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DEVELOPMENT OF A METHODOLOGY TO CONDUCT USABILITY
EVALUATIONS FOR HAND TOOLS THAT MAY REDUCE THE AMOUNT OF
SMALL PARTS THAT ARE DROPPED DURING INSTALLATION WHILE
PROCESSING SPACE FLIGHT HARDWARE

by

MS. DARCY HAGIST MILLER
B.S.I.E. University of Oklahoma, 1986

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Major Professor: Dr. Pamela McCauley-Bell

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THESIS APPROVAL

The members of the Committee approve the thesis entitled Development of a Methodology to Conduct Usability Evaluations for Hand Tools That May Reduce the Amount of Small Parts That are Dropped During Installation While Processing Space Flight Hardware, of Darcy H. Miller, defended November 1, 2000.

Dr. Pamela McCauley-Bell, Chair

Dr. Linda Malone
Committee Member

Dr. Mansoor Mollaghasemi
Committee Member

It is recommended that this thesis be used in partial fulfillment of the requirements for the degree of Master of Science from the Department of Industrial Engineering and Management Systems in the College of Engineering and Computer Science.

Charles H. Reilly, Department Head

Issa Batarseh, Assistant Dean for Graduate Studies

Martin P. Wanielista, Dean of College

Patricia J. Bishop
Vice Provost and Dean of Graduate Studies

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ABSTRACT

Foreign object debris (FOD) is an important concern while processing space flight hardware. FOD can be defined as "The debris that is left in or around flight hardware, where it could cause damage to that flight hardware," (United Space Alliance, 2000). Just one small screw left unintentionally in the wrong place could delay a launch schedule while it is retrieved, increase the cost of processing, or cause a potentially fatal accident. At this time, there is not a single solution to help reduce the number of dropped parts such as screws, bolts, nuts, and washers during installation. Most of the effort is currently focused on training employees and on capturing the parts once they are dropped. Advances in ergonomics and hand tool design suggest that a solution may be possible, in the form of specialty hand tools, which secure the small parts while they are being handled.

To assist in the development of these new advances, a test methodology was developed to conduct a usability evaluation of hand tools, while performing tasks with risk of creating FOD. The methodology also includes hardware in the form of a testing board and the small parts that can be installed onto the board during a test. The usability of new hand tools was determined based on efficiency and the number of dropped parts. To validate the methodology, participants were tested while performing a task that is representative of the type of work that may be done when processing space flight hardware. Test participants installed small parts using their hands and two commercially

available tools. The participants were from three groups: (1) students, (2) engineers / managers and (3) technicians. The test was conducted to evaluate the differences in performance when using the three installation methods, as well as the difference in performance of the three participant groups.

The results of the research indicate that there are significant differences in some of the usability indicators for the three installation methods, although there was not one overall significant indicator. This was achieved by considering both the objective data that was gathered through observation during the study and the subjective data that was gathered during the post test survey. It was also shown that although the three participant groups performed differently, they all showed the same results when comparing the installation methods to each other. Therefore, it would be reasonable to predict that future studies could show a difference in the usability of different installation methods. Also, when technicians are not available, it may be reasonable to use students, engineers, or managers, although this should be approached with caution.

The research provides a methodology and hardware to conduct usability tests on hand tools. Use of this methodology and hardware during the development cycle could possibly lead to a reduction in the risk of creating FOD while using the new tools. As a result, this has the potential to minimize delays in processing schedules, reduce the cost of processing, and potentially reduce the risk of a fatal accident.

DEDICATION

This thesis is dedicated to my husband Jim Miller, and my two daughters, Alyssa and Shannon. They were with me through it all, with love and support. Also it is dedicated to my mother, Barbara Hagist, and my father, Dr. Edward Hagist, who were there in the very beginning with encouragement. Nothing worthwhile is ever accomplished alone.

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There are also other people who deserve my gratitude. My good friend Loretta Moore encouraged me to return to school. My colleague, Faith Chandler, conceived of the original idea for the testing board that became a central part of the thesis. Alan Littlefield took the ideas for the board and created a design that far exceeded my expectations. The NASA Prototype Shop brought the design to life, and exceeded my expectations even more. Kristine Krivicich added real world experience to the testing. Kimberly Shanks was enthusiastic and helpful with the data entry and analysis. Without all twenty of the test participants, the experiment would not have been possible.

Finally, I would like to thank NASA, Kennedy Space Center for awarding me the fellowship that allowed me to complete the master's degree and thesis. This was an exceptional opportunity.

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CHAPTER 1

INTRODUCTION

Just one small screw or washer, unintentionally dropped near space flight hardware, could become a deadly projectile during a space shuttle lift off, if not retrieved. In the best case, the dropped screw is noticed and picked up, causing only a slight distraction in the assembly of the flight hardware. In a more serious case, a team of foreign object debris (FOD) experts may have to come to the scene and engineer a way to remove a small washer from inside of a flight component. If they fail, the hardware may have to be removed and disassembled to remove the FOD. In any situation, an insignificant event such as a dropped screw could, without warning, become a significant event. To prevent this, there are teams of people within organizations and professional societies, such as the National Aerospace FOD Prevention Society, that are dedicated to reducing FOD in critical areas. If a solution were found to reduce the amount of FOD that was created while installing small parts, there would also be applications for it in areas such as ground processing for space missions, military aircraft, private airlines, and even while in space. Other areas where this type of FOD could be hazardous or delay a schedule include the nuclear industry, electrical power plants and construction sites.

This chapter is divided into the following sections to provide an introduction to the research:

- 1.1 Foreign Object Debris
- 1.2 Significance of Hand Tool Usability Testing
- 1.3 Statement of the Problem
- 1.4 Research Implications

1.1 Foreign Object Debris (FOD)

FOD can be defined as "the debris that is left in or around flight hardware, where it could cause damage to that flight hardware," (United Space Alliance, 2000). The sources and types of FOD can be varied in a work environment. This study is focusing specifically on small parts, including screws and washers, that can be dropped while being installed when doing ground processing of space flight hardware, such as for the International Space Station.

In the best of conditions, there is always a possibility of dropping a small part. But the job of installing screws and washers becomes more difficult when clean room gloves are placed on the hands that are manipulating the small parts. To add to the difficulty, the people doing the installation may have to position their forearms, wrists and fingers in awkward postures. Many times this is done blindly, where the technicians have to reach into an area that can not be seen to install screws. Other distractions may occur, including local conversations and discussions that are heard over the communication network. Conditions such as glare or low lighting, and temperature variations may also make the job more difficult. All of these factors could potentially

increase the risk of dropping parts, creating FOD, which makes this a challenging issue to address.

1.2 Significance of Hand Tool Usability Testing

In this study, it is proposed that the users may be better at preventing FOD from occurring if they were given the proper tools to secure the small parts. This assumes that the end users have the most control over the dropping of parts. The evaluation of hand tools may lead to better designs that can help users prevent FOD from occurring. This works in concert with the existing capture programs that are in effect to catch the parts if they are dropped, such as using netting under the area that is being worked.

Currently, most of the emphasis on FOD prevention is on awareness programs and capture of the dropped parts. The awareness programs focus on the end user of the tools and small parts to assure that they understand the importance of reducing FOD.

When new hand tools are designed to reduce the risk of dropping small parts, consideration must be given to the human factors that reduce injuries and cumulative trauma disorders. The efficiency of the tool must also be considered if the tool is to be accepted in the workplace. Martin et al., 1996 developed a model that shows an interaction between work factors, tool factors, stress factors, worker factors and the resulting performance and health of the individual (Chaffins, 1999). This illustrates that good hand tool design may reduce the risk of dropping parts, while also having the benefit of reducing the risk of injury.

A usability testing methodology could benefit the hand tool designers during the initial design and development phase and could be used to determine which existing

hand tools and newly developed prototypes give the best performance. By providing a physical model that allows participants to do tasks that are representative of the actual work that is performed, the designers can study many hand and wrist orientations in a short time. By studying existing tools as they are used in typical orientations, and redesigning to keep the hand in a more neutral position, improvements can be made. Having the ability to do usability testing in a controlled environment gives participants the freedom to drop parts in a non-critical area, without harm to hardware. Creating a test environment allows the designers the ability to actually use the tools in typical orientations to generate new design ideas that may not have been seen by merely observing technicians in the field. Prototype designs can be tested for usability before being mass-produced, reducing the possibility of releasing a faulty design.

1.3 Statement of the Problem

The objective of this study was to develop a methodology and hardware to assess FOD risk by using various hand tools when handling small parts. This was accomplished by developing an approach to conduct usability evaluations for hand tools that are used during the installation of the small parts. Usability can be determined by measuring the efficiency, the rate of dropped parts, and participants' satisfaction in task performance. In order to provide a measure of efficiency, two main products were produced, which are the methodology for conducting usability testing of hand tools, and the hardware for conducting these tests.

The test methodology that was proposed could be used to test existing hand tools and future prototypes. The methodology will benefit future tests by providing a baseline

for measuring usability based on efficiency, the number of dropped parts, and participants' satisfaction. To make the future studies more cost effective, the study compared the performance of technicians, managers and engineers, and students, to determine if participants other than technicians could be used to get comparable results. This is because technicians are often not as readily available as the other two categories of participants.

The hardware consists of a 30" X 40" aluminum testing board which allows users to test the hand tools in various configurations that are representative of what is seen in the work environment. The board was designed to be used for this experiment, and also to be used to test many hand-wrist orientations, various small parts, and various hand tools. The board is portable, so it can be used in different orientations, and work environments. It is also clean room compatible. This design will accommodate many future applications for testing and training. This will potentially lead to identifying the best tools for the job and training people to use them more effectively, which may result in a reduced risk of producing FOD in the workplace.

1.4 Research Implications

The test methodology and hardware can be used to test prototype and existing hand tools for any area that processes critical hardware using small parts, such as screws, washers, nuts and bolts. The primary focus of the study was for ground processing of flight hardware at the National Aeronautics and Space Administration (NASA), Kennedy Space Center (KSC). But the same problems of foreign object debris exist in other

NASA Centers, the military, manufacturing facilities, and private airlines. Improvements to reduce FOD could save lives in any of these industries.

The implications of FOD go beyond earth and into space. On the International Space Station and future long duration space missions, there will be activities that require assembly and repair, which include installation of similar small parts. In any of these instances, there exists the possibility of dropping just one small part, which could lead to delays, expenses and safety hazards as here on earth. If this problem is not solved here on earth, it will be taken to Mars. Although this methodology is intended for ground operations, a similar methodology could be adopted for low gravity experiments. This could have similar impacts to those on earth, by preventing time delays, damage to hardware, and injuries to explorers during space missions.

CHAPTER 2

LITERATURE REVIEW

This chapter presents the results of a literature review of relevant topics in addressing the problem defined to be *the development of a methodology to conduct usability evaluations for hand tools that may reduce the amount of small parts that are dropped during installation while processing space flight hardware*. The goal of this research was to develop and test a methodology for conducting usability testing on hand tools. Additionally, this methodology will be applied to several installation methods, which include two hand tools and hand installation. Ideally, the methodology and assessment will promote development of hand tools and procedures that reduce the risk of FOD and hand injuries.

The results of the research include the development of the hardware and methodology for testing the tools. To develop the methodology and hardware design, a review of the literature was undertaken in these relevant areas:

- 2.1 Foreign Object Debris (FOD)
- 2.2 Boeing Study Information
- 2.3 Hand Tool Design

- 2.3.1 Hand Tool Use
- 2.3.2 Importance of Good Hand Tool Design
- 2.3.3 Design Principles for Safety and Effectiveness
- 2.3.4 Other Factors that Affect Hand Tool Performance
- 2.3.5 Commercial Hand Tools
- 2.4 Evaluation Techniques
 - 2.4.1 Usability Evaluations for Hand Tools
 - 2.4.2 Related Hand Tool Research

Foreign Object Debris (FOD) is discussed in this literature review to give an understanding of its impact and why it is important to conduct research to reduce it. A study was conducted by Boeing at the Kennedy Space Center to identify problem areas and common beliefs about the problem of losing and dropping small parts, which result in FOD (Boeing Corporation (b), 2000). A survey of hand tool design literature was conducted to give an overview of the criteria that can be applied to prevent discomfort, injuries, and also potential dropping of parts. Hand tool standards were covered briefly to familiarize the reader with the hand tools that are being tested. Finally, usability evaluation techniques were discussed.

This research was conducted in an environment where space flight hardware is processed. The results could also be relevant to any critical area where FOD could cause a concern, or where better hand tool design could reduce the risk of injuries.

2.1 Foreign Object Debris (FOD)

Foreign object debris (FOD) is an important concern while processing space flight hardware. In this environment, FOD can be defined as the debris that is left in or around flight hardware, where it could cause damage to that flight hardware (United Space Alliance Ground Operations, 2000). The sources of FOD can be varied to include tools or fasteners, such as screws and washers, that the technicians are using to complete the job. Accessories such as tape, wire, paper, and cloth can become FOD when left in or near flight hardware (National Aeronautics and Space Administration, 2000).

An example of FOD that caused damage to flight hardware occurred in July, 1999, when the coolant tubes on a main engine of the space shuttle Columbia were punctured during the STS-93 mission (National Aeronautics and Space Administration, 1999). Although this did not affect the success of the mission, it demonstrates how FOD can cause damage that could potentially be fatal to the crew.

The problem of FOD is not unique to the space industry, it is also a significant concern for commercial airlines, airports, aircraft manufacturers, and the military (United Space Alliance, 2000; United Airlines, 2000; Rocketdyne, 2000). The National Aerospace FOD Prevention Society (2000) has members from all around the United States and from various aerospace industries who are concerned with FOD. FOD can cause millions of dollars in damage each year to airports, airlines, and airport tenants.

Programs to reduce FOD in the airline industry include training and motivation, inspections, maintenance and coordination between workgroups. The training can include instruction in how to identify FOD, and motivation can be improved by showing

the consequences of FOD. The Federal Aviation Administration (FAA) and the International Civil Aviation Organization (ICAO) require airport personnel to conduct daily inspections of the airplane maneuvering areas to remove FOD. Other airline and airport personnel are required to look for FOD throughout the day. To maintain control of FOD, programs are in place to sweep the area regularly to gather loose debris. Magnetic bars can be used to collect metallic material. Other methods include locating FOD containers in convenient places to collect debris, providing wind barriers and netting to restrict the movement of FOD. FOD committees are often formed to communicate problems and solutions between work areas (Bachtel, 1998).

These programs have similarities to the space industry, except magnetic tools are typically not acceptable. They emphasize awareness and containment of tools and retrieving parts after they are dropped, either through netting or tools and procedures to retrieve lost items.

Another form of FOD could be a small particle of dust or a piece of hair that can result in damage to sensitive hardware. Clean room environments, clothing, and specific procedures are used to reduce the risk of exposing hardware, and therefore reducing the risk of damage due to the small particles.

For the purpose of this study, the small parts such as washers and screws that are dropped during installation will be discussed. This was chosen, not because it is the biggest source of the FOD problem, but because it is an important part of the problem that has not been addressed to a large extent. It is also difficult to retrieve small parts once they get inside of the flight hardware, especially washers, because of their shape (Boeing (a), 2000). The emphasis, to date, has been to reduce the amount of parts that are

dropped either by awareness of the employees to motivate them to be careful, or by creating ways to capture these small parts once they are dropped. There is a need for more research into developing tools that can hold the parts securely while installing them, that are affordable and compatible with flight hardware. An area that has had very little research is to conduct usability tests on the existing tools and prototypes to evaluate which would be the best for reducing the number of small parts that may be dropped during installation.

It is less important to be concerned with the number of parts that are dropped in the work environment than it is to realize the impact of just one small screw, when it is left, unintentionally, in the wrong place. It could delay the schedule while it is retrieved, increase the cost of processing, or cause a potentially fatal accident.

2.2 Boeing Study

A survey was conducted by Boeing ((b), 2000), to gather information on FOD that is generated by small parts, and how the small parts are handled when working on space flight hardware. The survey specifically looked at the current small parts storage containers and tools that are used to install small parts. Information was also collected regarding possible improvements and what the employees thought about FOD that is produced when handling small parts. The 56 respondents consisted of technicians (69%), quality inspectors (18%), engineers (10%), and task leaders (3%). Most had over six years of experience processing space flight hardware.

When asked what was the single largest contributor to FOD from handling small parts, the second most frequent response (12%) was "dropping". The most frequent response was "incompetence" (14%).

The majority of the respondents felt that the small parts were lost most often during installation (73%), while others believed the losses occurred either while removing them from ziplock bags (9%), passing them (13%), or transporting them (5%). 85% of those surveyed indicated that small parts are usually lost by being dropped, while 15% believed that parts were usually lost by being misplaced. The parts that were believed to cause the most trouble when being used were washers (43%), nuts (25%), and screws (13%).

When asked which they would prefer to aid in small parts handling, 79% chose a new container, and 21% chose a new tool. The Boeing project developed a prototype for the hand tool and a concept of the new container. However, this research focuses only on testing the hand tool, which was designed to prevent the dropping of small parts based on the input from the survey, discussions with other local users, and users from related industries, along with human factors design criteria for developing effective hand tools. The testing board for this research project was designed for multiple uses, including conducting a usability test for this new prototype tool. A usability test was completed by Boeing personnel using the testing board and a similar methodology as described in this thesis. The studies were coordinated so that future comparisons could be made. When a prototype of the small parts container is complete, it could be tested for usability with this methodology.

In summary, the Boeing study supports the research because it indicates that 12% of the respondents felt that dropping parts was the single largest contributor to the FOD problem. It would be reasonable to conclude that at least some of the other respondents felt that it contributed in some way. 73% of the respondents felt that when parts were dropped, it was during installation. Washers and screws were cited as being troublesome when being handled. 21% of the respondents felt that developing a new tool would be the best way to reduce the number of small parts that are dropped. Although this is not the majority, it shows that it may be a reasonable choice to reduce the FOD in an area. Based on this, and discussions with Boeing personnel (Boeing (a), 2000), the research was conducted on usability testing of the installation of screws and washers. When tested, a similar result may be found from other small parts, such as bolts, and spacers.

2.3 Hand Tool Design

To achieve the objective of designing a methodology and hardware for conducting usability evaluations on hand tools, it is useful to discuss the important aspects of hand tool design. Because there is a great deal of literature on the subject, the review is divided into 5 subsections:

- 2.3.1 Hand Tool Use
- 2.3.2 Importance of Good Hand Tool Design
- 2.3.3 Design Principles for Safety and Effectiveness
- 2.3.4 Other Factors that Affect Hand Tool Performance
- 2.3.5 Commercial Hand Tools

2.3.1 Hand Tool Use

Hand tools have been in use as long as mankind has been in existence. The tools we have today evolved from simple materials that early man found, such as stones, bones or pieces of wood, which fit the hand (Kroemer, Kroemer, Kroemer-Elbert, 1994). These early tools and the modern tools of today all help to overcome human limitations. The areas where machines or tools are superior to humans include strength, penetrability, bluntness, shortness, flexibility, and limited speed. (Cacha, 1999)

- **Strength** – Human hand strength is relatively weak, compared to tools, which can magnify grip strength. A bolt cutter is an example of a tool that increases grip strength.
- **Penetrability** – Because the human hand tissue and skin are soft in comparison to many materials, it is difficult to abrade most materials. Wood saws and files are examples of tools that can abrade softer materials.
- **Bluntness** – Human fingers are relatively blunt and broad, which means that most materials can not be pierced or penetrated, and small objects are difficult to grasp and manipulate easily. Tools that compensate for this are scissors, chisels, knives and drills. Tweezers can be used to help grasp small objects.
- **Shortness** – Human hands and arms are limited in length, so tools such as tongs and pruning poles can increase the reach.
- **Flexibility** – The human hand may not be able to maintain its rigidity when holding objects over long periods of time, due to fatigue. Tools such as a hammer or tongs can hold their rigidity, which will help to maintain control of an object.

- Limited speed – The speed that a human moves a tool is limited. By extending the length of the arm of a tool such as a sledge hammer, the end of the hammer moves faster and impacts with a greater force.

The human/hand tool relationship involves movement of the hand, arm and tool.

There are five basic motor activities that are used when doing work, such as using hand tools. These movements are (Cacha, 1999):

- Positioning - Moving the body and tool into position, such as placing a screw starter and screw into a hole.
- Repetition - Repeating uniform movements of the body and tool, such as turning the screw.
- Continuous - Long uninterrupted movement of the tool.
- Serial - Movements that require several sequential movements, such as hitting a nail repeatedly with a hammer.
- Static - An immobile position, such as for the upper arm, while the hand is inserting and turning a screw.

2.3.2 Importance of Good Hand Tool Design

Although tools have the advantage of helping people overcome their limitations, inappropriate hand tool design can result in occupational injuries of the forearm and hand. Additionally, when individuals have experienced these injuries or early symptoms, this can theoretically result in an increased likelihood of dropping parts, leading to FOD, (McCauley-Bell, 2000).

