Abstract

BAJAJ, KOMAL - Redesign and evaluation of the grocery store Self-Checkout Systems from Universal Design perspectives. (Under the direction of Dr. Gary A. Mirka)

Each one of us is physically challenged at some point in life. Old age, extreme statures (short or long, thin or fat), or some accident might produce conditions wherein we are unable to continue our work like we normally do. So it is in the best interests of everyone to design a product that accommodates the needs of all of its users. Being ergonomists, our task is to assess the existing products and services, showing where and how they fail to 'fit' the user (in every sense of the word) and suggest ways to improve the fit in order to make the products and services safer, more comfortable and more productive for the whole range of people who use them – including children, the elderly and the disabled. "Universal design is the design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design"- Ron Mace (1994). In this sense, the two fields – Ergonomics and Design – merge.

In the summer of 2002, while interning with the Center for Universal Design, Raleigh, NC, I had the opportunity to get involved in a focus group study of the recently emerged grocery store Self-Checkout Systems (SCO's). People with various kinds of disabilities – mobility, hearing, vision, perceptual and cognitive disabilities – were asked to perform the process of Self-Checkout (SCO) in actual grocery stores. Although no quantitative variables were analyzed in that study, it was observed that the SCO's were far from being usable by the disabled population. Thus, emerged the idea of applying my knowledge of ergonomics to the redesign of one of the most prevalent models of the SCO

(the U-Scan Express) so that the redesigned system is more 'universally' acceptable than the existing system. Because of time and resource constraints, the redesign focused on the accessibility for wheelchair users and non-wheelchair users from the physical perspective considering ergonomic factors such as fit, reach, posture etc.

Two prototypes – one of the conventional SCO and another of a redesigned version – were built in the Ergonomics Laboratory at North Carolina State University. Fifteen subjects – five wheelchair users and ten non-wheelchair users – were asked to simulate the process of self-checkout on the two different workstations. The workstations were evaluated on the basis of productivity, posture and users' subjective feedback.

Results indicate that productivity was not significantly affected across workstations, for either of the two user groups. Posture was significantly improved across workstations for both the groups. Shoulder posture was significantly improved for both the groups –a maximum shoulder angle reduction of 64% for wheelchair users and 69% for non-wheelchair users was recorded. Trunk posture was significantly improved for wheelchair users with a maximum trunk angle reduction of 66.5% while for the non-wheelchair users, the trunk flexion angle did not significantly increase. Subjective feedback from both the groups showed a preference for the new design in terms of ease, accuracy, quickness and overall preference although, the preference was higher for the wheelchair group than the non-wheelchair group. The average scores of both the user groups on 'willingness' in using the redesigned system in preference to the existing system were also above neutral – all five of the wheelchair users and 8 out of 10 of the non-wheelchair users responded with a score above neutral for willingness. Thus, it was concluded that the redesigned SCO would be more 'universally' acceptable than the conventional/existing SCO.

Redesign and Evaluation of the grocery Store Self-Checkout Systems from Universal Design Perspectives

By

Komal Bajaj

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Dedication

The fact that I have written this thesis could not have been a fact had I not been fortunate enough to have parents and family like mine. In India, girls generally don't get as much liberty as boys do but my parents probably gave me even more. My parents and my sister supported me (at times willingly, at times reluctantly) in whatever I decided to do. It is only because of their stalwart support in all aspects - emotional, physical, financial – that I have been able to realize my dreams, goals and ambitions and continue to build them up. It is said that one good thing leads to another. My sister and my parents stood by me through all odds and helped me achieve what I had sought out to achieve. Because of this, today I carry with myself the belief and faith, that in life, anything is possible and so, be not afraid to dream and think big. In essence, they gave me wings to fly. I hereby, dedicate this work of mine to these three most precious persons in my life.

To Sonu di, alias Kiran – my sister, my confidanté, my best critic – for cultivating my interest in reading, for teaching me the meaning of commitment and honesty (with my own self, my work and my relations), showing me the joy of welcoming life with an open heart, mind and soul and above all, believing in me when I myself had started questioning my abilities.

To Mummy and Papa – Mrs. Kamal Bajaj and Mr. S.L.Bajaj – my mother for teaching me that the one thing you can ask from God, which encompasses everything we desire from life, is to give peace and happiness to everyone; never before had I realized that there could be such a simple formula to happiness. She also taught me the virtue of patience and perseverance. To my father, an Electrical Engineer by profession, who showed me by his own example, that in order to strike it big, one must not be afraid to take risks in life; my father quit his job to establish his own business and my mother fully supported him in doing that. From him I learnt that if you do not acknowledge failures then there is no failing; that success and failure, profit and loss, winning and losing are all part and parcel of life and so you should treat them all just the same. What is important is to never stop working. Looking at my father working in his factory, I developed an immense respect for the engineering profession and was thus inspired to become an engineer myself.

