based on survey responses if the subject agreed that the exoskeleton eased and helped the task or hindered the task. The factors on whether the exoskeleton helped or hindered did not indicate a significant response. The result may indicate the need to reduce the error tolerance in our current response metric.

We intend to further expand our analysis to utilize the video capture and segment the subject to analyze the subject's range of motion based on skeletal joint angles [20]. In cursory visual assessment of the videos, it was noted that subject's often have differing angles in the knee and back when comparing postures between the subject wearing the exoskeleton (squat lifting technique) and the subject without the exoskeleton (stoop lifting technique). The squat lifting technique has been widely regarded as a means to avoid lower back strain, while the stoop technique has cited benefits of ease, reduced energy consumption, and increased stability [21]. We intend to further explore analysis methodologies regarding the support of the exoskeleton for completion of repetitive, physically strenuous tasks, as well as the ability to enable the subject to perform tasks with more ergonomically sound postures.

Conclusions

The NIST Human Subject's study was approved and is underway beginning with the load positioning task test. A Position and Load Test Apparatus for Exoskeletons (PoLoTAE) was designed to include six generic tasks typical of industrial environments, including load handling. Load handling tasks are a current ASTM F48 work item towards a standard test method. The study used a data collection system of cameras, monitors, and HR monitors and the subject completed a survey after the completing the task. Results showed that the combination of HR and other test data from video and the survey provided additional information beyond just HR. For example, subject comfort level may affect HR. Uncertainties were from: data units conversion, subjective exoskeleton fit to the subject by the briefly-trained research team, subject responses to survey questions about exoskeleton fit, HR monitor devices, and subjective review of video and of survey responses. Initial analysis is based on the Spearman rank correlation and results are shown in Tables 1 and 2 with respect to final and task heart rate differential. Trends showed high significance with respect to gender, anthropometry, and fit. As in section VI C, females and those who indicated prior pains generally had lower heart rates in wearing the exoskeleton relative to the baseline. Shoulder width also appeared to have an impact on the subject's physical exertion.. Survey responses of whether the exoskeleton helped or not did not indicate a significant response. However, when asked outside of the survey if the subjects felt the test method exercised the potential capabilities of the exoskeleton, a unanimous affirmative was received by all subjects.

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