To understand how injuries can occur, it is necessary to understand the basic movements of the hand and wrist. Figure 1 illustrates how the hand can be deviated in two planes. Dorsiflexion (dorsal flexion) occurs when the hand is rotated toward the dorsal aspect (back) of the hand (toward the forearm). Palmar flexion occurs when the palm of the hand is rotated toward the soft aspect (belly) of the forearm. Radial deviation is the movement of the hand toward the radial bone (toward the thumb). The ulnar deviation is a rotation in the opposite direction of the radial deviation (Cacha, 1999), toward the ulna bone in the forearm (or toward the little finger). The extension and flexion of the fingers are illustrated in Figure 2.

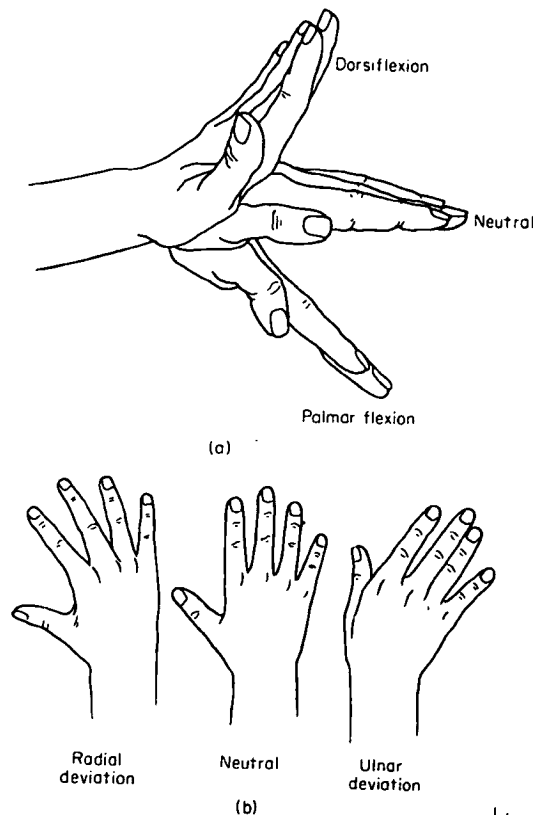


Figure 1. Hand Positions (Reprinted from Sanders and McCormick, 1993):
a. Illustration of Palmar Flexion, Dorsiflexion
b. Illustration of Radial and Ulnar Deviations

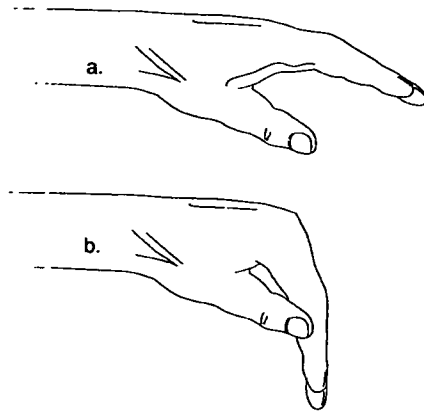


Figure 2. Finger positions (Reprinted from Cacha, 1999)

a. Fingers Extended

b. Fingers Flexed

Connective tissues of the body include bones, ligaments, tendons, fascia and cartilage. For the purpose of the hand tool design, it is appropriate to look at the whole bone and note that it has qualities of strength and stiffness, which support the other tissues of the body. The bones transmit and absorb forces. Ligaments and tendons are composed of dense connective tissues. The ligaments connect bone to bone and the tendons connect the muscles to the bone. Each tendon is surrounded by a long thin tube called the tendon synovium. It contains synovial fluid, which acts as a lubricant to reduce the friction where the tendon goes through confined area. Fascia is also a dense connective tissue, but it covers organs and keeps them separate from one another. Cartilage can be found in the ear, nose and respiratory tract, and intervertebral discs (Chaffins, 1999).

Poor hand tool design could result in either acute (instant) trauma, or subacute (cumulative) trauma. Acute trauma occurs immediately while the tool is used, including dislocations, sprains, and strains (Cacha, 1999). Cumulative (or repetitive, overuse

disorders) trauma develops over time, as the tool is used. Repetitive, manual movements of the hand and wrist can cause cumulative trauma disorders for many workers (Cacha, 1999; Chaffin, Andersson & Martin 1999). In 1988, the Department of Labor, reported that cumulative trauma was responsible for 48% of all industrial illnesses in the United States (Sanders and McCormick, 1993). Cumulative trauma syndrome is not new to modern work conditions. It was first reported over 130 years ago (Kroemer, Kroemer, Kroemer-Elbert, 1994).

Pathological results of these cumulative traumas are musculoskeletal disorders, which involve muscle, bone, cartilage, tendons and ligaments. The disorders are often categorized as nerve disorders, tendon disorders, and neurovascular disorders. These may affect the nervous system, or movement of the body (Cacha, 1999, Kroemer, Kroemer, Kroemer-Elbert, 1994).

Nerve disorders are caused by damage or pressure to the nerves when a nerve is close to an inflamed tendon. The pressure from the swollen tendon may cause symptoms in areas that are distal (remote) to the original site of the injury. One of the most common cumulative trauma nerve disorders is carpal tunnel syndrome (CTS). When the tendons, which pass through the carpal tunnel, have excessive tension, they will swell. Figure 3 shows the cross section of the carpal tunnel in the wrist and the associated carpal bones, ligaments, tendons and median nerve. When the tendons swell, additional pressure is put on the median nerve which passes through the carpal tunnel. Symptoms of tingling, pain and numbness can be present in the first three fingers and base of the thumb when there is pressure on the median nerve (Cacha, 1999, Chaffins, 1999, Sanders and McCormick, 1993). The negative effects of repeated movements, forceful movements and static

muscle loading are increased by inappropriate postures (Kroemer, Kroemer, & Kroemer-Elbert, 1994). When the wrist is bent in palmar flexion or ulnar deviation, symptoms are more likely to occur (Cacha, 1999, Salvendy, 1997). Also, pinch grips, where an object is grasped between the thumb and tips of the fingers, and vibrations contribute to CTD (Salvendy, 1997).

Tendon disorders commonly occur where a tendon inserts into a bone near a joint. Edema, which is fluid buildup can cause symptoms of local aches, pains, tenderness or swelling. Common tendon disorders include (Cacha, 1999, Sanders and McCormick, 1993):

- Tendinitis results in inflammation, caused by higher than normal tension placed upon the tendon and sheaths.
- Tenosynovitis occurs in areas where tendon is covered by a sheath, called the synovium. Extreme repetition may cause excessive synovial fluid to be produced, which causes pain and swelling.
- Stenosing tenosynovitis caused by a constriction of the tendon sheath in the area of the inflammation, caused by repetition. It happens at the base of the thumb to the tendons that connect the thumb to the forearm. Trigger finger (stenosing tenosynovitis crepitans) is a related disorder, which results in the swelling of a tendon because of the mechanical pressure from a sharp handle, causing the locking of the tendon inside the sheath. This causes jerking movements of the finger.
- Ganglionic Cysts result from a disorder of the tendon sheath that starts with a cyst, or fluid filled sack, that pushes through the skin at the wrist.

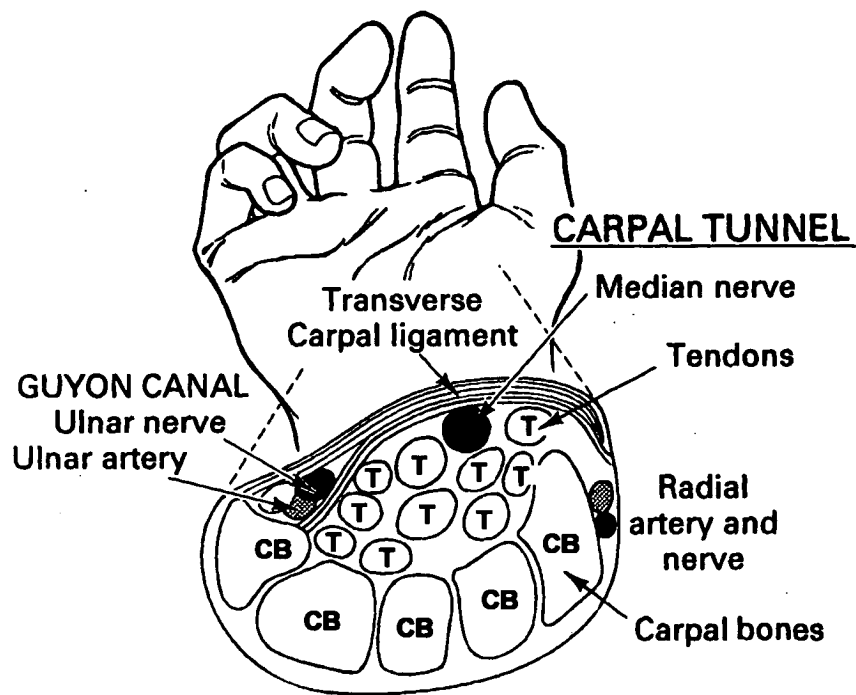


Figure 3. Cross-Section of Carpal Tunnel (Modified from Kroemer, Kroemer & Kroemer-Elbert, 1994)

Neurovascular disorders involve both the nerves and the blood vessels. Blood circulation is affected. The most common Neurovascular disorder is thoracic outlet syndrome. It has similar symptoms to carpal tunnel syndrome, but has a different cause. Muscular tension causes compression upon the nerves that pass between the thorax and the upper arm (Cacha, 1999).

2.3.3 Design Principles for Safety and Effectiveness

A hand tool should be designed to safely extend or improve the strength and effectiveness of the human (Woodson, Tillman, Tillman, 1992). It is a complex ergonomic task to design a hand tool which fits the dimensions of the human hand, while

using the strength and motion capabilities of the hand-arm-shoulder system (Kroemer, Kroemer, Kroemer-Elbert 1994).

There are many aspects to hand tool design. Mechanical factors, Anthropometric factors, anatomical considerations, ergonomic considerations, work environment issues, and the physical characteristics of the tool must be considered in the design (Woodson, Tillman, Tillman, 1992). The anthropometric dimensions of humans are important in effectiveness when grasping, holding, manipulating or guiding a tool. This is especially important when designing the handle of a tool. The anatomy of the hand must be considered, including understanding that an operator's wrist, arm and hand have specific rotational characteristics, so limb rotational excess should be reduced when a tool action that requires thrust, rotation or both. Ergonomic considerations include reducing the human energy expended to complete a task. Factors include mobility, dexterity, equilibrium and posture (Kroemer, Kroemer, Kroemer-Elbert 1994).

A great deal of research has been conducted in the area of hand tool design. As a result, there are many recommendations for designing good hand tools that are safe and effective. These recommendations are discussed below.

Hand tools should be designed to fit the contours of the hand. The user should be able to hold the tools securely without overloading the body (Kroemer, Kroemer, Kroemer-Elbert 1994).

An important principle for the hand tool user is to maintain a straight wrist. The wrist should be in general alignment with the forearm, not flexed, extended, or pivoted (Sanders and McCormick, 1993; Kroemer, Kroemer, Kroemer-Elbert 1994).

The hand tool should be designed so the user can avoid ulnar and radial deviation, dorsiflexion, and palmar flexion (See Figure X.). This should be done by bending the tool, not the hand or wrist (Kroemer, Kroemer, Kroemer-Elbert 1994). It is also important to avoid designing tools that require working with a flexed wrist and extended arm at the same time, or tools that require flexion of the distal phalanges (Last joints) of the fingers (Salvendy, 1997). Tools can cause ulnar deviation or palmar flexion, particularly when rotating, for example, when inserting screws into holes. This may cause the wrist tendons to inflame, resulting in tenosynovitis (Putz-Anderson, 1988)

When a wrist is fully extended, but not over-extended, the grasping power is 100% and the pinching or holding power is 50%. The manipulative effectiveness is 50%
When the wrist is fully flexed, the hand is close to 100% effective in manipulation, the grip strength is about 50, and the hand had almost no holding power (Putz-Anderson, 1988).

Another important principle in hand tool design is to avoid repetitive finger action by the user. If the index finger is used excessively to operate a trigger, a condition known as trigger finger can develop, in which the afflicted person is able to flex, but is unable to extend the finger actively. Sanders and McCormick:

A common complaint about hand tools is the location of the handle. When incorrect, it can force workers to bend the wrist during use. If the tool is used repetitively with a deviated wrist posture, the tendons in the hand become strained and an inflammatory condition can be created which can cause hand pain (Putz-Anderson, 1988).
Handles should contact as much of the hand and fingers a possible, with a diameter of approximately 1.25 - 1.75 inches. The minimum handle length should be 5 inches.

Narrow tool handles should be avoided so that large forces are not concentrated onto small areas of the hand (Cohen, Gjessing, Fine, Bernard, and McGlothlin, 1997).

Assure the center of gravity of the tool is located close to the body and the tool is balanced. Align the tool's center of gravity with the center of the hand that is holding it, or near the point of support (Salvendy, 1997; Kroemer, Kroemer, Kroemer-Elbert 1994).

Tool handles should have a fairly high coefficient of friction to allow the user to have a secure grip. Also, The tool material should not conduct electricity (Kroemer, Kroemer, Kroemer-Elbert 1994).

The weight of the tool should be minimized to reduce fatigue and to minimize the force required to operate the tool (Kroemer, Kroemer, Kroemer-Elbert 1994; Salvendy, 1997; Cohen, Gjessing, Fine, Bernard, and McGlothlin, 1997).

Special purpose tools should be designed that can be adjusted to fit the worker and the workstation configuration. Form-fitted tools are often only good for the average size hand. In the past, tools have been designed with a limited population in mind. As the workforce diversifies, there will be greater individual differences in workers physical dimensions and strength (Putz-Anderson, 1988) The tools should generally be designed to fit the central 90% of the user population, rather than just the average size individual. Because it is usually very difficult to design for the entire population, the design will often exclude the smallest 5% of the user population, which is usually female. It will also exclude the largest 5% of the user population, which is usually male (Kroemer & Grandjean, 1999).

It is necessary to remember women and left-handers, since women make up approximately 50 percent of the population and left handers make up 8 to 10 percent.

Therefore it is important that hand tools accommodate this portion of the population. Additionally women have smaller hands and less grip strength than most men, necessitating the design of hand tools and devices that reflex the anthropometric and ergonomic differences between men and women. (Sanders and McCormick, 1993)

A survey of on-the-job complaints from 1400 Air Force women stated that two tool related problems resulted because of their hand length and grip strength. The Air Force women's average hand length was over 2 cm (0.8 in.) shorter than that of the average male. On average, the grip strength of women is two-thirds that of men.

Another important principle is to design the tool for safe operation. Pressure spots in the hand (called pinch points) should be avoided. This can be accomplished by eliminating pinching hazards, sharp corners and edges in the design of tools (Sanders and McCormick, 1993)

Another related principle is to avoid tissue compression stress, which is caused when considerable force is applied with the hand. This occurs when there is an obstruction of the blood flow, or ischemia, resulting in numbness and tingling of the fingers. Two common tasks that can cause tissue compression stress are squeezing pliers or scraping paint with a paint scraper. A resolution of this problem is to design the handles of tools to have large contact surfaces to distribute the force over a larger area and to direct force to less-sensitive areas, such as the tough tissue between the thumb and index finger (Sanders and McCormick, 1993).

Tools should be designed to be used with either hand (Salvendy, 1997; Cohen, Gjessing, Fine, Bernard, and McGlothlin, 1997; Sanders and McCormick, 1993). This includes left-handed people in the user population. It also allows the user to switch hands

when appropriate to allow access to the work area or to rest one hand while working with the other.

The relationship between the tool and the human can be described as a closed loop or an open loop system. In a closed loop system, the human regularly monitors or controls the tool based on regular feedback that is received from the tool (Cacha, 1999). The case of inserting screws by hand or with a tool would be an example of a closed loop system. It would be important to have proper feedback to the user to locate the hole, know when the screw is threaded properly, and to know when the screw is secure, so it can be released and the user can go on to the next task. In an open loop system, the human activates the system, and then has no more interaction with it, such as turning on a switch to a tool or machine, where the operator no longer has input.

Hand vibration induced by such tools as chain saws, pneumatic drills, grinding tools, and chipping hammers should be considered in tool design. Vibration contributes to hand-arm vibration syndrome, which is damaging to the nerves and smooth muscles of the blood vessels in the hand. Sanders and McCormick (1993) suggests that hand-arm vibration exposure can be reduced by:

- Selecting tools with low vibration.
- Properly maintaining tools.
- Use vibration-reducing gloves.
- Minimize the grip force that is required to secure the tool.
- Reducing the amount of time that a worker is exposed to vibration by alternate tasks to include tasks that do not use of vibrating tools, and limit the number of days that the vibrating tools can be used by an individual worker.

In summary, there are many factors to consider when designing hand tools that are effective with a low risk of injury. These factors include mechanical, anthropometric, anatomical, ergonomic, and environmental. Fortunately, there are many guidelines to assist in the design. Primarily the designer should choose to bend the tool, rather than the wrist of the user. Repetitive finger action should be avoided. The tool should be lightweight and the center of gravity should be close to the hand that is holding it. The tool should be designed to fit the central 90% of the population, and be adjustable, where possible for a custom fit. Women and left-handers are a significant part of the population, so they must be included in the design. Avoiding pinch points and tissue compression is important. Finally, the effects of vibration need to be minimized.

2.3.4 Other Factors that Affect Hand Tool Performance

In order to conduct a usability test that will give results that can be used in the actual work environment, it is important to note some of the other environmental factors that may affect the performance of the user (dropping a part). These factors include protective clothing, fatigue, time pressure, awkward postures, distractions, boredom, temperature, humidity, precipitation, shift work hours, eating habits, external lighting, glare, noise and distractions, temperature and humidity (Kroemer and Grandjean, 1999).

For this research, the impact of protective clothing may be significant, particularly the use of gloves. Gloves are often used with hand tools for protection against abrasions and cuts, and temperature extremes. Gloves are also worn in clean room environments to protect the flight hardware that is being worked on. Heavy gloves can reduce grip strength and dexterity (Sanders and McCormick, 1993). Gloves that are too thick can

affect the user's grasp because the fingers are spread apart. Gloves also interfere with the tactile feedback, so tools are often gripped too tightly to compensate. This causes more static forces in the tendons, which may contribute to a risk of CTDs. The use of thin rubber gloves can reduce power grip strength by 15 to 20% (Putz-Anderson, 1988).

2.3.5 Commercial Tools

The Boeing Small Parts Handling study (2000) that was conducted at the Kennedy Space Center was motivated by the need reduce the amount of small parts that were dropped near flight hardware. Through observation and surveys, the team concluded that one solution was to find a better hand tool that would secure the parts to reduce the risk of dropping. The tool needed to fit a set of design criteria that was developed through more surveys, usability testing, and interviews with subject matter experts.

In the initial phase of the project, the team surveyed the industry and found no single solution that met their criteria. Instead, they found good features from many tools that are both common and specialty tools.

The relevant tools came from commonly available tools to all industries, and specialty tools for the medical industry. For example, in the medical industry, there are kits with tools and small containers that contain the screws that are used for reconstructive surgery. The screws are stored on a small board within the container. The user simply presses the screw starter tool into the board, and the screw is inserted into the tool. The part is secure during installation, and it is released by pushing or pulling a mechanism on the handle. The screw is never loose or within the hands of the user. This

could not use different sizes of screws and could not install other parts, such as washers or spacers.

Many tools incorporated the use of magnets, which is not acceptable near flight hardware. The tools had various devices to hold the screw in place. Some were very secure, and others could easily be knocked off. Some could only hold particular types of screws, while others could hold several small parts at a time, such as a screw (Phillips or flat head), washers, spacers, and nuts.

Through surveys with other aerospace operations companies, it was concluded that the solution was still not found for reducing the number of dropped parts near flight hardware. Therefore, the team proceeded to design a better tool system, which also includes a bin to hold the small parts, similar to the medical industry example.

2.4 Evaluation Techniques

This section discusses evaluation techniques, based on usability engineering principles that can be used to determine the most effective hand tools for reducing FOD. It also reviews three studies that evaluated powered hand tools. This section is divided into the following sections:

- 2.4.1 Usability Evaluations for Hand Tools
- 2.4.2 Related Hand Tool Research

2.4.1 Usability Evaluations for Hand Tools

When designing hand tools there are many standards and guidelines to choose from. For example, when the Boeing team conducted their evaluation and design of the

new hand tool, they noted ten documents that they needed to comply with in order to operate at the Kennedy Space Center, or another NASA Center. In addition, these documents required compliance with the Occupational Safety and Health Administration (OSHA) Standard 29 CFR 1910, and the human factors military standards, MIL-STD-595 (Boeing (b), 2000).

In addition to these general standards, the American Society of Mechanical Engineers (1993, 1996, and 1984) has published standards for Flat Tip and Phillips Screwdrivers, Pliers, and Nut drivers. These standards give information on the materials, markings, blades, handles, and performance requirements. The performance requirements relate to tests of hardness, load, heat tolerance, flammability, and solvent damage.