Biography

Komal was born on November 18, 1977 in a small city, Jalandhar, in the agriculturally prosperous state of Punjab in North India. She is the youngest of the three daughters of Mr. S.L.Bajaj and Mrs. Kamal Bajaj. Her father is an Electrical Engineer and runs his own small industry, manufacturing transformers, in Jalandhar. Her mother is a house lady and assists her father in work. Her eldest sister, Kiran, is a multifaceted person, having earned degrees in Fashion Designing, Visual Merchandising and Fitness Training.

She was nine when, inspired by her father, she decided to become an engineer. After completing her tenth grade with 90% from St. Joseph's Convent School in Jalandhar, she got admission in the prestigious Delhi Public School, R.K. Puram in New Delhi for her high school education. She completed her Bachelor's in Industrial Engineering from Shaheed Bhagat Singh College of Engineering and Technology, Ferozepur, Punjab. During this time, she worked as an Industrial Engineer trainee with BPL Ltd., Noida for six months. It was there that her projects in Work Study and Time Study triggered her interest in Ergonomics. She wanted to integrate the field of Ergonomics and Industrial Design. To pursue her interests, she came to North Carolina State University to join the Masters program in Industrial Engineering specializing in Ergonomics with a minor in Industrial Design. Here, she worked as a Research Assistant for Dr. Carolyn Sommerich for one year and Dr. Gary Mirka for another. She also interned with the Center for Universal Design, Raleigh during the summer of 2002.

Her fields of interest are Ergonomics and Design. Outside of her career, she enjoys dancing, traveling, swimming, tennis and reading.

Acknowledgement

I used to wonder – what moves the world? I think I have a vague understanding of this now. It is people who believe in productive achievement. I am happy and feel fortunate to have met such people in my life. One thing you realize when you sit to think about the influence that people and things have in your accomplishment of a task like this is that there is no way you can ever 1) thank them all and 2) thank them enough. Acknowledgement is the least I can do to express the immense gratitude, reverence and sincerity I feel towards everyone who helped me in completing my work, for it is not just about completing my work but about shaping my whole value system, my convictions, my perceptions of this world and the people in it and my idea of life in general that have been influenced by coming in contact with them.

First and foremost, I would like to thank (and 'thank' would be an understatement) Dr. Gary Mirka, the chairperson of my advisory committee who is also my idea of an absolute human being, for his constant support, motivation and an extremely positive influence on my life. He is the kind of person who enthuses you with a very positive energy and attitude towards any task you wish to undertake and helps you through to the end. There is absolutely no way in which I could have completed this work without his guidance and support.

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I would like to acknowledge the support of my parents and my sister, who never stopped believing in me. Although they are geographically far from me, just talking to them helps me through my tough times.

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Then I would like to acknowledge a person and few things not immediately related with this thesis but who (or which) have a special place in my life. Among things, my car (for driving me to the lab and back without fail, without questions, without ever getting irritated with my odd timings), my laptop for never hanging up on me in my crucial times, our lab (for offering me a quiet place to work at all times) and my corner workstation in the lab.

And last, but not the least, thanks Yojan, for giving me some of the most cherishable memories of my life.

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What has truly changed is the role that technology plays in people's lives: first wonder, then comfort carrier, now technology is a way of being.

1 Introduction

Being 'high tech', today, is somewhat a primary necessity just as eating bread or drinking water. It is no longer something special or a new attractive quality that could, alone, inspire consumers to purchase. It has to be there and at the highest level of performance, but something extra needs to be offered to differentiate one's product from the thousands of others that feature the same performance and functionalities.

How can then companies retain (or gain!) competitive edge in a market characterized by price erosion and saturation? How can they respond to the challenge of keeping leadership in the 'no needs' market? Is technology push the answer to the challenge? No. It is just a repetition of the conventional way of doing things, which sooner or later will stop providing the desired results because, over the years it has become evident that adding too many functionalities to a product can actually be counterproductive. The usability of a product with too many functionalities can, in fact, become so complicated so as to make the extra function/s totally useless (FORM, 2002).

Of course technological innovations continue to create value, but they are no longer the sole qualities that persuade consumers to purchase or use a product. Rather, people are experiencing some sort of confusion in front of the ever-increasing amount of gadgets and functionalities they are faced with. Can design, then, play a role in making technology less intimidating, more friendly, more human, more inviting and more usable to the user? Presented below are a few concepts in design, which go in favor of this speculation.

1.1 User Centered Design (UCD)

The term User Centered Design (UCD) is a philosophy as well as a strategy. It is a philosophy that places the user (as opposed to the 'thing' or product) at the center of the design process. It is a strategy that follows the 'out-in' route–starting out from the end user of the product and converging all his/her needs to meet in the product.