These are important standards and tests that analyze the physical aspects of the tool itself, and even the human factors considerations. In order to understand how well a new tool will be accepted and used, the entire system needs to be considered, which includes the human, the task that will be conducted with the tool, and the actual work environment where it will be conducted. The concept of usability engineering integrates all three components into one system, the human, the activity, and the context (Rubin, 1994).

Usability is a component of a larger issue, which is the system acceptability. System acceptability determines whether the system is good enough to satisfy the customers and all of the potential stakeholders. Figure 4 shows a model of the attributes of system acceptability, where usability is only one of the components. With the example of the hand tool, the system acceptability is met only when all of the attributes are met to

some degree. As with conducting a usability evaluation, it is necessary to set goals, and prioritize the level of importance for each of the components of the system. When the system is being designed, there are always trade-offs, because it is rare that all of the requirements can be satisfied completely. If the customers and designers can agree on the most important attributes, then an optimal design can be developed, even though it may not fully meet some of the lower ranking attributes.

In Figure 4, it can be seen that two of the important attributes for the system acceptability are social acceptability and practical acceptability (Nielsen, 1993) In the case of the hand tool, the technicians who use it must determine that it is acceptable to use within the group. It must not violate any of their preconceived notions about how their work should be conducted. It must also be demonstrated to the technicians and their management, that the hand tool will be effective and useful, and that the benefits outweigh the costs of implementing it. It must meet the expectations of compatibility and reliability. A tool is determined to be useful if it can be used to achieve a desired goal. Utility is an attribute of usefulness which addresses whether the function of the tool, in theory, can achieve the goal. In contrast, usability addresses how well the technicians can use the tool in the actual work environment.

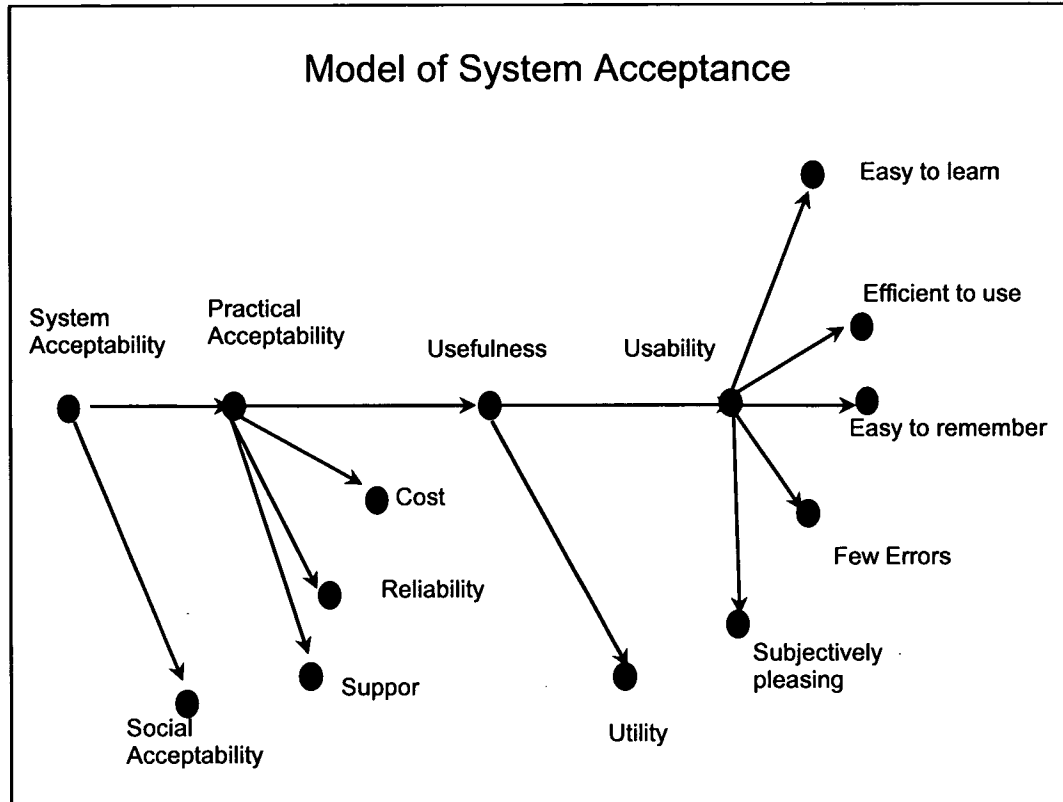


Figure 4. Model of the Attributes of System Acceptability (Adapted from Nielsen, 1993)

This leads to the attributes of usability, which can be described and measured in the following ways (Nielsen, 1993):

- **Learnability (Easy to learn).** The focus is on the novice user who may not have a lot of exposure to the system. The system needs to be easy to learn so that the user can get started quickly doing productive work with little or no training. The user's first impressions are important, because the system may not be given a second chance if the user is not initially pleased. Learnability can be measured by timing the novice users performing representative tasks. As an example, the ease

of learning how to use a new hand tool is not a strong factor when determining the usability, because they are known to be relatively simple to learn. The more complex learning takes place with the arm-hand-tool system to find the most effective way to install the screws into the test board.

- Efficiency (Efficient to use). The focus is on the expert user after the system is learned when there is a high level of productivity. Efficiency can be measured through timing and observation of expert users performing representative tasks. In the case of the hand tool design, the amount of time that it takes to install a screw with the tool could be measured.
- Memorability (Easy to remember). The focus is on the intermittent or casual user after the system has been learned. The system should be easy to remember, even after a significant period of time after the last use. Measurement can be made by timing and observation of the casual users after they have not used the system for a while. Again, this could be done with the hand tool testing, although it would not be a critical factor as compared to the error rate.
- Errors (Few errors). The focus is on reducing the number of errors that are made by people of varying experience levels. An error is any action that does not accomplish the intended result. If the user does make an error, recovery should be easy. The errors are measured by counting the error rate. For example, when the objective is to reduce the amount of FOD that is generated, then the number of parts that are dropped during the testing would be a very important factor in determining the usability.

- **Satisfaction.** The focus is on how pleasant and likable the system is to use, as determined by the operators of the system. This can be measured subjectively through a satisfaction questionnaire after the test, and through observation of body language, attitude and remarks made during test. Psychophysiological factors can also be measured, such as heart rate, pupil dilation, and blood pressure. A perceived exertion rating such as the Borg CR10 Scale (Borg, 1998, Appendix D) could be used to gather a subjective rating of physical exertion that is determined by the test participant. Data that shows voluntary usage is a strong indicator, if available.

Determining which attribute is the most important for system acceptability is an individual matter. Because there are many ways to measure usability, a list of detailed attributes should be determined based on the customers' and stakeholders' needs. Then a priority needs to be established for each attribute. The combination of the attributes and their priorities determine the usability goal for the project. It is usually not possible to achieve optimal ratings for all of the usability attributes, because they often conflict. Therefore, if the goals and priorities are established early in the design cycle, before the evaluation begins, then trade-offs can be made more objectively (Nielson, 1993; Mayhew, 1998).

When determining the usability of a system, the theoretical usability can be determined by applying guidelines, standards or heuristics (rules of thumb). But to know how the system will perform in a real application, user testing is necessary. It should be done in an environment that is as close to the actual one as possible, while still allowing

control over the testing. This gives insight into how people will actually use the product or system, and it will expose surprises before the product is used in a critical work area, or mass-produced.

When conducting a usability test, as with any type of research, the test should have a high degree of reliability. This would mean that the same results would be achieved if the test was repeated. The test should show a high level of validity, meaning that the test results are meaningful outside of the laboratory (Nielsen, 1993). Prior to running a test, careful attention should be given to the details when preparing the data sheets, the test instructions, the informed consent form, and other related documentation. The physical layout of the room and the environmental conditions such as light, temperature, noise and distractions can all affect the outcome of the study. The environmental conditions should reflect the actual work environment as much as possible. When conducting the actual experiment, the experimenter should use a script to ensure that all participants are exposed to the same information (Rubin, 1994).

Even with the most careful planning, it is very important to conduct a pilot test of the experiment, using all of the documentation, with the environmental conditions that will be expected. This will identify problems with the testing methodology, and the environment and it will also identify ways to improve the experiment (Rubin, 1994).

In summary, usability evaluations can be an effective way to predict how a system or product will function in the real work environment. In many cases, time and money can be saved when developing new products. In the case of this research, there is a potential to reduce the risk of producing FOD, which could potentially save lives.

2.4.2 Related Hand Tool Research

When reviewing the relevant literature, three studies were found which had similarities to this research. All three studies involved powered hand tools. No human factors research was found for non-powered hand tools such as a screw driver or screw starter, although much of the data from the powered hand tool studies is relevant. In each case students were used for the first phase of the experiment, then experienced workers were brought in to compare the results. In one case, only two experienced workers participated to validate the results, and in the other cases, an equal number of experienced workers and students participated. In all cases, the results indicated that the analysis of the student data and the experienced worker data showed similar findings.

There were many differences from this research. All three studies had the objective of producing guidelines for workstation design or tool selection. In all of the cases, the focus was on the workstation design. In all cases, the work area was clearly visible to the participants. This is in contrast to this study, which is emphasizing the variability in the working conditions that the technicians must face, with particular attention focused on workspaces that are hard to access and are not easily visible.

Kattel (1998) conducted research to determine the effects of the type and size of rivet guns on hand-arm vibration. Data was collected on the vibrations that are transmitted from three locations on the hand and arm while using the various rivet guns. The main objective of the research was to develop ergonomic guidelines that can be used to select and use hand tools.

Ten inexperienced students participated in the study, along with two experienced professionals. The means and standard deviations were compared to the students and there was no difference. This was done to validate the study. Subjects performed tasks using prescribed conditions, which included 3 wrist postures and 2 applied forces. Existing data was used to determine the recommended forces and hand-arm deviations.

Schulze (1998) conducted research to evaluate four pneumatic screwdrivers in a simulated and an actual furniture assembly operation. The simulated tests were conducted in three workstation orientations. The objective was to determine the most effective combination of workstation and pneumatic screwdriver type.

18 students and 16 employees of a furniture manufacturing facility participated in the study. The simulation was conducted by setting screws into a flat metal sheet that was laying on the work surface. The experienced workers also assembled an actual student desk.

The number of errors was counted. The errors included dropped screws, but this was not separated from the other errors, such as an improper screw setting. The implications of dropping a screw were not discussed. The time to complete the task was also recorded. Physiological performance indicators such as heart rate and grip strength were taken, along with detailed anthropometric measurements. A subjective assessment was made for each task, using a body part comfort/discomfort survey.

Ulin (1991) conducted research to develop guidelines for the use of powered hand tools by using psychophysical data. The objective of the research was to determine the effect of tool shape, tool mass, work location, work orientation, and frequency on the ratings of perceived exertion. The perceived exertion was also measured using the Borg

CR10 Scale (Borg, 1998). Guidelines for both the hand tools and the workstation configurations were developed. Both students and experienced workers participated in the study, and both were found to have similar results in preferences. The participants were asked to drive screws with a pneumatic screwdriver into perforated sheet metal. Specific recommendations for preferred height for vertical and horizontal surfaces were made as related to the preferred tool characteristics.

For this research, only three studies were found that relate to human factors evaluations of hand tools, particularly screw starters or screw drivers. Kattel (1998) stated that little quantitative methods or evaluative data are available for hand tools. This is an indication that there is still a great deal of benefit that can be gained from researching the development of testing methodologies for hand tools. There were no studies that conducted research on hand tools with the objective of reducing FOD. This is an area that appears to be in need of further research.

CHAPTER 3

METHODOLOGY

The following methodology was designed to achieve the research objectives of developing a test methodology and hardware to assess FOD risk. This methodology is based on information contained in the literature review as well as consultation with subject matter experts. The chapter is divided into the following sections:

- 3.1 Participants
- 3.2 Experimental Task
- 3.3 Apparatus
 - 3.3.1 Testing Board
 - 3.3.2 Hand Postures Used with Testing Board
 - 3.3.3 Equipment
- 3.4 Procedure
- 3.5 Experimental Design
- 3.6 Summary

3.1 Participants

Eighteen people participated in the study. This included 6 students, 6 managers / engineers, and 6 technicians. In addition, two students participated in a pilot test of the experiment. Each group of 6 included 3 males and 3 females. The students were

recruited through an e-mail message that was sent to approximately 20 summer students. The managers and engineers were recruited through an e-mail message that was sent to approximately 200 people. The technicians were assigned by their supervisor, based on their availability. The male technicians were assigned from a different organization than the female technicians. All participants worked at the Kennedy Space Center (KSC), FL. All participants were over 18 years old, which is representative of the workforce at KSC. There is no size or weight restriction for KSC employees, so there were no similar restrictions on the volunteers.

3.2 Experimental Task

The experimental task was completed by each of the participants as described below:

- Each participant was asked to install screws into the usability testing board, (Figures 5, 6 and 9) using three different methods, which included using two different tools (Figure 7) and using their hands only.
- Each participant conducted three trials, one for each installation method.
- For each trial, 4 practice screws and washers were installed onto the testing board.
- Then each participant installed 24 screws and washers for the actual trial. The 24 holes that were used to install the screws and washers were located in 8 groups on the testing board with three screws in each group. Each group was in a different orientation. Yellow boxes were put around the four groups that can be seen from the front. Group numbers were labeled on the front and back of the board. Figure 6 shows groups 1 through 4, and Figure 5 shows groups 5 – 8.

For all of the groups (#1 - #8) the participants were located in front of the board, and they put their arm through the hole to insert the screws from the backside of the board. In Figure 6, the screws are installed into groups 1 through 4 in the orientation shown by the arrow. For group numbers 5 – 8 (Figure 5), all of the screws were inserted, pointed from the back of the board, to the front, directly toward the participant, requiring the participant to reach around the obstacles. The obstacles that are attached to the back form a 90-degree angle with the board, where the screws can be inserted (Figure 10).

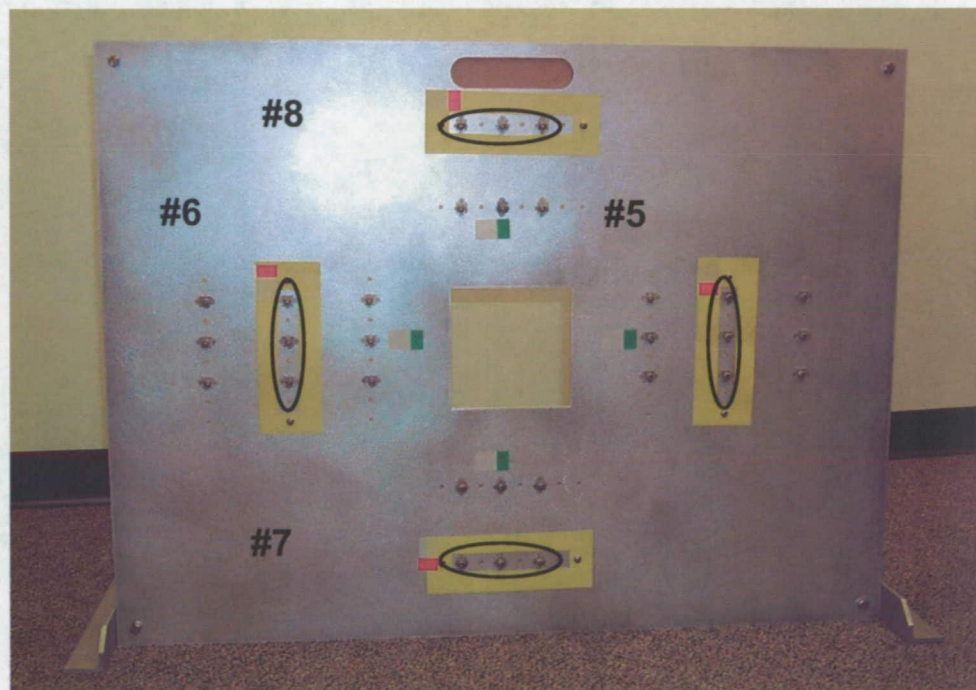


Figure 5. Hand tool usability testing board – Front view, with group numbers

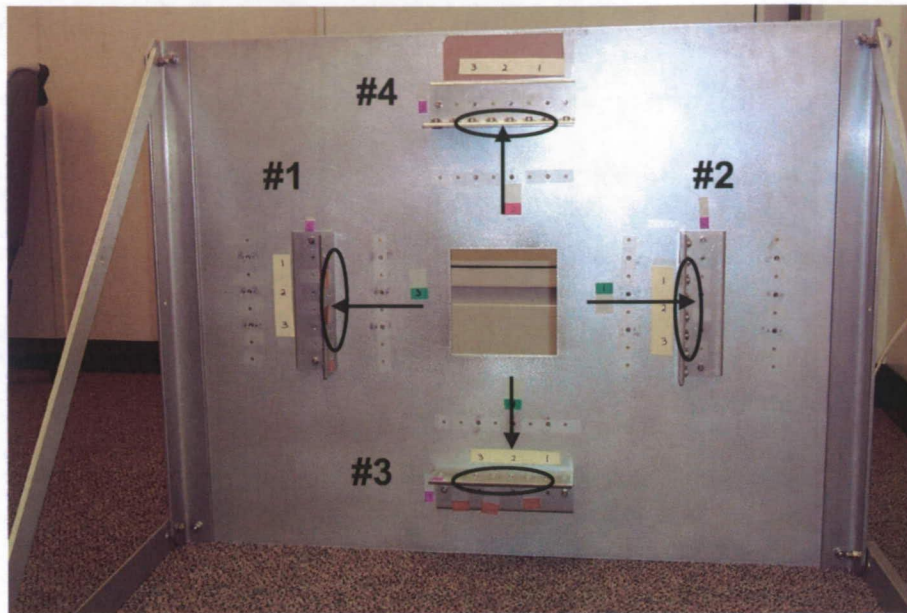
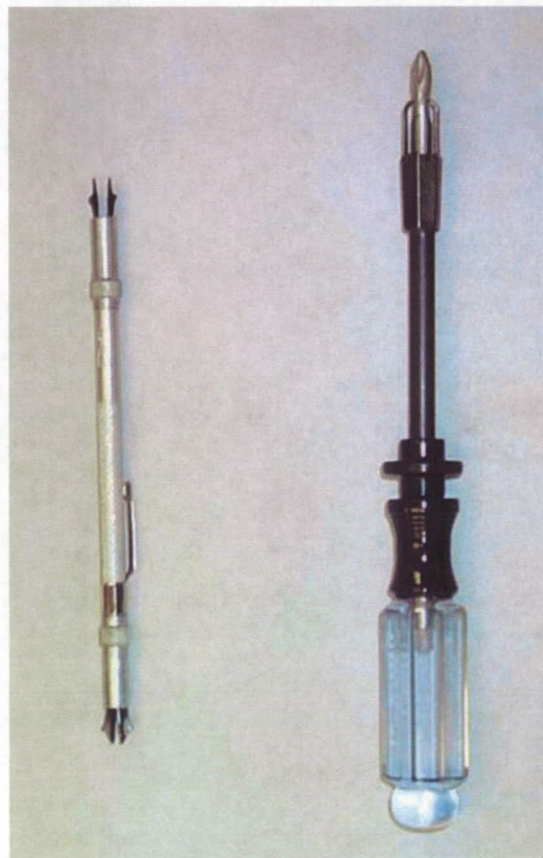


Figure 6. Hand tool usability testing board – Back view, with group numbers



Tool A

Tool B

Figure 7. Hand Tools Used for Experimental Task

3.3 Apparatus

In this section, the hand tool usability testing board will be discussed, along with the various hand postures that are used with the testing board. The other equipment is also discussed. This section is divided into the following subsections:

- 3.3.1 Testing Board
- 3.3.2 Hand Postures Used with Testing Board
- 3.3.3 Equipment

3.3.1 Testing Board

The aluminum hand tool testing board, seen in Figure 5, was designed specifically for this test, but was also designed to allow testing of a variety of conditions and to test new tools in the future. Figure 8 shows the checklist for the design of the hand tool testing board. The checklist was developed prior to designing the testing board. Information for the checklist was taken from the Boeing Study (Boeing (b), 2000), and interviews from subject matter experts in the areas of design, FOD control, and Human Factors.

The testing board is 30" X 40", made of ¼" aluminum, and weighs less than 40 lbs (Figure 9). The first consideration was for safety of the participants. All edges were smooth, and the board was secure. The board was designed so that it would not wear significantly over time, and so that it would be representative of actual work that is performed near flight hardware. The testing board was also designed to be cost effective by using non flight rated materials that were similar in durability to the flight materials.