User Centered Design (UCD) seeks to answer questions about users and their task goals, then use the findings to drive development and design. It is '*designing of the experience*'- a philosophy that is built upon the idea that people no longer need irons or coffee makers or sofas; What they actually need are pressed shirts, hot coffee, and comfortable seating to relax.

UCD seeks to answer questions such as (Katz-Haas, 1998):

- Who are the users of the product?
- What do the users want the product to do for them?
- What are the user's experience levels with the product and things like it?
- In what sort of environment will the users be using the product?
- What information might the users need to use the product?
- How do the users think the product should work?

By seeking answers to such questions and incorporating them into design of the product, UCD can improve the *usability* and *usefulness* of everything from 'everyday things'

(Norman, 1988) to software to information systems to processes – anything with which people interact. As such, UCD concerns itself with both '*usefulness'* and '*usability*'.

Usefulness: It relates to *relevance* i.e. whether the functions, information, etc., match with what the user actually needs or expects from the product.

Usability: It relates to the ease-of-use i.e. how easy or intuitive is the use of the product to the user.

Thus, UCD, in microcosm, means *designing things for people.*

1.2 Design For All (DFA)

Design is far more than mere styling. Not only the aesthetics of design have evolved in the last years, but the very meaning of the interaction between people and technology has changed, and thus has design. A successful product is one which provides anthropologically relevant solutions, one which caters to the different needs of different people.

The traditional approach to this issue has seen the vast majority of products developed for the 'average' and 'able-bodied' population. One aspect of this issue is the way in which data is presented in percentiles. The percentile is a univariate statistic which refers to only one characteristic in isolation telling us little or nothing about other body dimensions. As such product design for a typical range of population might consider 5^{th} percentile female stature to 95^{th} percentile male stature. It would seem that the chosen range covers 90% of the population but in reality, an x^{th} percentile has poor correlation between dimensions and therefore, the design might not cater to tall people with relatively short arms or short people with relatively long legs, for example. To exacerbate this problem an increasingly large proportion of the global population is disabled or has functional limitations due to injury, illness or ageing. The special requirements of these people are then left to individual customizations for individual types and degrees of impairment. The Design For All philosophy aims at accommodating this population also.

Design For All is a holistic approach focused on product accessibility and usability aimed at providing products that meet the requirements of a larger proportion of the population. Such products would incorporate features that accommodate and appeal to able-bodied users and those who are older or disabled, significantly reducing the need for bespoke designs and individual customizations (Marshall, et al., 2001).

1.3 Universal Design

Universal Design strives to integrate all people, including those with disabilities, the elderly and children into population data for ergonomic design. Some changes required to accommodate the disabled actually benefit the whole population. And, they can be achieved relatively inexpensively with a little forethought ('Dezignare Interior Design Collective' article).

Universal design is the design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design (Mace, 1994). The intent of universal design is to simplify life for everyone by making products, communications, and the built environment more usable by as many people as possible at little or no extra cost. Universal design benefits people of all ages and abilities. There are seven basic principles of Universal Design as established by the Center for Universal Design, Raleigh, NC. They are described below:
(http://www.design.ncsu.edu:8120/cud/univ_design/princ_overview.htm)

Principle 1. **Equitable Use**: The design should be useful and marketable to people with diverse abilities. It should provide the same means of use for all users; Identical whenever possible; Equivalent when not. Take for example a door handle: It should be designed in such a way that all the people with their different abilities should be able to use it to open or close a door. When the handle is not suitable for use by some people, there should be an equivalent substitute present to facilitate opening or closing of the door, e.g. push buttons for wheelchair access.

Principle 2. **Flexibility in Use**: The design should accommodate a wide range of individual preferences and abilities. It should provide choice in methods of use, accommodate right- or left-handed access and use, facilitate the user's accuracy and precision and provide adaptability to the user's pace.

Principle 3. **Simple and Intuitive Use**: Use of the design should be easy to understand, irrespective of the user's experience, knowledge, language skills, or current concentration level. This means that the design should be consistent with user expectations and intuition and accommodate a wide range of literacy and language skills.

Principle 4. **Perceptible Information**: The design should communicate necessary information effectively to the user, regardless of ambient conditions or the user's sensory abilities. This means that it should use different modes (pictorial, verbal, tactile) for redundant presentation of essential information, provide adequate contrast between essential and redundant information and provide compatibility with a variety of techniques or devices used by people with sensory limitations.

Principle 5. **Tolerance for Error**: The design should minimize hazards and the adverse consequences of accidental or unintended actions. Therefore, the design should arrange elements to minimize hazards and errors: most used elements, most accessible; hazardous elements eliminated, isolated, or shielded. It should also provide warnings of hazards and errors.

Principle 6. **Low Physical Effort**: The design should be used efficiently and comfortably and with a minimum of fatigue by all people. Therefore, it should provide for use in neutral body position, use reasonable operating forces, minimize repetitive actions and minimize static postures for long time intervals.