Checklist for Hand Tool Testing Board Design

- Safety
 - No rough edges
 - Rounded corners
 - Stable
- Must not wear over time (1st test is the same as the last test)
- Representative of difficult tasks that would be performed on flight hardware
 - Choose the smallest screw hole size that would also be typical of what is used during flight hardware processing. Smaller screws are typically harder to handle, and may possibly cause more drops.
- Sturdy, so that the subjects don't have to hold the board while performing the task.
- Strong, so that the board will not flex while subjects perform tasks.
- Flexibility in testing
 - Accommodate the test for the initial research, plus provide the greatest flexibility for future usability testing.
 - Accommodate various reaches
 - Insert screw from back of board to front, by reaching through arm hole to the right, left, up, down
 - Insert screw into obstacle, directly right, left, up or down
 - Movable obstacles to force the users to reach around
 - Ability to test while user adds a face plate to the board
 - Should accommodate different types of screws, bolts, nuts, and washers that have the same diameter.
 - Accommodate testing of various hand tool design solutions
- Arm hole size
 - Representative of confined tasks
 - Must fit large person (95th % for fist or grasp of hand, and biceps)
- Cost effectiveness
 - Representative of flight hardware, but less expensive materials (ie. Use non-flight hardware with a similar resistance.)
- Portable. Less than 40 lbs. (Woodson, 1992)
- Clean room compatible so testing can be done in high bay areas.

Figure 8. Checklist for Hand Tool Testing Board Design

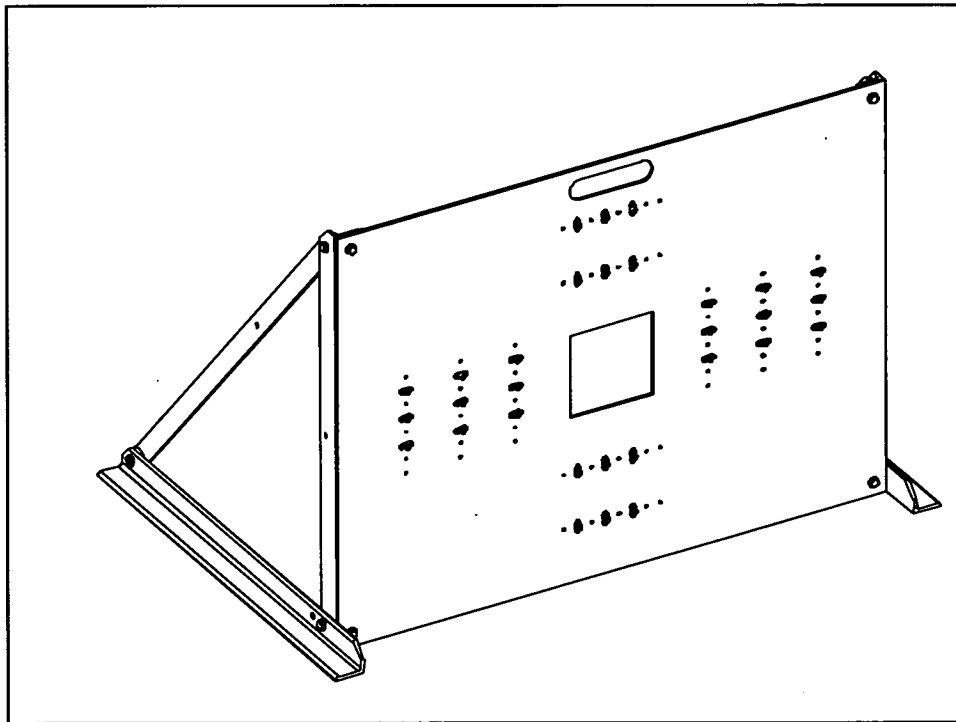


Figure 9. Hand Tool Usability Testing Board

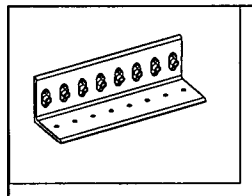


Figure 10. 2" wide aluminum obstacle used on back of testing board

The hand tool usability testing board, referred to as the “testing board”, folds for carrying and can stand securely when assembled. Figure 10 shows an example of one of the four obstacles that were placed on the back of the testing board. When installed, it requires the participant to reach around an obstacle, which is a 2" wide piece of angled

aluminum to access the screw hole that is to be used. The board was designed so that a variety of shapes could be attached to the board to allow testing in many orientations. The first and last holes in each group are provided to allow installation of various obstacles to the back of the testing board. The board can also be placed in different orientations to simulate the real work environment.

Figure 11 shows a drawing of the testing board, along with dimensions. There are 10 groups of holes on the testing board. Only 8 of the groups were used in this research. Each group has 3 open holes and 3 holes with floating 3/16 " nut plates attached. For this research, only the holes with the attached floating nut plates were used. The nut plates are commonly used in the flight hardware processing environment. The plate holds the nut over the hole, but allows it to move slightly to line up with the hole and screw.

For this test, the board was placed on the ground. The users were required to put their hands through the armhole in the center of the board to insert the screws and washers from the back of the board. This limited the visibility to both the hand and the screw to only the area that could be seen by looking through the armhole. Participants were not allowed to look at the back of the testing board by looking over it or around it on either side. The participants needed to deviate their wrists and hands in order to complete the task. They also needed to get into various awkward postures, such as kneeling, laying down, and twisting and turning the neck in order to install the parts. This is a common situation in the workplace.

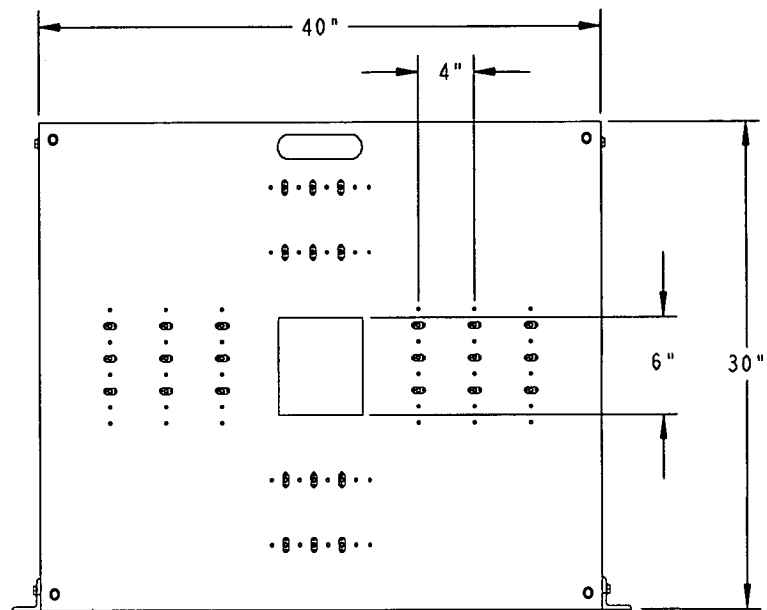


Figure 11. Dimensions for Hand Tool Usability Testing Board

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3.3.2 Hand Postures used with Testing Board

A variety of hand positions were required to complete the experimental task, which is also common when working on space flight hardware. The photographs below (Figures 12-19) show the general hand positions that were used when installing screws by hand. Because the wrist and hand positions varied, only general comments on wrist and hand deviation are made for each group. All positions required pinch force and repeated rotation while turning the screws. To install the screws and washers, participants had to locate the hole, put the screw in the hole, turn the screw and release the screw.

Group 1: Reach to the right (90-degree angle).

In group 1, the participants were required to reach forward through the armhole, and then reach to the right. This produced a slight dorsiflexion at the wrist with flexed fingers (Figure 12). Because most subjects were right handed, they often found this to be challenging. One strategy to compensate for this was to reach through the hole with both arms, so that both hands could be used to locate the hole. This was more common when using the tools for installation, rather than the hand.

Group 2: Reach to the left (90 degree angle).

Because most participants were right handed, this group was not as challenging as group 1. Figure 13 shows a straight wrist, and flexed fingers.

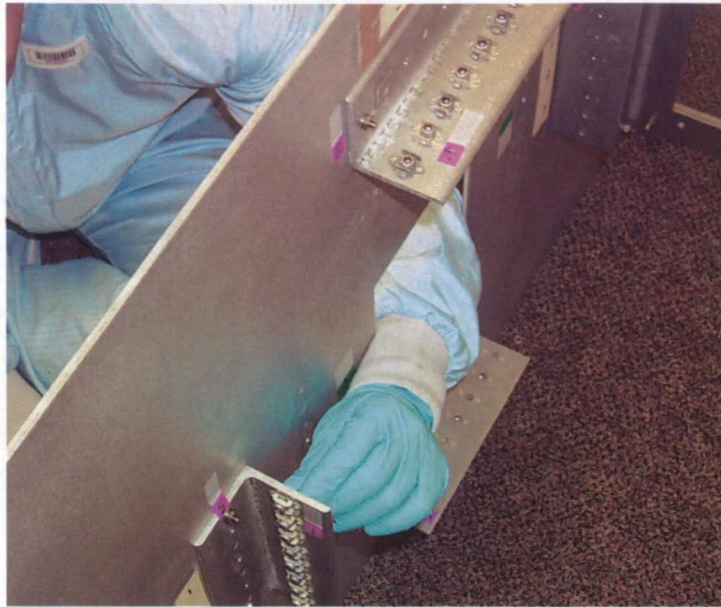


Figure 12. Technician installing screw into hole in group 1



Figure 13. Technician installing screw into hole in group 2

Group 3: Reach straight down (90 degree angle).

This appeared to be the least stressful position for the participants, because they could reach down and keep the wrist in a fairly straight position, with flexed fingers, while performing the task (Figure 14).



Figure 14. Technician installing screw into hole in group 3

Group 4: Reach straight up (90 degree angle).

Some participants had to struggle to locate the holes initially for group 4. They used a variety of body positions, which affected the hand posture greatly. For example, some people chose to lie flat on the ground while looking up at the hole. And others chose to lean over their knees and turn their heads to see the holes. Others chose to sit and locate the holes by feel. While turning the screw, the wrist remained in a fairly straight position, with a slight ulnar deviation and flexed fingers as seen in Figure 15.



Figure 15. Technician installing screw into hole in group 4

Group 5: Reach to the right and around the obstacle (180 degree angle).

This group required palmar flexion of the wrist and strong finger flexion (Figure 16). Most people chose to look through the holes for groups 5 - 8 to help position the screw initially. This caused the body posture to be bent forward with the head turned to the left.

Group 6: Reach to the left and around the obstacle (180 degree angle).

This group also required palmar flexion at the wrist and strong finger flexion. The participants often bent forward to look through the holes to help position the screws (Figure 17).



Figure 16. Technician installing screw into hole in group 5



Figure 17. Technician installing screw into hole in group 6

Group 7: Reach down and around the obstacle (180 degree angle).

This group required palmar flexion with a slight radial deviation, and strong finger flexion (Figure 18). The participants typically found that the hole was harder to locate. They had to put their heads on the floor to see through the hole if they chose to locate it visually. Once the hole was located, they could maintain a more upright body position, which reduced the stress on the wrist and hand while turning the screw.



Figure 18. Technician installing screw into hole in group 7

Group 8: Reach up and around the obstacle (180 degree angle).

This group of holes was easier to locate visually than the other groups of holes because it was near eye level (Figure 19). Significant palmar flexion with ulnar deviation was required to insert and turn the screws.



Figure 19. Technician installing screw into hole in group 8

Figures 20-30 illustrates additional variety of hand and wrist positions for various groups while using different installation methods. The positions varied by person and within each installation, the participant would use a combination of positions to locate the hole, put the screw into the hole, turn the screw, and release the screw.



Figure 20. Group 8, Tool A



Figure 21. Group 8, Tool A



Figure 22. Group 6, Tool A



Figure 23. Group 8, Hand Installation



Figure 24. Group 4, Tool B



Figure 25. Group 5, Tool A



Figure 26. Group 5, Tool B



Figure 27. Group 7, Tool A

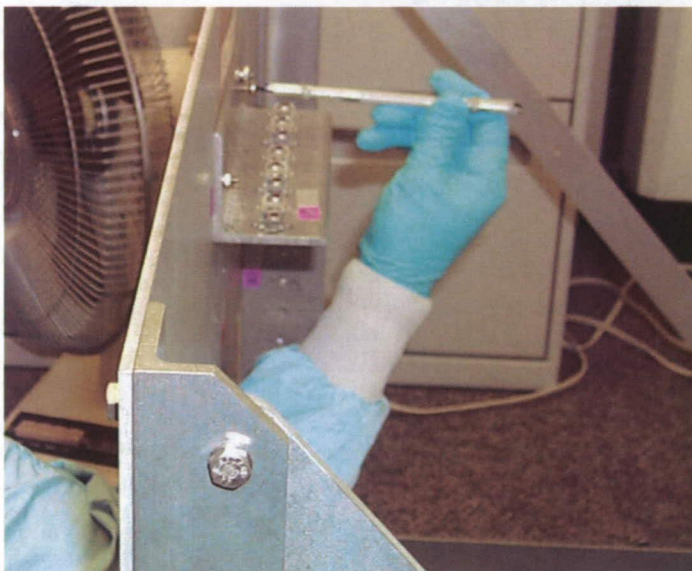


Figure 28. Group 8, Tool A



Figure 29. Group 2, Tool B



Figure 30. Group 5, Tool B

3.3.3 Equipment

Three methods of installation were tested, including:

- Installing the screws by hand,
- Using Tool A - a commercially available screw starter (Figure 7), and
- Using Tool B - a commercially available screw starter (Figure 7).

These methods were considered to be a reasonable choice because in the work environment technicians often install small parts by hand. The tools were chosen because they were from reputable companies and the tools were readily available to everyone.

The first screw starter, called Tool A in the experiment, was about the size of a pencil and had a screw starter at each end which was inserted into the head of a Phillips screw (Figure 7). The second tool, referred to as "Tool B", was similar in shape and size to a traditional Phillips screwdriver, but it had two "grippers" at the end to secure the screw and washer. The "gripper" is controlled with the thumb near the handle of the tool.

A #10-32 X .75 inch Phillips screw was used, along with a #10 washer (Industrial Fasteners Institute, 1988). These were chosen to be representative of small parts that cause a problem when processing space flight hardware, based on discussions with subject matter experts.

A digital stopwatch was used to determine the time to insert each group of three screws. The data was recorded manually. A small, portable tape recorder was used to play a tape of the conversation that would be typically heard over a communication network.

The test participants were dressed in clean room suits, nitrile gloves, boots, and head covers, which are worn in the clean room work environment in the Space Station

Processing Facility. Various sizes were on hand to accommodate all body sizes. The materials are all light weight, and intended to be used in a nonhazardous work environment. Safety glasses were worn when installing the screws that seemed to have a potential to hit the participant in the eye. This was based on hole position and the type of tool. Screws in group 4 could potentially fall into the participants' eyes while they were being secured, and the screws occasionally popped off of Tool A and traveled several feet.

3.4 Procedure

Participants were greeted and taken into the testing room. They were seated in a chair while they were read the instructions, which included informing them of the risk level, and that they were free to leave at any time (Appendix A). Then they signed a consent form (Appendix B). Prior to beginning the test, they dressed in clean room suits, gloves, boots, and head covers. Each participant completed 3 trials, and they were randomly assigned the order for the trials. The orders were HAB, ABH, or BHA, where:

- H = hand installation,
- A = Tool A, and
- B = Tool B.

The experiment was designed so that one male and one female participant from each participant group (student, manager/engineer, or technician) completed the trials in each of the three orders.

During the test, participants sat or laid on the floor. They were allowed to choose the position that they felt was best for them to accomplish the task. A tape was played

from an actual conversation that was recorded from the voice communication while processing space station flight hardware. This was done to include additional distractions to the task that would be typical of a work environment, and to add realism to the task.

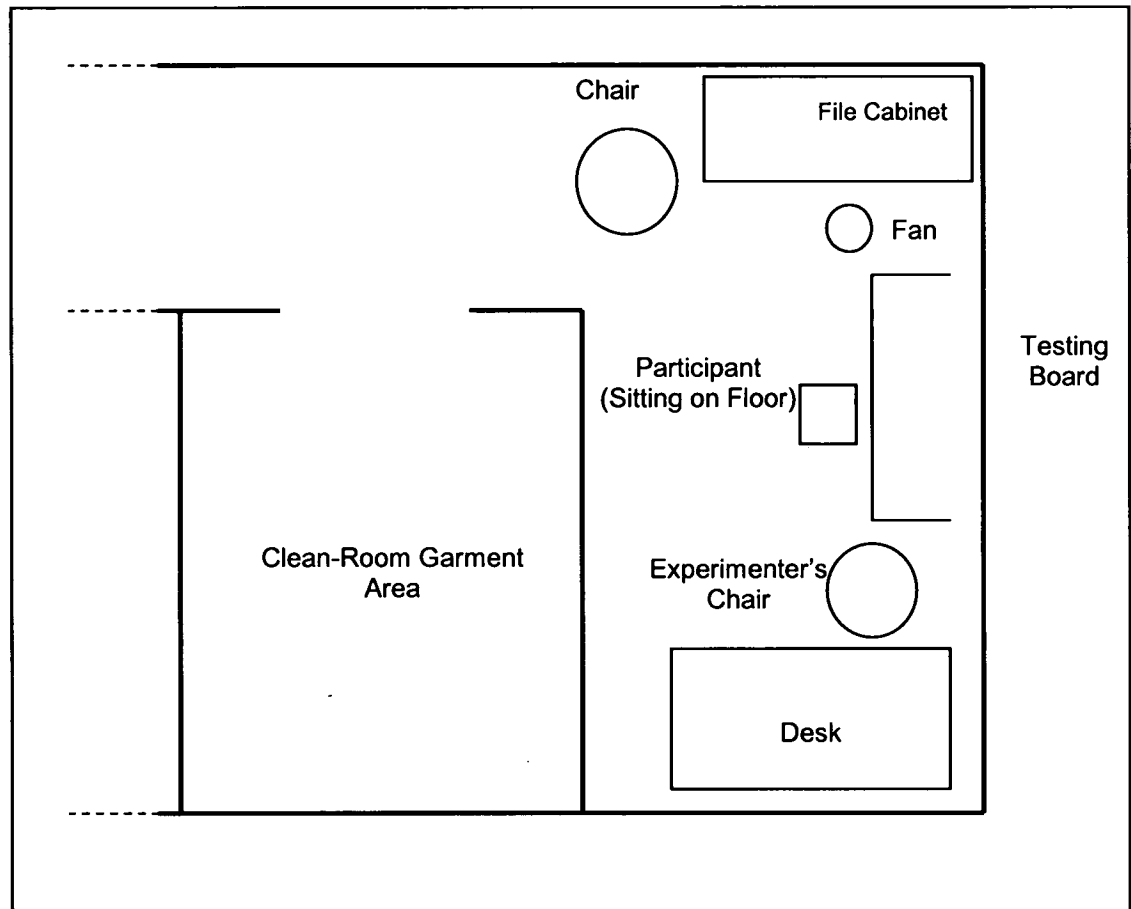


Figure 31. Layout of Testing Area

The time to complete each of the 8 groups of three screws was recorded for each of the 3 trials (Appendix C). In addition, the number of "drops" and the number of "assists" were recorded. A "drop" was counted when a washer, screw or combination of

the two fell. “Assist” was defined for this study as any time that the screw and washer were not successfully inserted into the hole as described in the instructions, but was not actually dropped. This included the times when the tool came off the screw and it was not completely inserted. If the screw could be pulled directly from the hole without turning it, then the participant was asked to start over. If the screw could not be pulled directly from the hole without turning it, then the participant finished tightening it by hand.

After each group of three holes was complete, the participants were asked to rate the level of perceived exertion based on a Borg CR10 Scale (Borg, 1998), that was placed on the wall at their eye level (Appendix D). Participants were told that this was the physical exertion that they felt, not the mental exertion, or difficulty locating the hole.

When all 3 trials were complete, the participant removed the clean room garments, and filled out a post test questionnaire (Appendix E). After the questionnaire was filled out the participants were allowed to ask any questions about the purpose for the experiment and the tools.

3.5 Experimental Design

18 trials were conducted, one for each of the 18 participants. The experimental design (Table 1) shows that for each trial, there was a different combination of participant type, installation order and gender.

Table 1. Experimental Design

<u>Participant Type (3)</u>	<u>Installation Method Order (3)</u>	<u>Gender (2)</u>
Student	Hand - Tool A - Tool B	Female
Student	Tool A - Tool B - Hand	Female
Student	Tool B - Hand - Tool A	Female
Student	Hand - Tool A - Tool B	Male
Student	Tool A - Tool B - Hand	Male
Student	Tool B - Hand - Tool A	Male
Manager/Engineer	Hand - Tool A - Tool B	Female
Manager/Engineer	Tool A - Tool B - Hand	Female
Manager/Engineer	Tool B - Hand - Tool A	Female
Manager/Engineer	Hand - Tool A - Tool B	Male
Manager/Engineer	Tool A - Tool B - Hand	Male
Manager/Engineer	Tool B - Hand - Tool A	Male
Technician	Hand - Tool A - Tool B	Female
Technician	Tool A - Tool B - Hand	Female
Technician	Tool B - Hand - Tool A	Female
Technician	Hand - Tool A - Tool B	Male
Technician	Tool A - Tool B - Hand	Male
Technician	Tool B - Hand - Tool A	Male

In this experiment the factors that are of interest include the type of participant and the gender. The order that the tools were used was randomized to eliminate the effect of order. This is a balanced design.