Principle 7. **Size and Space for Approach and Use**: Appropriate size and space should be provided for approach, reach, manipulation, and use regardless of user's body size, posture, or mobility. Therefore, the design should make reach to all components comfortable for any seated or standing user, accommodate variations in hand and grip size and provide adequate space for the use of assistive devices or personal assistance.

Interior designers often utilize these principles in a variety of ways including the proper layout of furniture and equipment, handicap accessibility in commercial or public facilities, special equipment needs in healthcare, retail, and other commercial venues, as well as, lighting, furnishings, ergonomic workstations, proper flooring and more.

1.4 The Role of Ergonomics in Design

Most people who have heard of ergonomics have the general idea that it is something to do with seating or with the design of car controls and instruments. It is. But it is much more! Ergonomics is the application of scientific information concerning humans to the design of objects, systems and environment for human use. In essence, Ergonomics is 'fitting the job to the man' (Grandjean, 1988).

People come in all shapes, sizes and vary in abilities, needs, initiatives, dexterity, intelligence, visual acuity, imagination, determination, upper back strength, age, leg length, etc. The task of ergonomists is to take this variability into account while influencing the design of products or services for people who use them. Even the simplest of products can be a nightmare to use if poorly designed. That is why it is important that designers of products adopt an ergonomic, user-centered approach to design by studying people and their relationship with the product. This is especially important with 'inclusive design' where everyday products are designed with older and disabled users in mind, excluding as few users as possible. This is where ergonomics integrates with design, especially Universal Design.

Ergonomists work to improve the quality of our lives, increase our safety and enhance performance by providing solutions for workstations, tools, equipment, protective wear, cleanliness and worker well-being. Ergonomic programs help management identify hazardous conditions, provide training, analyze data, establish prevention control measures and evaluate progress. Specialties have developed in the field to include Physical Ergonomics and Cognitive Ergonomics.

Cognitive ergonomics, or human factors engineering, is concerned with the user's mental understanding of a system and their ability to effectively function within it. An example of this is seen in aviation. It is important that the displays and controls of an airplane cockpit are situated such that the pilot can successfully navigate a plane by obtaining the necessary information without making critical errors. While there are certainly important cognitive factors to consider in ergonomic, user-centered design, the main focus of the current work is in physical accommodation and therefore, more emphasis is placed on that aspect in the following sections.

1.4.1 Physical Ergonomics

Physical ergonomics focuses on the way the human body works within a system in order to develop working environments conducive to their physical well-being. An example of this would be the design of keyboards such that they position the wrist in a comfortable and safe working posture even with the repetitive motions involved in keyboarding. An important component of conducting physical ergonomics studies is anthropometry.

1.4.1.1 Anthropometry

Anthropometry is defined as the measurement of human body and its biomechanical characteristics (Adams, 1989). Biomechanical refers to the mechanical (machine-like) capabilities of the human musculoskeletal system. Thus, this field measures our sizes and how we move easily. Anthropometric data permit the designer to design to fit the individual; Design to include as large a population as possible i.e. minimize the number of people excluded by the design (Konz, 1990). There are two basic types of anthropometric measurements – 1) static anthropometric measurements and 2) dynamic or functional anthropometric measurements.

1.4.1.1.1 Static Anthropometry

Static anthropometric measurements are measures of the physical dimensions of the human body often used to determine the size and spacing requirements of work space, e.g. standing height, weight, wing span, seat to elbow height, etc. Most existing anthropometric data on U.S. adults comes from the U.S. military personnel but this data cannot be applied to accommodate the disabled population. In collecting the static anthropometry of the disabled population, challenge is faced in determining the body landmarks and measurement procedures. Goswami (1997) examined six international studies of people with lower limb disorders and discovered that, for a combined total of 58 body size descriptors measured in the studies, not a single dimension was found in common. Goswami also could not find a single study that attempted to standardize either body landmarking or measurement procedures.

1.4.1.1.2 Functional Anthropometry

Dynamic or functional anthropometric measurements quantify the dynamic properties and capabilities of an individual, simple examples of which include strength and endurance. These measures are often used to match the dynamic characteristics of controls to user. Examples of such measures include range of motion of various joints, force of leg pushes, etc. Bradtmiller and Annis (1997) compiled seven separate studies of people with disabilities and compared workspace dimensions obtained from that to workspace dimensions obtained from a study conducted on the U.S. Army personnel; they found that the group with disabilities showed as much as twice the variability of the non-disabled sample in most cases. One reason for this has been attributed to the great number of disabilities, which, in turn, can cause a wide variety of changes in body size, posture as well as function. Anthropometry data so far collected on groups with disabilities involves specialized populations (Damon and Stoudt, 1963; Goswami et al., 1987; Molenbroek, 1987), and therefore has limited application for federal agencies that must concern themselves with the general U.S. population of individuals with a wide variety of disabilities.