3.6 Summary

The methodology that was described in this chapter was designed to achieve the research objectives of developing a test methodology and hardware to assess FOD risk when using hand tools. By selecting three groups of participants, data was gathered on the performance differences between technicians, managers and engineers, and students. This offered additional data regarding the types of participants that could be used in future studies of this type. The actual work tasks are always performed by technicians, although they not as easily accessible for testing as the other groups. Also, the design was balanced with half males and half females, while rotating the order of installation method to randomize the effects of order.

The task and the testing hardware were described, along with the criteria that was used to develop the testing board. Photographs and descriptions of some of the various hand positions were included to show the variety of positions that were used. Variation was seen based on the location of the screw holes, the flexibility of the participants, and the experience level of the participant. The variability seemed to be particularly noticeable for the holes that were rated as being most difficult.

While conducting the experiment, it was found that the technicians generally liked the test, and expressed that it was realistic as compared to some of the work that they do at the Kennedy Space Center. They were generally enthusiastic about participation and gave good suggestions for improvement in future research. These suggestions are discussed in Chapter 5. It appears that the suggestions would not affect the validity of this test.

Currently, there has been little research into developing a systematic way to test hand tools for usability. Nothing similar to the methodology and hardware presented in this chapter has been found. Therefore the study, including the methodology and hardware described in this chapter makes an original contribution to the research literature and can be used for future analyses.

CHAPTER 4

RESULTS

This chapter presents the results and associated analysis of the experiment that was conducted to achieve the research objectives of developing a test methodology and hardware to assess FOD risk. The chapter was divided into two sections:

- 4.1 Results
- 4.2 Discussion

4.1 Results

An analysis was conducted to determine if there was a difference in the performance of the participants when they used three different installation methods, which included two different tools and installation by hand. Objective data was collected during the testing, which included the average time for installation of each group of three screws, and the average number of parts that were dropped during installation. For each of these, tests were conducted for all of the participants and then separately by subsets of that group, which included males, females, technicians, students, and managers/engineers. Subjective data was collected from the post-test questionnaire, which related to ease of use for the three installation methods, force required, comfort levels, likelihood to drop

parts, and physical characteristics of the hand tools. Tests were conducted for these characteristics using all of the participants. The post-test survey also summarized personal data, such as hand preference. A total of 27 statistical tests were conducted to determine if there was a difference in performance when using different installation methods.

Table 2 shows which methods of installing the screws are significantly different from the others for the 27 separate tests. For each response a Friedman test was run using Minitab 13.0 to test the hypothesis:

H_0 = probability that all three methods were equal

H_a = probability that at least two of the methods were different

Based on the p-values, which were below 0.05 for all 27 tests, there is sufficient evidence to reject H_0 , and conclude that there is a difference in at least two of the installation methods for each of the 27 tests that were conducted (Mendenhall & Sincich, 1995).

A multiple comparison procedure was used to determine specifically which methods were different from each other (Daniel, 1990). These are indicated in the last three columns in Table 2 with an (*). For example, the average time for each group is significantly different for each method of installing the screws when comparing all of the participants. When only the males are compared, then the average time per group is only significantly different when comparing tool A and using the hand.

Table 2. Multiple Comparison Tests for the Differences Between Installation Methods (A = Tool A, B = Tool B, and H = Hand)

$\alpha = 0.10$					(**s show Sig. Difference)		
	Response	# Methods compared	Sample	Sample Size	A - B	A - H	B - H
During Test:	Avg. Time Per Group	3	All Participants	18	*	*	*
	Avg. Time Per Group	3	Males	9		*	
	Avg. Time Per Group	3	Females	9		*	
	Avg. Time Per Group	3	Technicians	6			
	Avg. Time Per Group	3	Students	6		*	
	Avg. Time Per Group	3	Mgrs. / Engineers	6		*	
	Avg.# Drops	3	All Participants	18	*	*	
	Avg.# Drops	3	Males	9	*	*	
	Avg.# Drops	3	Females	9	*		
	Avg.# Drops	3	Technicians	6	*		
	Avg.# Drops	3	Students	6	*		
	Avg.# Drops	3	Mgrs. / Engineers	6	*		
	Exertion	3	All Participants	18	*		
Post Test:	#4. Easy/Hard Rank	3	All Participants	18	*	*	
	#5. Comfort Rank	3	All Participants	18	*	*	
	Force Required	3	All Participants	18	*		
	Hand Comfort	3	All Participants	18	*	*	
	Fore Arm Comfort	3	All Participants	18	*		
	Upper Arm Comfort	3	All Participants	18	*		
	Tool/Part Setup	3	All Participants	18	*	*	
	Tool/Part Release	3	All Participants	18	*	*	
	Likelihood to drop parts	3	All Participants	18	*	*	
	Perceived speed	3	All Participants	18	*	*	
	Tool Balance	2	All Participants	18	*		
	Tool Shape	2	All Participants	18	*		
	Tool Size	2	All Participants	18	*		
	Tool Weight	2	All Participants	18			

The average time to install the washers and screws into each group of holes on the testing board is shown in Figure 32. The time began when the participants reached for a

part, and the time ended when the third screw for the group was installed and the participant moved their hand back. As seen in Table 2, the time difference between all three installations is significantly different.

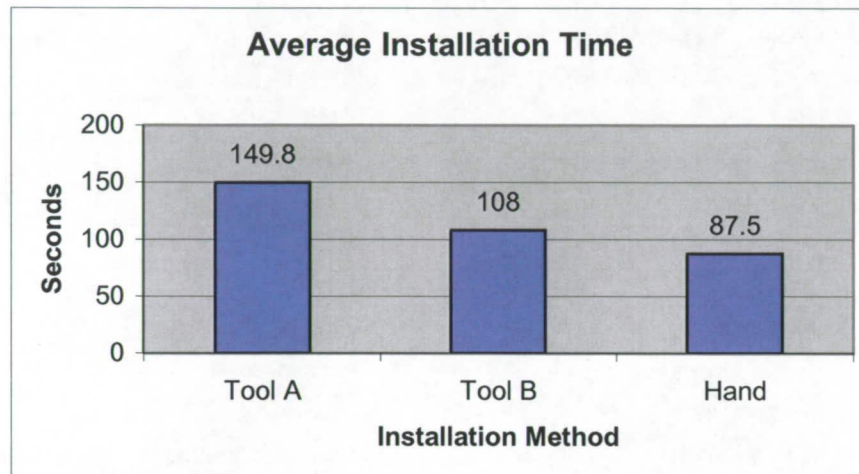


Figure 32. Average Time to Install 3 Screws into Each Group

For the experiment, a total of 432 screws and washers were installed for each installation method (18 participants X 8 groups of holes X 3 holes per group). Figure 33 shows the number of parts that were dropped during installation while using each of the three installation methods. Table 2 shows that there is a significant difference between the number of parts that were dropped when using tool A and tool B, and there was also a significant difference when using tool A and installing by hand. It should be noted that there was not a statistically significant difference between the number of parts that were dropped when using tool B and installing by hand. For tool A, there were a total of 129 parts that were dropped while installing 432 screws. Note, it is possible to have more than one part dropped for any hole. Similarly, there was one part dropped using tool B,

and there were 16 parts dropped while installing by hand. Also note that if a combination of a washer and screw was dropped together, it was counted as only one drop.

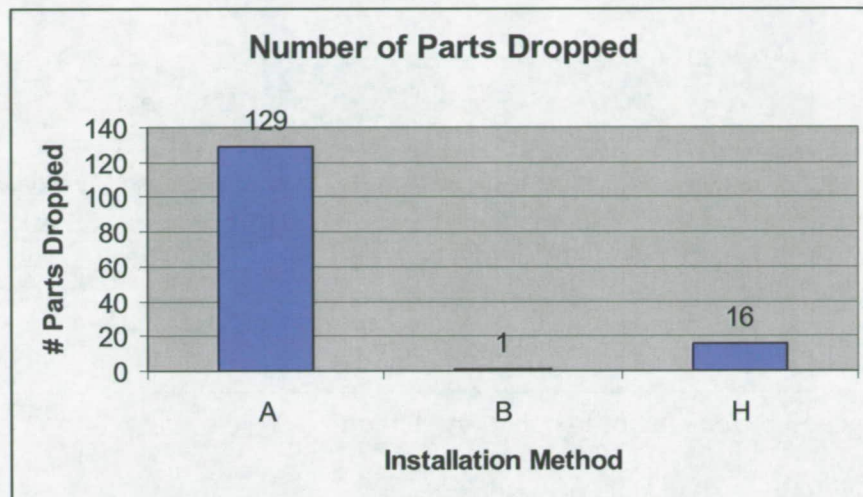


Figure 33. Number of parts dropped for each installation method

In the post-test survey, participants were asked to rank the three installation methods in four ways. The first was an overall ranking, in which they were asked to rank the methods, where a (3) indicates that the method is easiest to use, a (2) indicates it is medium, and a (1) indicates that it is the hardest to use (Figure 34). They were asked to rank the tools for comfort. They rated the tools according to how likely they would be to drop a part while using the tool. They also ranked the perceived speed of installation with each tool. The survey results show that the participants preferred tool B in all four categories. The hand installation was the second favorite choice, and Tool A was the least favorite choice.

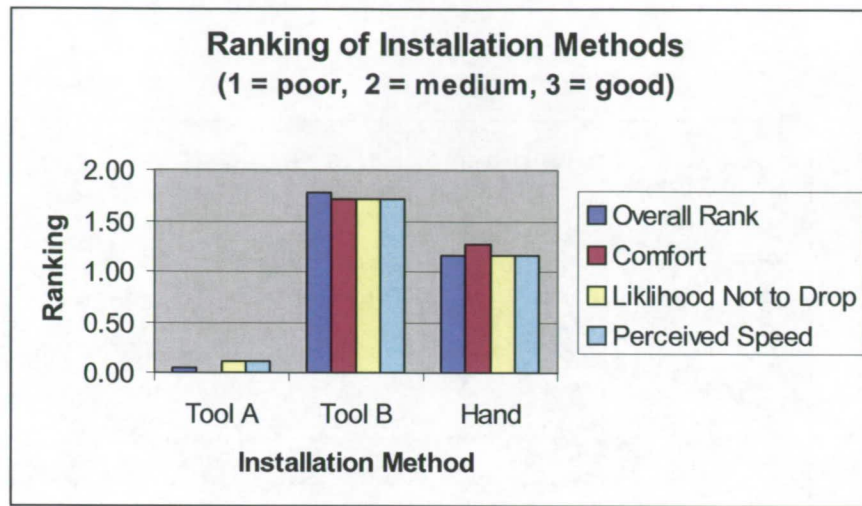


Figure 34. Ranking of Installation Methods

Figure 35 shows how the participants rated the installation methods in the post test survey for six characteristics. A rating of (1) was considered to be very poor, and a rating of (6) was considered to be excellent. The category of “tool force” indicated how much force was required to install the screws. In this case, a rating of (1) means that the participant felt that the force was much higher than was comfortable for them. A rating of (6) means that the force required was not a problem for them. The participants also rated their hand comfort, fore arm comfort, and upper arm comfort while installing screws with each tool. The rating for tool/part setup indicated how easy or difficult it was to get the screw ready for installation. With the tools, this would mean securing the screw on the tool. With the hand installation, it would mean gaining control of the screw in the hand before beginning to install it. The rating for the tool/part release was for the act of releasing the screw from the tool when the insertion was complete. For the hand installation, this simply meant releasing the fingers from the screw.

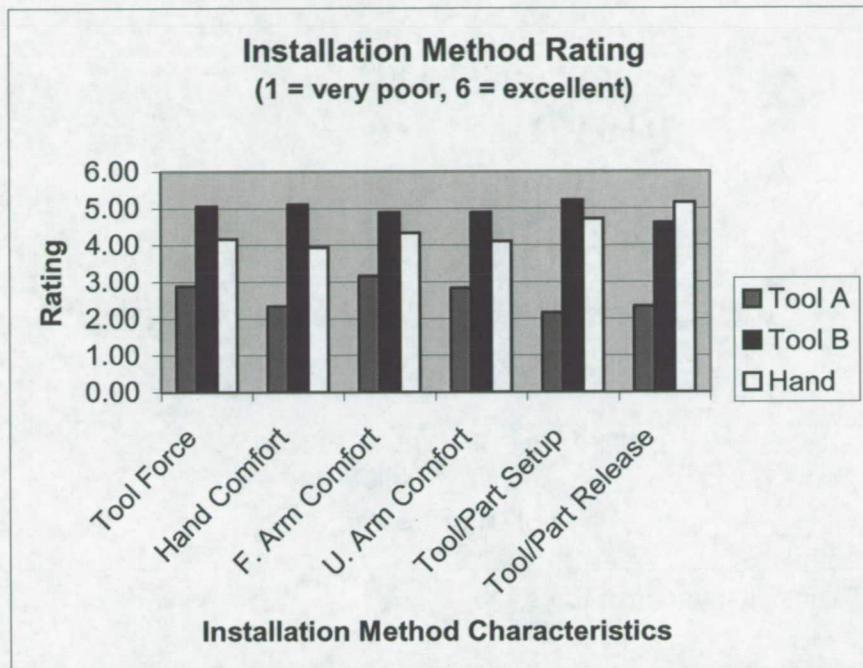


Figure 35. Installation method Rating

The results of the post test survey show that Tool B was preferred in all categories except for the tool release. This would be expected, because the release of the screw after insertion requires very little effort. Hand installation was the second choice in all but the tool release category. Tool A was, again, the least favorite choice.

Figure 36 shows how the participants rated the characteristics that only applied to the tools, and not the hand installation. A rating of (1) indicates very poor, and a rating of 6 indicates excellent. Tool B was rated higher than Tool A in all categories.

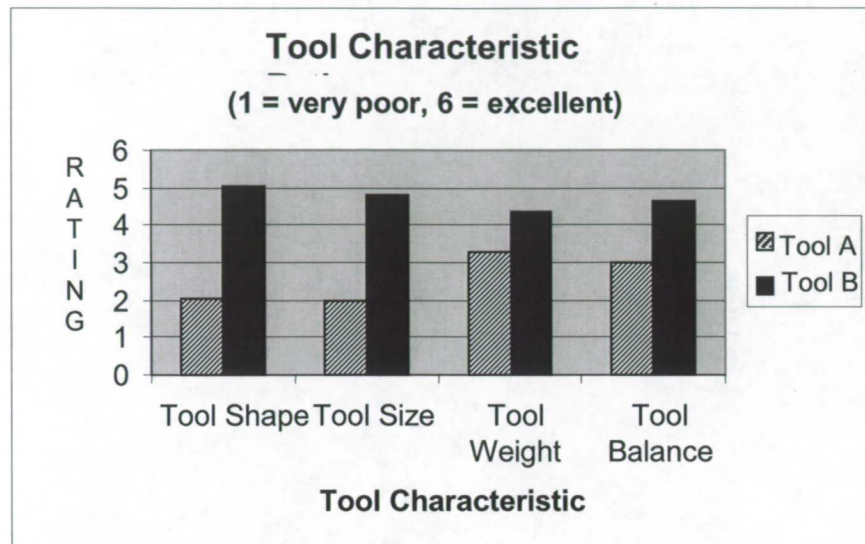


Figure 36. Tool Characteristic Rating

Figure 37 shows how the participants rated the installation into each of the eight groups of screw holes on the testing board. Group 3 stands out as being the easiest. This was the installation straight down at a 90 degree angle from the board. Group 8 was the second easiest, followed by group 2. Group 8 required the participants to reach up and around the obstacle. They could comfortably see through the holes at near eye level. Group 2 required a reach to the left, which was likely to be easier for most of the participants because most were right handed. Reaching to the left was easier, because they could use their right hand. The hardest groups were reported to be 4, 5 and 7. This was straight up, reaching to the right, around an obstacle, and reaching down and around the obstacle, respectively. The groups that were most uncomfortable were the same as the groups that were rated as being hardest.

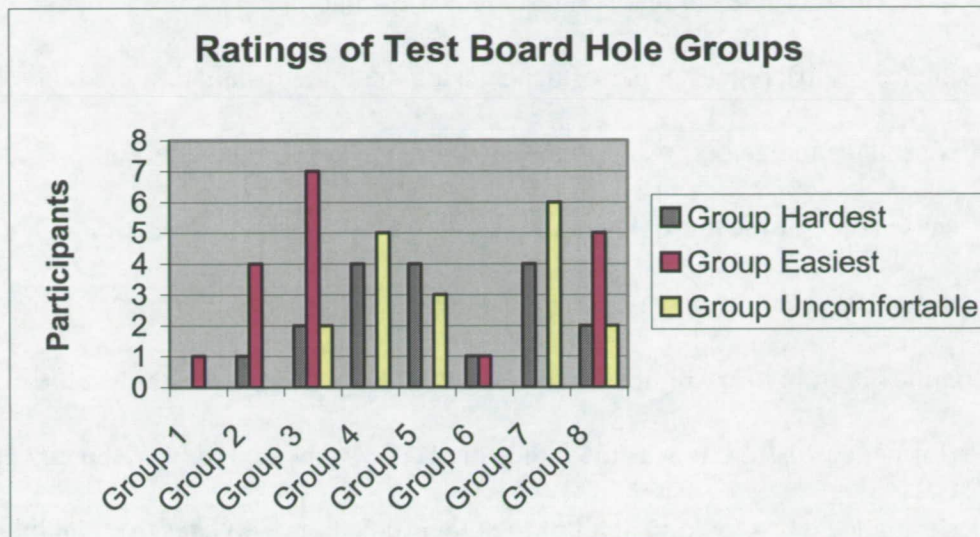


Figure 37. Ratings of Test Board Hole Groups

Figure 38 shows the average perceived exertion level for each installation method.

This is a subjective rating that was given by the participants after each group of three screws was inserted.

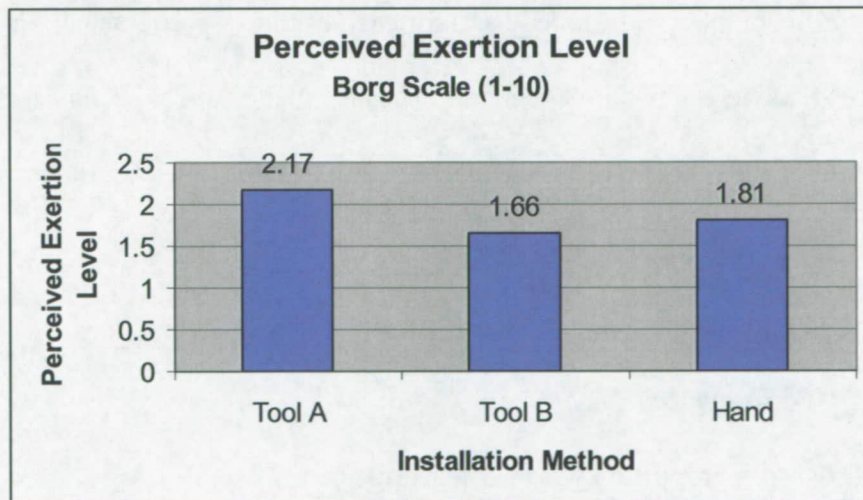


Figure 38. Perceived Exertion Level for Each Installation Level

The multiple comparison tests indicated that there is some statistically significant evidence of differences in performance using the three installation methods for the 27 performance indicators (responses) listed in Table 2. Further analysis was conducted because some of the multiple comparison tests were inconclusive, although it was noticed that the data from these same indicators appeared to be very consistent, when presented graphically in Figures 32-38. It appeared that the hand installation had the highest performance when time was the indicator. Tool B appeared to have the highest performance when looking at all of the other indicators. So a test of hypothesis was conducted for a proportion to obtain further statistical evidence of a difference in performance between the installation methods. For this test, p was the proportion of times that performance was as predicted. Tests of proportion were performed for all of the 27 responses listed in Table 2.

Table 3 shows a sample of how each of the 27 tests was conducted. This sample test was for the number of dropped parts for each of the 18 participants. There were three hypotheses that were stated independently because the results of each of the tests were independent of the others. In this case, the installation method with the least number of dropped parts indicated the highest performance.

H_0 : Performance of B $\leq$ A; $p \leq 0.5$

H_1 : Performance of B $>$ A; $p > 0.5$

p = proportion where B performs better than A

H_0 : Performance of H $\leq$ A; $p \leq 0.5$

H_2 : Performance of H $>$ A; $p > 0.5$

p = proportion where H performs better than A

H_0 : Performance of H $\leq$ B; $p \leq 0.5$

H_3 : Performance of B $>$ H; $p > 0.5$

p = proportion where H performs better than B

The data in Table 3 was simplified by coding it as follows:

1 = The performance statement is true (1st row of table: B $>$ A, H $>$ A, or B $>$ H)

0 = There is no difference in performance

(1) = The performance statement is false

When observing the performance of B compared to A, in the second column of Table 3, it can be seen that the value of p is 1.00, the calculated z -value is 4.24 and the value of z with $\alpha = 0.10$ is 1.28. Therefore, since the calculated z -value is greater than $z_{0.10}$, there is enough evidence to reject the null hypothesis and accept H_1 , indicating that the performance of tool B is better than the performance of tool A when considering the number of parts that are dropped. Similarly, the performance using hand installation was better than when using tool A. In contrast, for the last hypothesis, H_0 was not rejected, therefore there is not enough evidence to show a difference in the performance between hand installation and installation using tool B. A similar analysis was conducted for the remaining responses.

Table 3. Sample Calculation of Proportions

Total Drops (All Participants)	Performance		
	B > A	H > A	B > H
S001	1	1	0
S002	1	1	1
S003	1	1	1
S004	1	1	(1)
S005	1	1	1
S006	1	1	0
ME001	1	1	1
ME002	1	(1)	1
ME003	1	1	0
ME004	1	1	0
ME005	1	1	0
ME006	1	1	0
T001	1	1	0
T002	1	1	0
T003	1	1	0
T004	1	1	0
T005	1	1	1
T006	1	0	1
Total # 1's	18	16	7
p [^]	1.00	0.89	0.39
z	4.24	3.30	-0.94
Z _{0.10}	1.28	1.28	1.28

Table 3 was shown as an example of how the proportion, p, was calculated for one performance indicator, dropped parts. When time was the response, the hypothesis was slightly different, since the hand installation appeared to be the most efficient.

Ho: Performance of B ≤ A; p ≤ 0.5

H1: Performance of B > A; p > 0.5

p = proportion where B performs better than A

Ho: Performance of H ≤ A; p ≤ 0.5

H2: Performance of H > A; p ≤ 0.5

p = proportion where H performs better than A

Ho: Performance of $H \leq B$; $p \leq 0.5$

H3: Performance of $H > B$; $p \leq 0.5$

p = proportion where H performs better than B

Table 4 shows a summary of the test of proportions when time was the indicator of performance. This indicates that there was enough evidence to reject the null hypothesis and conclude that the performance was best when using hand installation, second best when using tool B, and the lowest performance was when using tool A.

Table 4. Summary of Test of Proportions when Observing Time for Installation

Response	Performance		
	B > A	H > A	H > B
Avg. Time Per Group	*	*	*

* Indicates the performance matches the prediction.

A final analysis was conducted to compare the results of the hypothesis tests for 16 of the 27 tests. Only 17 responses included all participants in the sample, and time was considered separately above in Table 4. The test of proportion for time and the number of drops showed that the performance was the same for each of the five subsets of the population, which included students, managers/engineers, technicians, males and females.

Table 5 summarized the test of proportions for 16 remaining performance indicators. Based on these results, there is enough evidence to reject the null hypothesis in the second column, so it can be concluded that the performance when using tool B is better than the performance when using tool A. In contrast, there is not enough evidence

to reject the null hypothesis for columns three and four, so there is also not enough evidence to conclude that there is a difference in overall performance when installing by hand or using tool A. Also there is not enough evidence to conclude that there is a difference in overall performance when using tool B and when installing by hand.

Table 5: Calculation of Proportions when Testing 16 Performance Indicators

Response	Performance		
	B > A	H > A	B > H
Avg.# Drops	*	*	
Exertion	*	*	*
#4. Easy/Hard Rank	*	*	*
#5. Comfort Rank	*	*	*
Force Required	*		
Hand Comfort	*	*	*
Fore Arm Comfort	*		
Upper Arm Comfort	*		
Tool Setup	*	*	
Tool Release	*		
Tool Drop (Likelihood)	*	*	*
Perceived speed	*	*	*
Tool Balance	*		
Tool Shape	*		
Tool Size	*		
Tool Weight	*		
Total # of Indicators	16	12	12
# of *'s	16	8	6
$p^{\wedge}$	1.00	0.67	0.50
z	4.00	1.15	0.00
$z_{0.10}$	1.282	1.282	1.282

* Indicates the performance matches the prediction, as listed in rows 1 and 3.

The post-test survey revealed that there were 14 right-handed participants, and 4 who use either hand. There were no left-handed participants. The height of the participants ranged between 62 and 78 inches. The height for 5th percentile for females is 60.2", and the height for 95th percentile for males is 73.5" for US adults between the age

of 19 and 60 years (Kroemer & Grandjean, 1997). All but two of the test participants were within this range. One male was 74 inches and one was 78 inches. Four of the males were only $\frac{1}{2}$ inch below the 95th percentile height (Figure 39). This is important because height can be used to estimate hand size [Chaffin, 1999]. So it would appear that the participants were, overall, taller than the normal US population, but the sample may be representative of the workforce at the Kennedy Space Center.

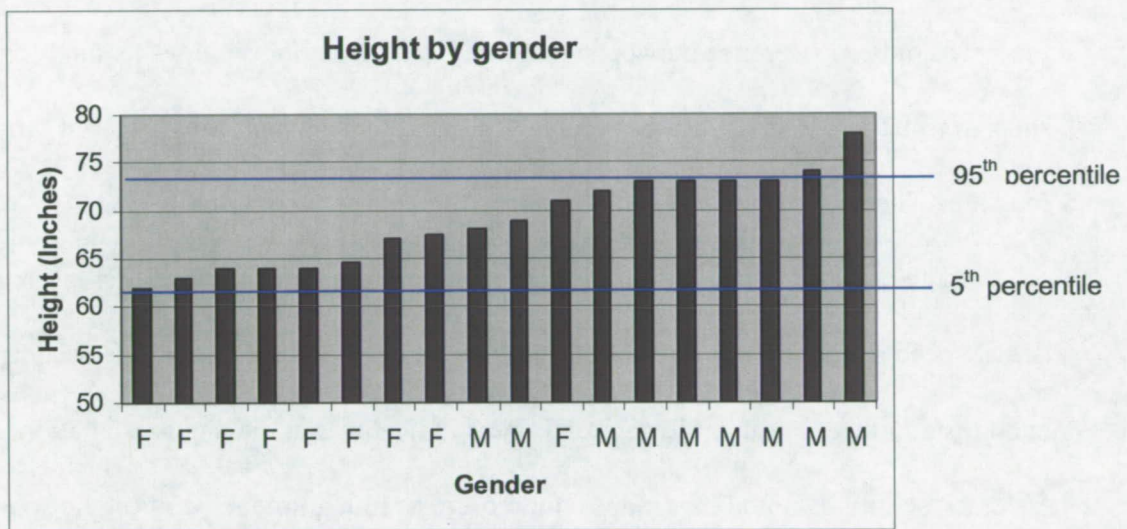


Figure 39. Participant Height by Gender

4.2 Discussion

The overall results of the research indicate that tool B would have a higher usability than tool A. When comparing tool A with hand installation, and comparing tool B with hand installation, the overall results are not conclusive. But there are individual indicators that show tool B has a higher usability than when installing by hand, and also the performance when installing by hand is better than when using tool A. Alternatively, there are some indicators that are inconclusive for both of these comparisons. Based on

the data collected and general comments from the participants, tool A was not a good choice for the installation of screws and washers for this configuration.

The time to install a screw and washer was recorded to provide a comparison in performance. Although this is less important than the number of parts that were dropped, it is a factor when designing a work task. There was a statistically significant difference in the time that it took to install screws for all three installation methods when all participants were included. See Table 2 and Figure 32. Multiple comparisons indicated there was only a difference between tool A and hand installation. Further analysis showed a statistical difference between all three methods when using a test of proportions for time. The performance was the same for all subgroups of participants.

The perceived speed of installation, as seen in Figure 34, was different than the actual speed as seen in Figure 32. Participants perceived that using tool B was faster than hand installation, although the recorded times indicated that the hand installation was faster. It should be noted that it does not require as much time to position the screw in the hand as it does to set it up in the tool, so that could account for a reduced installation time.

The more important indicator of usability for this experiment was the number of parts that were dropped. The analysis was done using the number of parts that were dropped during the installation, and did not include the parts that were dropped while setting up the screw and washer in the tool, or initially positioning the parts in the hand. When a washer and screw were dropped together, it was counted as only one part.

When considering all of the participants, the number of parts that were dropped was significantly different between tool A and tool B, it was also different between tool A

and hand installation. It was not, however, different between tool B and hand installation (Table 2 and 5). This would indicate that there was either not a significant difference in the number of parts that were dropped, or it could simply mean that the sample size was not large enough to make a conclusion. Similar results were found for the five subgroups of participants when using the test of proportions (Table 5).

Figure 33 shows the number of parts that were dropped for each installation method. The number of parts dropped was less for tool B than with the hand installation. The most parts were dropped when using tool A. Although these are not all statistically significant differences, this performance difference between installation methods is consistent with the subjective data that was gathered through the posttest survey (Appendix E).

Figure 34 shows that tool B was preferred by the participants over hand installation. Tool A was the least preferred method. The ratings included overall ranking of the installation methods, comfort while installing, perceived likelihood not to drop a part, and the perceived speed of installation. These ratings were shown to be significantly significant using the test of proportions in Table 5.

These results are also consistent with five of the six ratings that are summarized in Figure 35. Tool B was preferred, with hand installation ranking second, and tool A ranked third for perceived tool force required, hand comfort, fore arm comfort, and tool setup. Hand installation was naturally the easiest when releasing the part from the tool or hand. Of these, hand comfort was the only indicator that was significantly different between all three methods, as seen in Table 5.

The perceived exertion levels, based on the Borg CR10 Scale (Borg, 1998, Appendix D), also indicated that using tool B required the least amount of physical force, next was when using the hand, and third was when using tool A. Tool B was again preferred when compared to tool A for shape, size, weight and balance. These were all seen to be statistically significant in Table 5.

In summary, the number of parts dropped were significantly different between tool A and tool B, and also between tool A and hand installation (Table 2 and 5). Although the difference in the number of parts dropped was not statistically significant between tool B and the hand installation, the significant subjective factors for installation preference could possibly indicate that if tool B were used instead of the other two methods, there may be a reduction in the incidence of repetitive motion injuries. In addition to the safety improvements, this may lead to performance difference over time.

Based on this research there was evidence to suggest that managers/engineers or students could be used in place of technicians in this type of task, although this should be done with caution. It is preferred that technicians are used for the testing when they are available. When technicians are not readily available, the use of students or managers / engineers could potentially be a cost savings. Although all of the groups showed similar results in determining the best installation method, the technicians gave valuable qualitative information to validate the current research and gave suggestions for improvements to future research.

The holes on the testing board were located in eight groups. A second multiple comparison was done using only five of the groups. Three of the groups that were perceived to be the easiest were removed from the analysis to determine if only the

hardest positions could be studied in future experiments, to reduce the cost of the study.

The results were not the same, so it can not be concluded that the easiest positions could be removed from the study.

In summary, the results of this research indicate that the overall usability of tool B was better than tool A when considering reducing the number of small parts that are dropped during installation. There were also indicators that showed the performance when using hand installation was better than when using tool A, and performance when using tool B was better than when using hand installation. Therefore, using tool B may reduce the likelihood of dropping small parts in an actual work environment, as compared to hand installation and the use of tool A. In contrast, hand installation was the fastest method of installation.

CHAPTER 5

CONCLUSIONS

This chapter presents the conclusions from the research conducted to address the topic that was stated earlier as, “Development of a methodology to conduct usability evaluations for hand tools that may reduce the amount of small parts that are dropped during installation while processing space flight hardware.” The chapter is divided into two sections:

- 5.1 Summary
- 5.2 Areas for Future Research

5.1 Summary

This research achieved the objective of designing a test methodology and developing the hardware to conduct usability evaluations of hand tools. This was done with the purpose of reducing the FOD that results from dropping small parts when processing space flight hardware. This could contribute to improving the design of hand tools, which could lead to saving lives by reducing FOD, and also reducing injuries due to cumulative trauma disorders. Typically, resources are put into developing awareness programs and the capture of parts after they are dropped. This research takes the approach that designing and testing tools that will give the user more control over the

small parts while keeping the hand and wrist in a more neutral, unstressed position, may reduce the number of parts that are dropped.

The methodology and hardware were used successfully by Boeing Corporation to design and evaluate a prototype for a new hand tool (Boeing(b), 2000) that was specifically designed to reduce the number of small parts that are dropped when processing space flight hardware. The designers used the testing board to informally try out their first designs, and based on their observations, they made design changes. A usability test of the final prototype was conducted using a modified version of the methodology developed in this research.

The usability testing board and methodology were designed to be flexible so that many types of fasteners and hand tools could be tested in a variety of work environments, including clean rooms. This was observed to be valid when the Boeing study was conducted with little modification to the test methodology.

The methodology and testing hardware offer a way to quantitatively demonstrate the usability of a prototype hand tool to manufacturing companies. There is a significant investment in manufacturing, storing, distributing and marketing new tools, so having a quantitative measure may help to reduce the risk of failure. The statistical results of a usability test on a new tool could also be used for marketing purposes.

The research indicated that there were some differences in the usability indicators for the three installation methods. This accomplished one of the research objectives. This was achieved by considering both the objective data that was gathered through observation during the study, and the subjective data that was gathered during the post

test survey. Therefore it would be reasonable to predict that future studies could show a difference in usability of installation methods.

The study made a contribution to the research literature because there has been little work in the area of usability testing for hand tools, which applies ergonomic factors and usability engineering concepts. The design of the board is unique, and has many future applications.

5.2 Areas for Future Research

The technicians who participated in the study generally agreed that the experiment was similar to some of the tasks that are performed in the actual work environment, but they also gave suggestions to simulate the actual work environment. Some of these could be incorporated into a similar study in the future to make it more realistic. The technicians suggested that it was too comfortable, because the floor was carpeted, so the floor surface could be hard in a future test. Sometimes they use foam, which can slide and make the task more difficult. The technicians also suggested that an actual work area may be darker in some cases, and a task light could be used. An issue to consider is that when a light is placed behind the work area, it makes it easier to locate the holes because the light shines through the holes. More interruptions are typically encountered in the actual work environment. A tape of a conversation that would be typical over a communication network was played for this research, but a stronger distraction could be incorporated into the task. The technicians reported that there are usually people working all around them, and sometimes stepping over them. They are often stopped in the middle of a task to answer a question. A study that could simulate more of this

environment, while remaining consistent between participants may give new insight into the use of a hand tool.

The usability testing board could be used in the early design phase by letting designers informally use their prototypes and existing tools, or a short methodology could be developed for them to quickly test their designs.

Based on this research there was enough evidence to conclude that managers/ engineers or students could be used in place of technicians. Future research could be conducted to verify these results.

The hand tool prototype that was developed by Boeing((b), 2000), could be approved and modified as necessary to be used with flight hardware. Then it could be tested in an actual work environment. Results from observing it in the work environment could be compared with the results of the study that was conducted with the usability testing board and methodology to validate this research further.

This study revealed the variety of wrist, hand and body positions that were required to complete the task. For each task, the participant had to complete four subtasks, which included (1) locating the hole, (2) inserting the screw into the hole, (3) turning the screw, and (4) releasing the screw. Each of these requires a different posture. Further variations were seen because there were three installation methods, and individual differences in the strategies used to complete the tasks. Future studies could be conducted using the testing board to determine which postures would be most likely to lead to cumulative trauma disorders when using hand tools. Improvements could be made in hand tools by testing the postures that are required to complete the task.

Designing tools that can be customized to complete a task without using the positions that are higher risk may lead to reduced injuries.

As noted, individuals used different strategies to complete the tasks. Some were more successful than others. The testing board could be used to study the successful methods to develop better installation techniques that could reduce the number of dropped parts and the risk of injury. These techniques could be taught to the technician work force, and have an impact on reducing FOD and injuries. The testing board could also be used for the training.

The concepts that are used to develop and test hand tools to reduce FOD and the risk of injuries here on earth could also be used to develop tools with similar benefits in space. This could include the international space station, or long duration space missions, such as the exploration of Mars. Maintenance tasks on Mars will require the use of hand tools and small parts. Dropping parts or getting injuries when on a long duration space mission could have an even greater impact than it does on earth.

Because of the limited amount of research that exists for conducting usability evaluations on hand tools with the objective of reducing FOD, this study has made an original contribution to the research literature. Continuation of this research has the potential to produce practical results, which could ultimately save lives.

APPENDIX A
PRETEST INSTRUCTION
FORM

Participant: _____

**Hand Tool Evaluation Experiment
Pretest Instructions
2000**

GENERAL INSTRUCTIONS:

- ❑ **Thank you for participating** in this experiment! It should take less than 2 hours.
- ❑ **I will read** these instructions and check them off as we go through them, so that everyone hears the same things for the experiment.
- ❑ **The purpose** of the study is to evaluate which tools make it easier to install small parts such as screws, bolts, washers and nuts. With good tools for the job, people are less likely to drop parts, which may cause delays or safety concerns.
- ❑ **During the study, You will be installing** screws in the test board using different methods.
- ❑ First, you will put on a clean room suit, including boots, gloves and head cover.
- ❑ Before each study trial, you will have a practice session using one of the three installation methods.
- ❑ During the actual study trial, you will insert screws into holes in the board using your hand or one of two different tools.
- ❑ After you complete the study, I will ask you to fill out a questionnaire.
- ❑ **The risk level** for this experiment is no more than when using a screwdriver. You may experience minimal discomfort while reaching to install or remove a screw. If this bothers you, or you wish to stop the experiment for any reason, please do so at any time. Your safety is the most important consideration.
- ❑ **There is no time limit** for the study. I will be measuring the time it takes to insert the screws and the number of parts that are dropped. Both are equally important.
- ❑ **Although this is a study environment**, please try to work as you would in a regular work area, where it would be important not to drop parts, but you still need to maintain a time schedule.
- ❑ **All results from this study are anonymous.**
- ❑ **You may ask questions** any time.

- ❑ **Do you have any questions**, before I explain the practice session?
[Response]
- ❑ Before we begin, I need for you to **sign a consent form** that says you agree to participate in this study. **[Sign Informed Consent Form]**

PRACTICE SESSION #1

- ❑ **You will put on the clean room suit, boots, gloves and head cover.**

[suit up]
- ❑ **While you are working, I will be playing a tape** of a conversation that would be typical of what you may hear over the network. **[Turn on tape]**
- ❑ You **will start by practicing**, using (**your hand / Tool A / Tool B**) .
- ❑ You will put the washer on the screw. **[Demonstrate]**
- ❑ Then, you will reach into the hole and install it from the back. **[Demonstrate]**
- ❑ Turn the screw until you begin to feel a resistance from the captive nut plate on the front. This is approximately 6 turns. Don't make it hard to get out.
- ❑ You will practice by installing a screw into each of the four holes that are marked with green tabs. Go in order, starting with #1.
- ❑ Remember, we are testing the hand tool, not you!
- ❑ **Do you have any other questions**, before we begin the practicing?

[Practice - Experimenter: Check tightness of each screw after it is installed. It should be snug, but not tight.]

TRIAL #1

- ❑ You are ready to begin the first trial. You will install the screws and washers into the holes that have nut plates, which are inside the yellow boxes. The red tabs indicate the order. **[Point]**
- ❑ You will begin by installing the three screws in group 1 by putting your arm through the arm hole and installing the screw parallel to the board, **[Point]** After group 1 is complete, you will install the three screws in groups 2, 3 and 4. **[Point, and let participant look through arm hole to locate.]**
- ❑ When you are ready to do group 5, reach around the plate to install the screw so it is coming directly toward you. Continue this process for groups 6 through 8. **[Show all holes]**
- ❑ When you begin installing screws in a vertical group, start by installing the top screw and then work down. **[point]**
- ❑ When you begin installing screws in a horizontal group, start by installing the

- left screw first, then work to the right. **[point]**
- ❑ Turn the screw until you feel a resistance. This is approximately 6 turns.
 - ❑ **After each set of three screws**, I will ask you to rate the level of physical exertion that you feel according to the chart on the wall.
 - ❑ **I won't be talking to you very much** during the test, so that I don't distract you, and so that all of our participants are treated the same. But if you have any questions as you go, please feel free to ask.
 - ❑ **You will be given a 6-minute break** after each trial, which includes the eight groups of screws. Then you will repeat the process two more times with different methods of installing the screws.
 - ❑ **Do you have any questions?**

[Perform Trial #1]

- ❑ You have finished trial #1. Thank you. You need to take a 6 minute break.

[Experimenter - Remove screws from board]

PRACTICE SESSION #2

- ❑ It is time to start the second practice session. Are you ready?
- ❑ You **be practicing**, using (**your hand** / **Tool A** / **Tool B**) .
- ❑ Remember to put the washer on the screw. **[Demonstrate]**
- ❑ You will practice by installing a screw into each of the four holes that are marked with green tabs. Remember to go in order, starting with #1.
- ❑ **Do you have any other questions**, before we begin the practicing?