There are various sources available on anthropometric data – Humanscale (Diffrient et al., 1974), Bodyspace (Pheasant, 1986). In order to apply the available data, it is important to know the population for which the data will be used, because different groups of people have different anthropometry – women are different than men, Asians are different than Americans, older people have different physical characteristics than adolescents and certain groups of disabled people have different anthropometric characteristics than the able bodied. Thus in the following two sections we see the role that ergonomics has played for the able-bodied, as well as the disabled.

1.5 Ergonomics for the "able-bodied"

Throughout the ages we have seen environmental accommodation for humans playing its role in the design of products and environments. Beginning with the prehistoric tools fashioned as an extension of the hand, continuing with bows designed for the strength of the hunter, to the arrows whose length was determined by the draw of the bow, good design has always taken into account the needs of the user. Adaptation continued with Pakistani war chariots whose wheel spacing was almost identical to the standard wagon track and early railroad gauge. Body parts continued to be used by the ancient Egyptians when designing beds and boats and, in the Middle Ages to determine the seat height.

With the advent of the machine age, the machine took priority over the user, until World War II when the Department of Defense accumulated and issued human factors standards for designing the more complex war machines, then in use. Human Engineering continued to be used primarily by the military until the 1960's when the U.S. Department of Health, Education and Welfare published "Weight, Height and Selected Body Dimensions of Adults" (Stoudt et al., 1965).

Today ergonomics has developed into a science concerning itself with human beings and how we function in conjunction with a wide variety of equipment, products, methods and circumstances. It insures that products or services are safe, easy to use and efficient. Ergonomics studies physical attributes such as size, weight, height, strength, skill, speed and sensory abilities, along with thermal comfort, motion, vibration, posture and workload in order to increase performance, prolong endurance and reduce accidents. Ergonomics encompasses all human activity and relies on research and data of a wide variety of disciplines including Anthropometrics, Engineering, Biomechanics, Environmental Physics, Body Systems, Physiology, Applied Psychology and Social Psychology.

1.6 Ergonomics for the "differently-abled"

The 1970s saw the automotive industry compile data on children from infancy through the age of eighteen to increase safety, and the 1980's recognized the elderly as an increasing portion of the population with specific data collected on the body dimensions of the aged; reason being that with advances in medicine and rehabilitation techniques, and rapid proliferation of technology, increasing number of persons, with a wide variety of disabilities entered the mainstream of American life. The elderly, arbitrarily defined as those 65 years and above, began to be recognized as a distinct subgroup with special human factors needs; them being significantly smaller in stature and in many other body dimensions than the general population (Stoudt, 1981) and their needs, intent on maintaining independence, in many ways, mirroring the needs of people with disabilities. Yet, a study at the University of Virginia's Rehabilitation Engineering Center revealed that the information from people without disabilities is not directly applicable as design parameters for the majority of people with disabilities (Chung and Weimar, 1989).

Thus, the concept of *'Barrier-Free Design'* developed during the Civil Rights and Disability Rights Movements by those trying to prevent discrimination against people with disabilities. Physical barriers were recognized as a hindrance to a person's freedom. The 1990's finally acknowledged the special needs of the differently-abled and prohibited discrimination on the basis of disability through the enactment of the Americans with Disabilities Act (ADA) *(Public Law 336 of the 101st Congress, enacted July 26, 1990).*

1.6.1 The American with Disabilities Act (ADA)

This landmark piece of legislation recognizes the rights of Americans with disabilities to work, travel and do business in all public facilities. Barriers that had previously prevented people with disabilities from gaining access to offices, schools, airports, libraries and courthouses, to name a few, began to come down, thanks to the codification of ADA Accessibility Guidelines (ADAAG, latest amended 2002).

The ADA guidelines are found in 28 CFR 36 of the code of federal regulations. These guidelines encompass a wide range of built places and environments to accommodate wheelchair users e.g. protruding objects, ground and floor surfaces, parking and passenger loading zones, curb ramps, stairs, elevators, platform lifts, wheelchair lifts, windows, doors, entrances, automatic teller machines, etc. But these guidelines are not standards. The first publication of the guidelines was in 1991 and since then they have not changed much. This points out why there is a need for something even more standardized than these guidelines that could be applicable in designing for accessibility and use by all, including wheelchair users; ADAAG standards no longer suffice to ensure the accessibility they were meant to provide for a number of reasons. For one thing, many of the original standards were in all likelihood, based on seated measurements of adults without disabilities (Kristensen and Bradtmiller, 1997).