[Practice - Experimenter: Check tightness of screw]

TRIAL #2

- ❑ **You are ready to begin the second trial.** Install the screws in the same order that you did with the first trial, following the numbers on the red tabs. **[Point]**
- ❑ **You will be given another 6-minute break** after this trial, which includes the eight groups of screws
- ❑ **Do you have any questions?**

[Perform Trial #2]

- ❑ You have finished trial #2. Thank you. You need to take a 6-minute break now.

[Experimenter - Remove screws from board]

PRACTICE SESSION #3

- ❑ It is time to start the last practice session. Are you ready?
- ❑ You will **be practicing**, using (your hand / Tool A / Tool B).
- ❑ **[Demonstrate]**
- ❑ Use the same process as before, following the order of the numbered green tabs.
- ❑ **Do you have any other questions**, before we begin the practicing?

[Practice - Experimenter: Check tightness of screw]

TRIAL #3

- ❑ You are ready to begin the last trial. Install the screws in the same order that you did with the first trial, following the numbers on the red tabs.
- ❑ **Do you have any questions?**

[Perform Trial #3]

- ❑ You have finished all three trials, so you are finished with the basic part of the study. I have a form for you to fill out and then you will be done. You can remove the clean room suit, gloves and head cover now. Then come back and fill out the questionnaire.

[Post Test Survey / questions]

- ❑ **Thank you so much for your help in this study!**
- ❑ **Do you have any other questions?**

APPENDIX B

PARTICIPANT CONSENT FORM

**Hand Tool Study
Informed Consent Form
2000**

I agree to participate in this study, which is part of an educational research project and which will also be used to evaluate hand tools for processing flight hardware.

This experiment has been explained to me, and I understand the explanation. The experimenter has defined the procedures to be followed and the potential risks, discomforts, and benefits. I understand that the risks are no more than with using a screwdriver.

I have been given the opportunity to ask whatever questions I may have and all such questions have been answered to my satisfaction. In addition, I understand I am free to refuse to answer specific questions or items in the interviews or questionnaires.

I understand that all results from this study will remain anonymous.

I understand that **I AM FREE TO WITHDRAW** my consent and terminate my participation at any time during the experiment, and can do so without penalty.

Participant's Signature

Date

Experimenter's Signature

Date

APPENDIX C
SAMPLE DATA COLLECTION FORM

Sample Data Collection Form

GROUP 1												
	Start Time:											
	End Time:											
	Total:											
	Hole #1		Drop	Nearly Drop	Hole #2		Drop	Nearly Drop	Hole #3		Drop	Nearly Drop
	Screw:	Set-up			Screw:	Set-up			Screw:	Set-up		
		Install				Install				Install		
	Washer:	Set-up			Washer:	Set-up			Washer:	Set-up		
		Install				Install				Install		
	Both:	Set-up			Both:	Set-up			Both:	Set-up		
		Install				Install				Install		
Exertion?		0 0.5 1 2 3 4 5 6 7 8 9 10										

GROUP 2												
	Start Time:											
	End Time:											
	Total:											
	Hole #1		Drop	Nearly Drop	Hole #2		Drop	Nearly Drop	Hole #3		Drop	Nearly Drop
	Screw:	Set-up			Screw:	Set-up			Screw:	Set-up		
		Install				Install				Install		
	Washer:	Set-up			Washer:	Set-up			Washer:	Set-up		
		Install				Install				Install		
	Both:	Set-up			Both:	Set-up			Both:	Set-up		
		Install				Install				Install		
Exertion?		0 0.5 1 2 3 4 5 6 7 8 9 10										

APPENDIX D

BORG SCALE POSTER
For
PERCEIVED EXERTION

Rating of Perceived Exertion

- 0 Nothing**
- 0.5 Extremely Weak (Just Noticeable)**
- 1 Very Weak**
- 2 Weak (Light)**
- 3 Moderate**
- 4 Somewhat strong**
- 5 Strong (Heavy)**
- 6**
- 7 Very Strong**
- 8**
- 9**
- 10 Extremely strong (Almost Maximal)**
- * Maximal**

APPENDIX E
POST TEST SURVEY FORM

Participant # _____

Hand Tool Evaluation Experiment Post Test Survey 2000

1. What hand do you prefer to use while using hand tools such as a screwdriver?
___ Right Hand ___ Left Hand ___ Either
2. What is your height: ___ Feet ___ Inches
3. Approximately how many years of experience do you have in working with hand tools such as screwdrivers?
___ 0 - 1 years ___ 2 - 4 years ___ 5 - 10 years ___ Over 10 years
 - What has been the average number of hours / week that you have used hand tools over this period of time?
___ 0 - 1 hours ___ 2 - 3 hours ___ 4 - 8 hours ___ over 8 hours
4. Please rank the methods (Hand, Tool A, Tool B):
Easiest to use _____
Medium _____
Hardest to use _____
5. Please rank the methods (Hand, Tool A, Tool B):
Most comfortable to use _____
Medium _____
Least comfortable to use _____
6. Which group # was the hardest? 1 2 3 4 5 6 7 8
(See picture)
7. Which group # was the easiest? 1 2 3 4 5 6 7 8
8. Which group # was the most uncomfortable? 1 2 3 4 5 6 7 8

9. For each screw installation method, how would you rate each characteristic?

Tool A	Very Poor	Poor	Not Good	Good	Very Good	Excellent
Shape (How it fits in your hand)	1	2	3	4	5	6
Size (Handle Diameter)	1	2	3	4	5	6
Weight	1	2	3	4	5	6
Balance	1	2	3	4	5	6
Force required	1	2	3	4	5	6
Hand comfort	1	2	3	4	5	6
Fore arm comfort	1	2	3	4	5	6
Upper arm comfort	1	2	3	4	5	6
Use during setup of part	1	2	3	4	5	6
Use during release of part	1	2	3	4	5	6

Tool B	Very Poor	Poor	Not Good	Good	Very Good	Excellent
Shape (How it fits in your hand)	1	2	3	4	5	6
Size (Handle Diameter)	1	2	3	4	5	6
Weight	1	2	3	4	5	6
Balance	1	2	3	4	5	6
Force required	1	2	3	4	5	6
Hand comfort	1	2	3	4	5	6
Fore arm comfort	1	2	3	4	5	6
Upper arm comfort	1	2	3	4	5	6
Use during setup of part	1	2	3	4	5	6
Use during release of part	1	2	3	4	5	6

Hand Installation	Very Poor	Poor	Not Good	Good	Very Good	Excellent
Force required	1	2	3	4	5	6
Hand comfort	1	2	3	4	5	6
Fore arm comfort	1	2	3	4	5	6
Upper arm comfort	1	2	3	4	5	6
Use during setup of part	1	2	3	4	5	6
Use during release of part	1	2	3	4	5	6

10. Which installation method did you feel the most likely to drop a screw or washer?
___ Tool A ___ Tool B ___ By hand
11. Which installation method did you feel the least likely to drop a screw or washer?
___ Tool A ___ Tool B ___ By hand
12. Which installation method seemed the fastest?
___ Tool A ___ Tool B ___ By hand
13. Which installation method seemed the slowest?
___ Tool A ___ Tool B ___ By hand
14. Is this representative of some of the tasks that you may do in your work?
___ 1. Not similar to anything that I do (If not similar, please skip to #20.)
___ 2. Somewhat similar to some things that I do
___ 3. Similar to some things that I do
___ 4. Very similar to some things that I do
15. Is there anything in this study that is not representative of some tasks that you may do in your work?
___ No
___ Yes - please describe _____

16. Is there anything that should be included in this test to make it more representative of installing screws in your actual job?
___ No
___ Yes - please describe _____

17. Do you have any suggestions for the design of a tool to help install the screws in this study? ___ Yes ___ No

If yes please describe,

OPTIONAL QUESTIONS:

18. Age: ☐ 19 - 25 ☐ 26 - 40 ☐ 41 - 55 ☐ Over 55
19. Do you have any physical limitations that may have affected the test. (Sore finger from sports, soar arm from surgery, etc) ☐ No ☐ Yes
20. May we call you to ask if you would like to participate in future studies?
☐ No ☐ Yes

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Thesis Defense

Degree of Master of Science
Human Engineering and Ergonomics
Department of Industrial Engineering and Management Science
College of Engineering
University of Central Florida

Darcy Miller
November 1, 2000

1

Committee:

- ⊖ Dr. Pamela McCauley-Bell, Chair
- ⊖ Dr. Linda Malone, Committee Member
- ⊖ Dr. Mansoorh Mollaghasemi, Committee Member

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Agenda:

- ⊗ Introduction
- ⊗ Literature Review
- ⊗ Methodology
- ⊗ Results
- ⊗ Conclusions

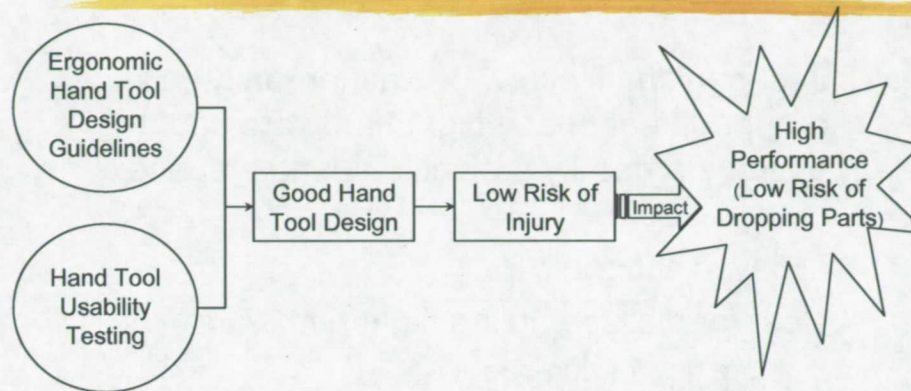
3

Introduction

- ⊗ Model for High Performance Hand Tool Design
- ⊗ Foreign Object Debris (FOD)
- ⊗ Statement of Problem

4

Model for High Performance Hand Tool Design



"High Performance" is defined based on user needs. In this research, reducing the risk of creating FOD by dropping parts was the highest priority.

5

What is Foreign Object Debris (FOD)?

☒ "The debris that is left in or around flight hardware, where it could cause damage to that flight hardware," (United Space Alliance, 2000).

6

Why is FOD A Concern?

- ⊗ Just one small screw or washer, unintentionally dropped near space flight hardware could become a deadly projectile during a space shuttle lift off.
- ⊗ Delay in schedule
- ⊗ Cost for disassembling flight hardware
 - ⊖ More risk for damage

7

Statement of the Problem

- ⊗ Objective: Develop a methodology and hardware to assess FOD risk by assessing various hand tools used to install small parts.
 - ⊖ Test methodology - Use for existing and prototype tools
 - ⊖ Hardware - Usability Hand Tool Testing Board
- ⊗ Compare performance of participant groups

8

Literature Review

- ☒ Foreign Object Debris (FOD)
- ☒ Hand Tool Design
- ☒ Evaluation Techniques

9

FOD

- ☒ Sources:
 - ☒ Tools, fasteners, such as screws, washers
 - ☒ Tape, wire, paper, cloth
 - ☒ Dust and small particles
- ☒ Problem not unique to space industry - commercial airlines, airports, aircraft manufactures, and the military. (United Space Alliance, 2000; United Airlines, 2000; Rocketdyne)
- ☒ \$\$ millions in damage annually to airports, airlines and airport tenants

10

Current Focus

- ☒ Training and motivation
- ☒ Daily inspections by airport personnel of airplane maneuvering areas (Required by FAA and International Civil Aviation Organization)
- ☒ Trained to look for FOD throughout the day
- ☒ FOD Committees formed
- ☒ National Aerospace FOD Prevention Society
- ☒ Retrieval of parts through netting
- ☒ Tools to retrieve small parts

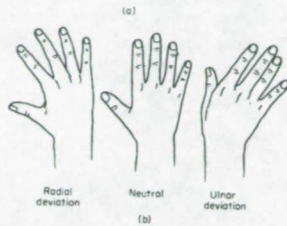
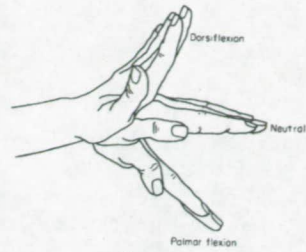
11

Hand Tool Design

- ☒ Inappropriate hand tool design can result in occupational injuries for the forearm and hand.
- ☒ Injuries or early symptoms can theoretically result in an increased likelihood of dropping parts - FOD (McCauley-Bell, 2000).
- ☒ Hand is the most effective in natural posture

12

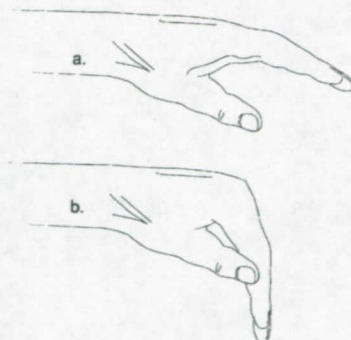
Hand Postures



Hand Positions (Reprinted from Sanders and McCormick, 1993):
 a. Illustration of Palmar Flexion, Dorsiflexion
 b. Illustration of Radial and Ulnar Deviations

13

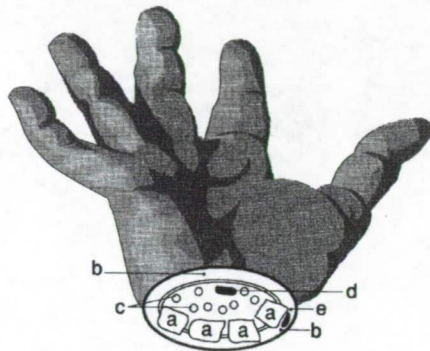
Finger positions



Finger positions (Reprinted from Cacha, 1999)
 a. Fingers Extended
 b. Fingers Flexed

14

Risk of Cumulative Trauma Disorders



Cross Section of Carpal Tunnel
(Reprinted from Cacha, 1999)

- a. Carpal bones (8)
- b. Ligaments
- c. Tendons
- d. Median Nerve
- e. Radial Nerve

15

Evaluation Techniques

- ⊗ Usability (Nielsen, 1993)
 - ⊖ Efficiency
 - ⊖ Few Errors
 - ⊖ Satisfaction
 - ⊖ Learnability
 - ⊖ Memorability
- ⊗ Vs. Standard Engineering tests of the tools
 - ⊖ Hardness
 - ⊖ Load
 - ⊖ Heat tolerance, Flammability
 - ⊖ Solvent damage

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Methodology

- ⊗ Participants
- ⊗ Experimental Design
- ⊗ Experimental Task
- ⊗ Apparatus
- ⊗ Procedure

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Participants

- ⊗ 18 participants
- ⊗ 9 males and 9 females
- ⊗ 3 participant types
 - ⊖ Technicians
 - ⊖ Managers / Engineers
 - ⊖ Students
- ⊗ All participants worked at the Kennedy Space Center (KSC)
- ⊗ All participants over 18 years old
- ⊗ No size or weight restrictions

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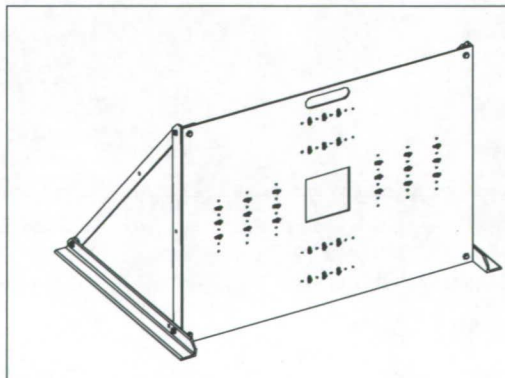
Experimental Design

Participant Type (3)	Installation Method Order (3)	Gender (2)
Student	Hand - Tool A - Tool B	Female
Student	Tool A - Tool B - Hand	Female
Student	Tool B - Hand - Tool A	Female
Student	Hand - Tool A - Tool B	Male
Student	Tool A - Tool B - Hand	Male
Student	Tool B - Hand - Tool A	Male
Manager/Engineer	Hand - Tool A - Tool B	Female
Manager/Engineer	Tool A - Tool B - Hand	Female
Manager/Engineer	Tool B - Hand - Tool A	Female
Manager/Engineer	Hand - Tool A - Tool B	Male
Manager/Engineer	Tool A - Tool B - Hand	Male
Manager/Engineer	Tool B - Hand - Tool A	Male
Technician	Hand - Tool A - Tool B	Female
Technician	Tool A - Tool B - Hand	Female
Technician	Tool B - Hand - Tool A	Female
Technician	Hand - Tool A - Tool B	Male
Technician	Tool A - Tool B - Hand	Male
Technician	Tool B - Hand - Tool A	Male

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Experimental Task

- ☹ Participants installed screws into the usability testing board

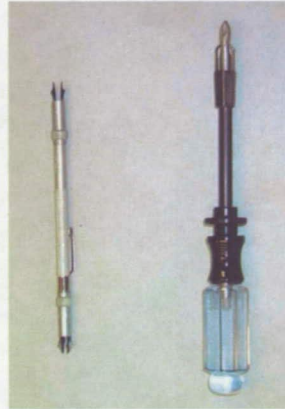


20

Experimental Task

⊗ 3 installation methods

- ⊖ By hand
- ⊖ Tool A
- ⊖ Tool B



Tool A

Tool B

21

Experimental Task

- ⊗ Each participant conducted 3 trials, one for each installation method
- ⊗ For each trial, 4 practice screws and washers were installed onto the testing board
- ⊗ Each participant installed 24 screws and washers for the actual trial
 - ⊖ 8 groups of three screws

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Apparatus

- ⊗ Testing Board
- ⊗ Equipment
- ⊗ Hand Postures Used with Testing Board

23

Testing Board Design

- ⊗ Developed checklist based on Boeing Study (Boeing (b), 2000), and interviews from subject matter experts in the areas of design, FOD control, and Human Factors.
- ⊗ Checklist was used for the design
- ⊗ Designed specifically for this test
- ⊗ Also designed to allow testing of a variety of conditions and to test new tools in the future.

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Testing Board

- ⊗ 30" X 40", made of ¼" aluminum,
- ⊗ Weighs less than 40 lbs
- ⊗ Holes in board
 - ⊖ Half are open
 - ⊖ Half have a floating (captive) 3/16" nut plate
 - ⊖ Floating nut plates commonly used with flight
- ⊗ Obstacles can be arranged to require various reaches



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Testing Board Use in Research

- ⊗ Testing board was placed on the ground.
- ⊗ Participants were required to put their hands through the armhole in the center of the board to insert the screws and washers from the back of the board.
- ⊗ Limited the visibility
- ⊗ The participants needed to deviate their wrists and hands in order to complete the task.
- ⊗ Required various awkward postures, such as kneeling, laying down, and twisting and turning the neck in order to install the parts. This is a common situation in the workplace.

26

Equipment

- ⊗ Two hand tools
- ⊗ #10-32 X .75 inch Phillips screws, #10 washers
- ⊗ A digital stopwatch
- ⊗ A small, portable tape recorder
- ⊗ A tape of a conversation that would be typically heard over a communication network.
- ⊗ clean room suits, nitrile gloves, boots, and head covers, which are worn in the clean room work environment in the Space Station Processing Facility

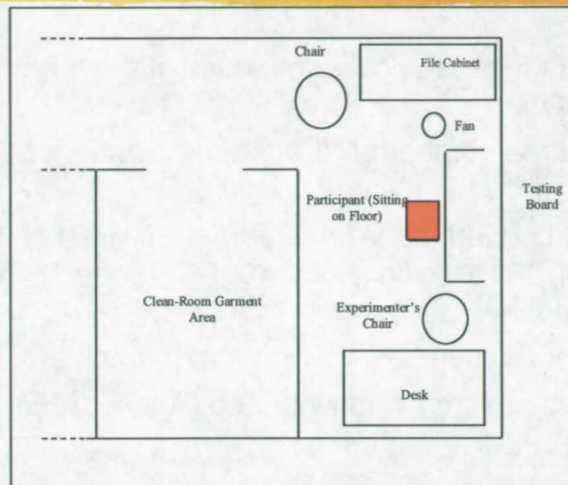
27

Procedure

- ⊗ Participants were greeted and taken into the testing room.
- ⊗ They were seated in a chair while they were read the instructions (Appendix A)
 - ⊖ Risk level
 - ⊖ Participants were free to leave at any time
 - ⊖ Consent form (Appendix B)

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Test Area Layout



29

Procedure (Con't)

- ⊗ Participants dressed in clean room suits, gloves, boots, and head covers.
- ⊗ Each participant completed 3 trials (One for each installation method)
 - ⊖ 4 practice installations
 - ⊖ 24 actual installations (8 groups of 3 holes)

30

Procedure (Con't)

- ⊗ Recorded the time to complete each of the 8 groups of three screws
- ⊗ Recorded the number of "drops", the number of "assists", and which part was dropped or assisted
- ⊗ Participants rated the level of perceived exertion based on a Borg CR10 Scale (Borg, 1998) after each group of 3 installations
- ⊗ Participant removed the clean room garments
- ⊗ Filled out a post test questionnaire (Appendix E).

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Hand Postures used with Testing Board

- ⊗ A variety of hand positions were required to complete the experimental task,
- ⊗ Common when working on space flight hardware.
- ⊗ The following photographs show the general hand positions that were used when installing screws by hand.
- ⊗ Wrist and hand positions varied
- ⊗ Only general comments can be made about wrist and hand deviation for each group.

32

Hand Postures Used with Testing Board

- ⊗ All positions required pinch force and repeated rotation while turning the screws.
- ⊗ To install the screws and washers, participants had to locate the hole, put the screw in the hole, turn the screw and release the screw.

33

Group 1 - Reach to the right (90° angle)

- ⊗ Reach forward through the armhole, and then reach to the right
- ⊗ Slight dorsiflexion at the wrist with flexed fingers
- ⊗ Challenging - most participants right handed



34

Group 2 - Reach to the left (90° angle)

- ☒ Straight wrist, and flexed fingers.



35

Group 3: Reach straight down (90° angle)

- ☒ This appeared to be the least stressful position
- ☒ Could reach down and keep the wrist in a fairly straight position, with flexed fingers



36

Group 4: Reach straight up (90° angle)

- ⊗ The wrist remained in a fairly straight position, with a slight ulnar deviation and flexed fingers
- ⊗ Some participants had to struggle to locate the holes, initially
- ⊗ Variety of body positions, which affected the hand posture greatly



37

Group 5: Reach to the right and around the obstacle (180° angle)

- ⊗ Palmar flexion of the wrist and strong finger flexion
- ⊗ Most people chose to look through the holes for groups 5 - 8 to help position the screw initially.
- ⊗ Caused the body posture to be bent forward with the head turned to the left.



38

Group 6: Reach to the left and around the obstacle (180° angle)

- ⊗ Palmar flexion at the wrist and strong finger flexion.
- ⊗ Participants often bent forward to look through the holes to help position the screws



39

Group 7: Reach down and around the obstacle (180° angle)

- ⊗ palmar flexion with a slight radial deviation, and strong finger flexion.
- ⊗ Holes harder to locate.
- ⊗ Put their heads on the floor to see through the hole if they chose to locate it visually.



40

Group 8: Reach up and around the obstacle (180° angle)

- ⊗ Easier to locate visually - near eye level
- ⊗ Significant palmar flexion with ulnar deviation was required to insert and turn the screws.



41

Other Hand Postures



Group 6, Tool A



Group 5, Tool A

42

Other Hand Postures



Group 5, Tool B



Group 2, Tool B

43

Results

- ⊗ Results
- ⊗ Discussion

44

Results

- ⊗ Analysis conducted to determine if there was a difference in the performance of the participants when they used three different installation methods

45

Objective Data - collected during the testing (2)

- ⊖ Average time for installation of each group of three screws
- ⊖ Number of parts that were dropped during installation
 - ⊖ Collected by type of part (Washer, screw or both)
 - ⊖ Captured number of "Assists"

46

Subjective Data - Post test Questionnaire (14)

- ⊖ Ranking - ease of use for the three installation methods,
- ⊖ Ranking - comfort
- ⊖ Rating of force required
- ⊖ Rating of comfort (hand, forearm, upper arm)
- ⊖ Rating - Tool Setup
- ⊖ Rating - Tool Release
- ⊖ Likelihood to drop
- ⊖ Perceived speed
- ⊖ Tool balance, shape, size, weight

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Hypothesis - Results

- ⊗ For each response a Friedman test was run using Minitab 13.0 to test the hypothesis:
 - ⊖ H_0 = probability that all three methods were equal
 - ⊖ H_1 = probability that at least two of the methods were different
 - ⊖ Friedman test chosen
 - ⊗ Compare relative value
 - ⊗ Small sample size

48

Table 2: Multiple Comparison Tests for the Differences Between Installation Methods (A = Tool A, B = Tool B, and H = Hand)

$\alpha = 0.10$					(*s show Sig. Difference)		
	Response	# Methods compared	Sample	Sample Size	A - B	A - H	B - H
During Test:	Avg. Time Per Group	3	All Participants	18			
	Avg. Time Per Group	3	Males	9			
	Avg. Time Per Group	3	Females	9			
	Avg. Time Per Group	3	Technicians	6			
	Avg. Time Per Group	3	Students	6			
	Avg. Time Per Group	3	Mgrs. / Engineers	6			
	Avg. # Drops	3	All Participants	18			
	Avg. # Drops	3	Males	9			
	Avg. # Drops	3	Females	9			
	Avg. # Drops	3	Technicians	6			
	Avg. # Drops	3	Students	6			
	Avg. # Drops	3	Mgrs. / Engineers	6			
	Exertion	3	All Participants	18			
Post Test:	#4. Easy/Hard Rank	3	All Participants	18			
	#5. Comfort Rank	3	All Participants	18			
	Force Required	3	All Participants	18			
	Hand Comfort	3	All Participants	18			
	Fore Arm Comfort	3	All Participants	18			
	Upper Arm Comfort	3	All Participants	18			
	Tool Setup	3	All Participants	18			
	Tool Release	3	All Participants	18			
	Tool Drop (Likelihood)	3	All Participants	18			
	Perceived speed	3	All Participants	18			
	Tool Balance	2	All Participants	18			
	Tool Shape	2	All Participants	18			
	Tool Size	2	All Participants	18			
	Tool Weight	2	All Participants	18			

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Conclusion

- ☹ There is sufficient evidence to reject H_0 ,
- ☹ Conclude that there is a difference in at least two of the installation methods for each of the 27 tests that were conducted (Mendenhall & Sincich, 1995).

50

Multiple Comparison Procedure

- ☒ Used to determine specifically which methods were different from each other (Daniel, 1990).

51

Table 2: Multiple Comparison Tests for the Differences Between Installation Methods (A = Tool A, B = Tool B, and H = Hand)

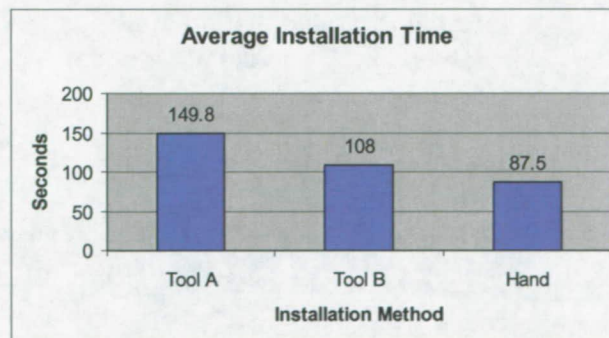
$\alpha = 0.10$					(*s show Sig. Difference)		
	Response	# Methods compared	Sample	Sample Size	A - B	A - H	B - H
During Test:	Avg. Time Per Group	3	All Participants	18	*	*	*
	Avg. Time Per Group	3	Males	9		*	
	Avg. Time Per Group	3	Females	9		*	
	Avg. Time Per Group	3	Technicians	6			
	Avg. Time Per Group	3	Students	6		*	
	Avg. Time Per Group	3	Mgrs. / Engineers	6		*	
	Avg. # Drops	3	All Participants	18	*	*	
	Avg. # Drops	3	Males	9	*	*	
	Avg. # Drops	3	Females	9	*		
	Avg. # Drops	3	Technicians	6	*		
	Avg. # Drops	3	Students	6	*		
	Avg. # Drops	3	Mgrs. / Engineers	6	*		
	Exertion	3	All Participants	18	*		
Post Test:	#4. Easy/Hard Rank	3	All Participants	18	*	*	
	#5. Comfort Rank	3	All Participants	18	*	*	
	Force Required	3	All Participants	18	*		
	Hand Comfort	3	All Participants	18	*	*	
	Fore Arm Comfort	3	All Participants	18	*		
	Upper Arm Comfort	3	All Participants	18	*		
	Tool Setup	3	All Participants	18	*	*	
	Tool Release	3	All Participants	18	*	*	
	Tool Drop (Likelihood)	3	All Participants	18	*	*	
	Perceived speed	3	All Participants	18	*	*	
	Tool Balance	2	All Participants	18	*		
	Tool Shape	2	All Participants	18	*		
	Tool Size	2	All Participants	18	*		
	Tool Weight	2	All Participants	18			

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Graphical Presentation of Subjective Data

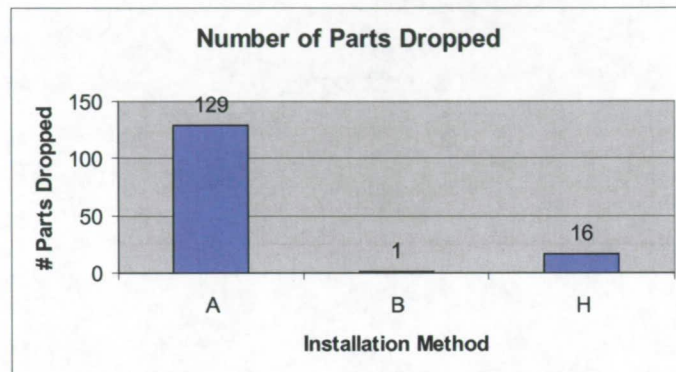
53

Average Time to Install 3 Screws into each Group



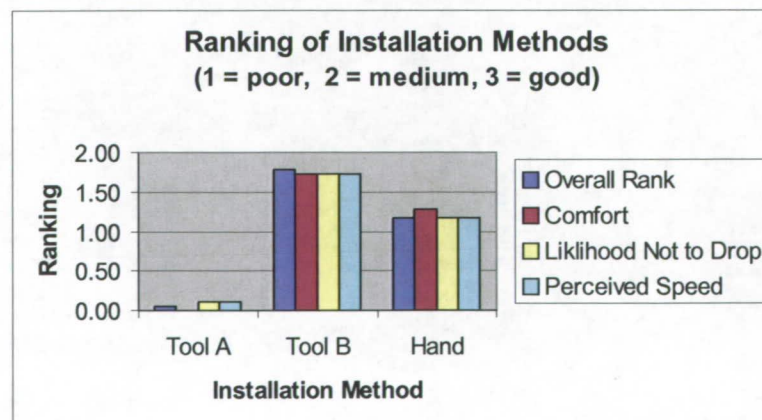
54

Number of Parts Dropped



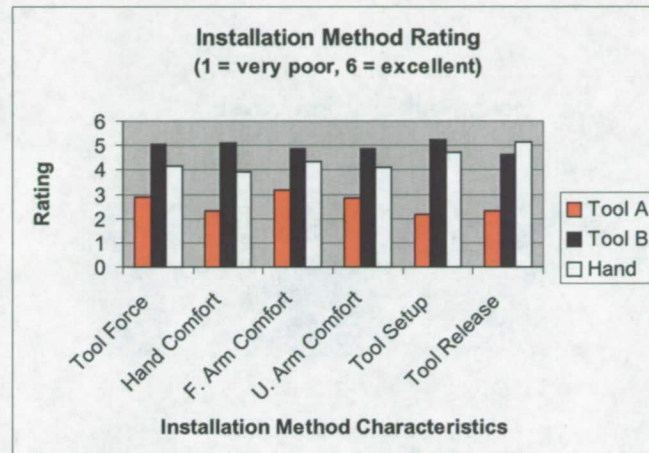
55

Ranking of Installation Methods



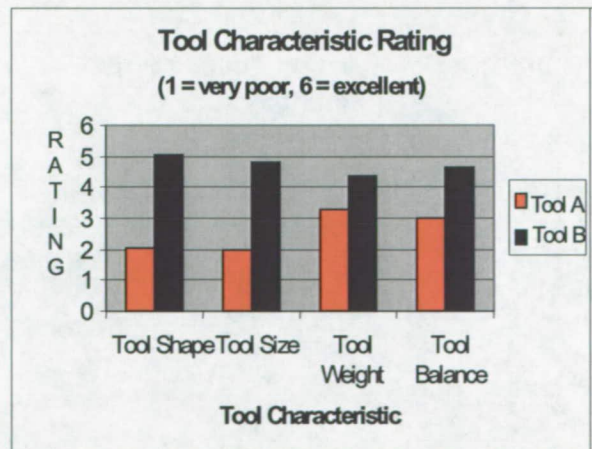
56

Installation Method Rating



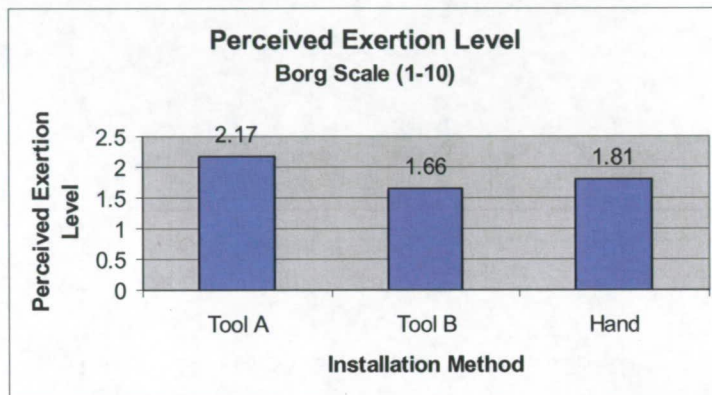
57

Tool Characteristic Rating



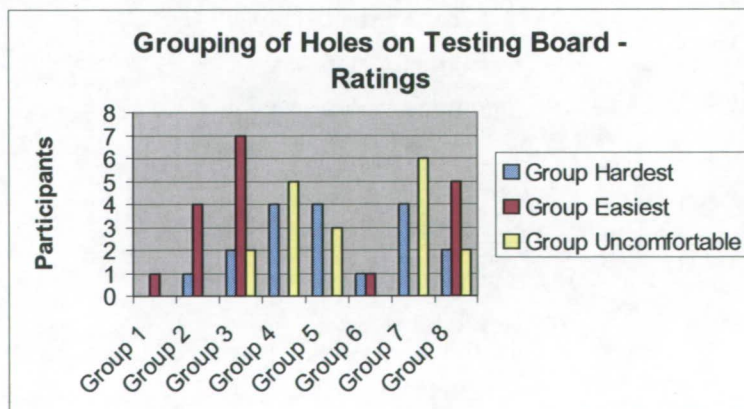
58

Perceived Exertion Level - by Installation Method



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Grouping of Holes on Testing Board - Ratings



60

Test of Hypothesis for proportion - Drops

- ⊖ H_0 : Performance of B $\leq$ A; $p \leq 0.5$
- ⊖ H_1 : Performance of B $>$ A; $p > 0.5$
- ⊖ p = proportion where B performs better than A

- ⊖ H_0 : Performance of H $\leq$ A; $p \leq 0.5$
- ⊖ H_2 : Performance of H $>$ A; $p > 0.5$
- ⊖ p = proportion where H performs better than A

- ⊖ H_0 : Performance of H $\leq$ B; $p \leq 0.5$
- ⊖ H_3 : Performance of B $>$ H; $p > 0.5$
- ⊖ p = proportion where H performs better than B

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Sample Calculation of proportion - Drops

Total Drops All Participants	Performance		
	B > A	H > A	B > H
S001	1	1	0
S002	1	1	1
S003	1	1	1
S004	1	1	(1)
S005	1	1	1
S006	1	1	0
ME001	1	1	1
ME002	1	(1)	1
ME003	1	1	0
ME004	1	1	0
ME005	1	1	0
ME006	1	1	0
T001	1	1	0
T002	1	1	0
T003	1	1	0
T004	1	1	0
T005	1	1	1
T006	1	0	1
Total # 1's	18	16	7
p^*	1.00	0.89	0.39

For B > A, $p > 0.5$, Reject H_0 , Accept H_1
Performance of B is better than A

For H > A, $p > 0.5$, Reject H_0 , Accept H_2
Performance of H is better than A

For B > H, $p < 0.5$, Fail to reject H_0
Not enough evidence to show difference

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Hypothesis Test for proportion - Time

- ⊗ H_0 : Performance of B $\leq$ A; $p \leq 0.5$
- ⊗ H_1 : Performance of B $>$ A; $p > 0.5$
- ⊗ p = proportion where B performs better than A
- ⊗ H_0 : Performance of H $\leq$ A; $p \leq 0.5$
- ⊗ H_2 : Performance of H $>$ A; $p \leq 0.5$
- ⊗ p = proportion where H performs better than A
- ⊗ H_0 : Performance of H $\leq$ B; $p \leq 0.5$
- ⊗ H_3 : Performance of H $>$ B; $p \leq 0.5$
- ⊗ p = proportion where H performs better than B

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Calculation of proportions - Time

Response	Sample	Sample Size	Performance		
			B > A	H > A	H > B
Avg. Time Per Group	All Participants	18	*	*	*
Avg. Time Per Group	Males	9	*	*	*
Avg. Time Per Group	Females	9	*	*	*
Avg. Time Per Group	Technicians	6	*	*	*
Avg. Time Per Group	Students	6	*	*	*
Avg. Time Per Group	Mgrs. / Engrs	6	*	*	*
Total			6	6	6
# times Performance matches H_0			6	6	6
$\hat{p}$			1	1	1

* Indicates the performance matches the prediction, as listed in row one.

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Hypothesis Test -

- ⊗ H_0 : Performance of $B \leq A$; $p \leq 0.5$
- ⊗ H_1 : Performance of $B > A$; $p > 0.5$
 - ⊖ p = proportion where B performs better than A
- ⊗ H_0 : Performance of $H \leq A$; $p \leq 0.5$
- ⊗ H_2 : Performance of $H > A$; $p > 0.5$
 - ⊖ p = proportion where H performs better than A
- ⊗ H_0 : Performance of $H \leq B$; $p \leq 0.5$
- ⊗ H_3 : Performance of $B > H$; $p > 0.5$
 - ⊖ p = proportion where B performs better than H

65

Calculation of proportion - Subjective Data

Response	Sample	Sample Size	Performance		
			B > A	H > A	B > H
Avg.# Drops	All Participants	18	*	*	
Avg.# Drops	Males	9	*	*	
Avg.# Drops	Females	9	*	*	
Avg.# Drops	Technicians	6	*	*	
Avg.# Drops	Students	6	*	*	
Avg.# Drops	Mgrs. / Engrs	6	*	*	*
Exertion	All Participants	18	*	*	*
#4. Easy/Hard Rank	All Participants	18	*	*	*
#5. Comfort Rank	All Participants	18	*	*	*
Force Required	All Participants	18	*	*	*
Hand Comfort	All Participants	18	*	*	*
Fore Arm Comfort	All Participants	18	*	*	*
Upper Arm Comfort	All Participants	18	*	*	*
Tool Setup	All Participants	18	*	*	
Tool Release	All Participants	18	*		
Tool Drop (Likelihood)	All Participants	18	*	*	*
Perceived speed	All Participants	18	*	*	*
Tool Balance	All Participants	18	*		
Tool Shape	All Participants	18	*		
Tool Size	All Participants	18	*		
Tool Weight	All Participants	18	*		
Total			21	16	16
# times Performance matches H_0			21	16	10
p^*			1	1	0.625

* Indicates the performance matches the prediction, as listed in row one.

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Boeing Study

- ⊗ Opinion Survey conducted by Boeing (2000)
 - ⊖ Gather information on FOD that is generated by small parts
 - ⊖ Current small parts storage containers and tools
 - ⊖ 56 respondents (technicians (69%); Quality inspectors (18%); Engineers (10%); Task Leader
 - ⊖ Believe that dropping parts is the second largest contributor (12%) to FOD when handling small parts

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Boeing Opinion Survey

- ⊗ Small Parts lost most often
 - ⊖ During installation (73%)
 - ⊖ Small parts are usually lost by being dropped (85%)
 - ⊖ Cause the most trouble when being installed:
 - ⊖ Washers (43%)
 - ⊖ Nuts (25%)
 - ⊖ Screws (13%)

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Boeing Products

- ⊗ Developed prototype for new hand tool
- ⊗ Developed concept for new small parts container
- ⊗ Conducted a usability test based on the methodology & hardware from this research

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Conclusions

- ⊗ Summary
- ⊗ Areas for Future Research

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Summary

- ⊗ Research accomplished the objectives:
 - ⊖ Develop a methodology & hardware for conducting usability testing for hand tools,
 - ⊖ with the goal of reducing FOD

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Areas for Future Research

- ⊗ Incorporate technician suggestions to make it even more realistic
 - ⊖ Hard floors
 - ⊖ More interruptions
 - ⊖ Various lighting conditions
- ⊗ Develop a shorter methodology for less formal testing in early design phase
- ⊗ Continue the development, testing and approval of the Boeing hand tool to be used on flight hardware

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More Areas for Future Research

- ⊗ Participants varied greatly in the hand postures that they used. Conduct related evaluations to determine which hand postures were least likely to cause injuries.
- ⊗ Design training plans teach these postures
- ⊗ Use similar testing methodology and hardware to develop hand tools that can be used on long duration space missions.
- ⊗ Limited amount of research for conducting usability evaluations on hand tools. None focus on reducing FOD.
 - ⊖ Continuing with similar research has potential to produce practical results, which could ultimately save lives.

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