1.6.2 Existing research on the Anthropometrics of Disability

In light of the fact that design professionals, consumer's rights advocates and government officials concerned with accessible and universal design are seeking more reliable data on anthropometrics in a form that they can use more effectively and efficiently, the Rehabilitation Engineering Research Center (RERC) on Universal Design at the School of Architecture and Planning at The State University of New York at Buffalo published a report on the Anthropometrics of Disability for the U.S. Access Board, Washington, D.C. in February 2002. The report was the outcome of a three day international conference held in Buffalo, NY, between May 31 and June 2, 2002, bringing together experts in the field of anthropometry and anthropometric issues related to people with disabilities.

The report sheds light on the major issues that need to be addressed in the field of anthropometry of the disabled population. It demonstrates the gap that exists between the need for knowledge and accurate reliable databases to address the anthropometry of the disabled population. Available databases are not providing the information that policy makers and designers need in a form that is easy to use. Even the U.S. Access Board, which has long relied on the findings of anthropometric studies in developing the ADA Accessibility Guidelines, has expressed the lack of a usable database on the characteristics of people with disabilities applicable to the conflicting needs of a broad range of users with little anthropometric commonality and emerging new conditions. As it enters a new research and rulemaking decade, the U.S. Access Board finds itself questioning the usefulness of human factors studies in determining parameters for building and facility design and is actively seeking approaches that may be more appropriate for a technological age (Thibault, 2001).

Computer human modeling is a rapidly advancing technology that offers significant potential benefits for analysis of accommodations for people with disabilities in general, and specifically wheelchair users (Roebuck, 2001). However, realization of such benefits requires adaptations and new developments that incorporate the special attributes of users with disabilities, particularly in regard to engineering anthropometry (Roebuck, 2001). The existing anthropometric and biomechanics databases pose limitations in the development and use of 3-D human modeling CAD systems, especially when designing for people who are older or have disabilities. The limitations arise from the fact that the designers need data that is relevant to the individual, the task and the environment simultaneously (Porter, 2001) and none of the existing models provide all this information simultaneously.

There is a tremendous variation in the terminology and definitions related to clinical measures of a wheelchair-seated individual. Standard definitions and terms are lacking for measuring and communicating critical postural information in a way that is uniformly useful to service providers, researchers, manufacturers and wheelchair users themselves (Hobson, 2001). In a study conducted by Ewa Nowak, the methods of determining arm reach zones were reviewed and evaluated in terms of their usability for the needs of shaping the life and work environment of people with disabilities. The methods can be divided into two groups – measurement of reach envelope using a 3-D reference system and determining reach envelopes mathematically using measurements of body links. The challenge for anthropologists, engineers and designers is to develop a method that is easier to use with people who have disabilities and also precisely estimates their reach envelopes (Nowak, 2001). We cannot rely on data from able-bodied people as a substitute for data on people with disabilities. The problem is aggravated by the fact that the data currently at the disposal of designers does not adequately reflect the characteristics of most people with disabilities, who tend to be more variable than able-bodied users (Molenbroek and Voorbji, 2001).

Developing computational techniques to substitute for direct measurements of all key body landmarks could reduce the difficulty of research on static anthropometry. However, computational approaches sacrifice an understanding of the natural dynamics of body function and require validation with actual measurements before one can rely on them (Paquet et al., 2001).

Another issue is that of functional anthropometry. Strength is a key variable in the ability to complete different functions. There is a need for studying strength, in its various dimensions and the need to study the correlation between strength and anthropometrics in the accomplishment of activities of daily living if we are to design for universally accessible environments (Weisman, 2001). Human reaching and object movement capability while seated is dependent on maximum muscle strengths in the torso, shoulder and upper extremity as well as balance (Chaffin et al., 2001). Empirical work was conducted at the University of Michigan Human Motion Simulation Laboratory, which produced posture data that can be used to define the strength and balance requirements of a task (Chaffin, et al., 2001). This data, along with muscle electromyographic data (EMG) is being used at the University of Michigan to understand the different levels of performance and exertion experienced when people with thoracic level spinal cord injuries perform seated reaching motions. Studies have been done on the biomechanics of wheelchair propulsion, relating the importance of biomechanics to injury prevention and safety for wheelchair users (Koontz and Cooper, 2001). Ringert et al. (2001) conducted a study on functional mobility for users of powered mobility devices, including scooters and power wheelchairs which examined the relationship of anthropometrics, type of mobility device and functional task completion as constrained or abetted by the environment. This study suggested that changes should be made to pertinent sections of codes and standards in order to take into account the requirements of powered wheelchair and scooter users.

Another problem faced in the design for wheelchair users is that it is not clear what critical sampling parameters should be used for the wheelchair user population (Bradtmiller, 2001). Ordinarily in sampling for anthropometric surveys, sex, age and race are used as the sampling parameters to account for much of the anthropometric variability in a non-disabled population but in anthropometry of the disabled, the type of disability also plays an important role in the eventual body size, shape, reach distances, strength and endurance characteristics of individuals (Bradtmiller and Annis, 1997). Two methods of sampling for anthropometric studies of persons with disability, as discussed by (Paquet, et al., 2001) are 1) framing samples based on type of mobility device used (e.g. manual wheelchair, power wheelchair, scooter etc.) and 2) sampling frame based on functional level of participants (as measured by scales like the Functional Independence Measure (FIM) or the Wheelchair Skills Test). Type of mobility aid used is a good variable for stratification in a study of wheelchair anthropometrics because it is constant across tasks, can incorporate a wide range of impairments and the number of users of a particular type of mobility aid can be determined quite easily (Paquet, et al. 2001). The difficulty also arises in the multiplicity of chairs and scooters in the market today. A 1995 study conducted by KRW Inc. for the U.S.

Architectural and Transportation Barriers Compliance Board revealed a listing of more than 125 models of scooters and power chairs (KRW Inc., 1995).

All such studies have revealed that new wheelchair technology, both in manual and powered devices, is resulting in different performance characteristics and new environmental needs; e.g. powered scooters were originally designed for outdoor use only, but are now being increasingly used indoors. So should built environments be designed to accommodate scooters or should scooters be designed to function in the built environments? Thus, changes in codes and standards may be needed to address trends in the use of wheeled mobility aids.

The need is therefore felt, to integrate research methods with design. Full-scale modeling can be used to measure functional abilities in context – an approach to physical modeling in which functional abilities are observed as users complete tasks in an environment that has realistic dimensions, tools and fixtures. Performance can then be mapped onto the environment to determine what is usable by the study group and to understand their preferences. Such information eliminates the need for the designer to interpret data from anthropometric databases or manipulate manikins (Steinfeld, 2001).

Another approach to 'designing for all' is to integrate a prototype 3-D computer manikin with a computer aided design system. Data from any study, if organized into the proper format could then be used to size the manikin (Eriksson, 2001). Llinas (2001) suggests the use of multi-sensor data fusion – an emerging field involving a wide variety of advanced methods of information processing – in the field of anthropometry in two ways: 1) integrating several streams of information collected on the same phenomenon, e.g. exertion data and kinematic data and 2) integrating data from different studies on the same issues.

Research is ongoing at the RERC on Universal Design, Buffalo, NY, on the construction of an anthropometrics database for the disabled population which could be used by designers, law-makers, ergonomists, engineers, architects, medical personnel and safety professionals in designing and developing barrier-free environments for all. The database would collect information including body sizes, reach capabilities, range of joint motion, strength and visual field data from several thousand children and adults, aged two and older with a wide range of disabilities. The research aims to address the following issues in anthropometrics of the disabled:

- Increasing standardization in methods of collecting anthropometric data
- Increasing use of functional approaches to research
- Developing computer simulation models
- Incorporation of behavioral and social factors
- Improving subject sampling
- Improving data collection methods

The information (from 500 wheelchair users) thus gathered from this project will be used to develop a prototype database for bathrooms and bathing facilities.

In the absence of any such anthropometric database or biomechanical model for the disabled, ergonomists still continue their endeavor to provide safe, easy to use and efficient products, services and environments. Below are a few examples of some noted efforts in integrating Ergonomics and Universal Design.

1.7 Wheelchair Accessibility Research in Product Design

Surveying the existing literature on the subject revealed that not much research has been done in the wheelchair accessibility issues of product design. Focus, at this stage, is seen primarily on the design and development of a model or database which would help various professionals to apply the disabled population data. One of the main reasons why no major research has been done in this field is the absence of such data or model.

Perhaps the most difficult problem presented by this population is its diversity. Bradtmiller et al. (1997) recommended that, for limited purposes, the population might be restricted to wheelchair users because, for 'limited purposes' it makes sense to focus on that portion of the range which is most different from the non-disabled population.

Examining the literature on the consideration of wheelchair accessibility in product design, reveals that a lot of research has been done in the field of designing built environments (ADAAG, 1991), accessible ramps, interaction of ground surfaces and wheelchairs, collection of anthropometry data and development of standards for ramps, grab-bars, lifts etc. in housing, public facilities and architectural design, but not much has been done in product design.

One product that has been researched is the automatic teller machine (Rogers et al., 1994). Then a very recent study has been done on the universal access in a photocopier (Eghtesadi, 2002). This research looks more at the human interface interaction issues in the universal accessibility, but, again, does not provide information on the design issues involved in hardware of the system.

A research study, examining the safety aspects of bathing for older people in wheelchairs, was conducted at the Center for Inclusive Design and Environmental Access, University at Buffalo, NY (Mullick, 1994). A study conducted by Budnick and Ross (1985), studying bathtub-related drownings between 1979-1981, showed that the bathtub is the second major site of drowning in the home after the swimming pool. According to the study, the common problems were maintaining balance while bathing, making transfers, lack of space, slippery floor conditions, inadequate lighting and excessive postural stress resulting from bending over. Recommendations were made focusing on enhancing security, making safe transfers, preventing slip conditions and preventing over-exertion by installing easy to use rescue devices located in a strategic position, smart alerting devices connected to a central monitoring system, providing for adjustable illumination level, anti-scalding device, employing the use of bathlifts, grab bars at strategic locations and strengthening soap holders, towel rods etc. so they can also serve as supports and make non-skid floor surfaces.

In another research study at the Center for Inclusive Design and Environmental Access, Buffalo, NY, by Steinfeld and Danford (1993), automated doors were evaluated from a universal design perspective. The study addressed the question of whether or not automated doors should be required and if so, when, and the technical criteria of how they should be designed for use in buildings. The human factors issues of door use were listed as altering gait, adjusting body posture, maneuvering within reach, applying force to overcome resistance of handles, switches, locks, door closers etc., perceiving and understanding door operation. The technology evaluated was pneumatic, hydraulic and electro-mechanical doors. Out of the three, electro-mechanical doors were found to be the most innovative from Universal Design perspective.

On the hi-tech side, rehabilitation engineers have developed “environmental control systems” (ECS) to help people with very severe disabilities use equipment in their homes or workplaces Steinfeld and Danford (1993). Computers with sophisticated “no hands” interfaces are the heart of such systems. People can access such systems using chin controllers, eye-gaze interfaces or speech recognition systems. ECS can also be integrated with electric wheelchairs, thereby, allowing people to use the same types of controls for both computer systems and wheelchairs. These wheelchairs have on-board microprocessors that are powerful enough to do many things in addition to controlling the wheelchair. By integrating ECS with electric wheelchairs, the number of devices necessary for independence is reduced. Also, the ECS can become portable so that it can give access to many devices outside the home.

In Japan, the train ticket vending machine has been designed for accessibility by wheelchair users and visually impaired, also. The MAE ticket machine has knee clearance, voice navigation, is designed specially to make the machine use easy for wheelchair users, visually handicapped people or illiterate people. Another example is the IT-G1000 telephone, with large visual display, auditory and visual feedback and carefully researched (through surveys in focus groups) size, shape and positioning of the buttons, which is made keeping in mind the needs of the older people. There are also talking ATM’s with touch screens, auditory feedback and accessibility for the wheelchair users.

Another product, which exhibits many characteristics as the ATM, is the recently emerged **Self-Checkout (SCO) System** at grocery stores. Self-checkout systems are retail systems that enable a customer to enter and pay for purchases without the aid of a cashier. According to industry surveys, in 2001 nearly a quarter of all supermarket chains offered self-checkout, up from 6 percent in 1999. A recent study by the Food Marketing Institute found that in stores that have them, about half of the customers use them.

1.8 Self-Checkout (SCO) Systems

It is believed that self-checkout (SCO) is the next retail revolution, the most recent big revolutions being (1) the ATM machines at retail financial institutions and (2) pay-at-the-pump technology at gas stations. It has been projected that self-checkout (SCO) is poised for dramatic growth in the coming years – it will occupy more than 25% of the retail market in the next two years (resource from IBM). The retail research firm IHL Consulting Group projects that, with advancements in technology, SCO systems could be installed in 95% of checkout lanes by the end of the decade. It is anticipated that U.S. consumers are as likely to use self-checkout as pay-at-the-pump (report from NCR study conducted in May 2003).

Consumers like SCO because it offers them privacy, convenience, speed, handling and trustworthiness. Privacy: because there are many items that consumers may feel uncomfortable in front of cashiers/other customers e.g. alcohol, tobacco, weight-loss, hygiene, birth control products etc. Convenience: Consumers clearly appreciate the convenience of being able to run in to a store to pick out the one or two little things they may have forgotten during their last trip to the store and pay for those items without hassle. Speed: Consumers may not be actually be able to scan, bag and pay for their transactions faster than cashiers, but because of the relief that SCO provides from waiting in lines, it is often perceived by the consumers that their entire trip to the grocery store becomes faster by SCO. Handling: a few bruised tomatoes, crushed loaves of bread, cracked eggs, etc., maybe enough to convert a conventional checkout user to SCO. Trustworthiness: Many consumers believe that the probability of being overcharged and/or treated unfairly is reduced if they scan things themselves. Thus consumers like SCO because it offers them more overall control in their shopping experience. New as SCO's are in terms of their emergence on the market scene, there has not been much research done on them from the perspective of their usability and functionality for all. In the summer of 2002, I had the opportunity to do some research on the SCO while interning with the Center for Universal Design.

1.8.1 Pilot Work on SCO

Market research revealed that there are three major manufacturers of the SCO system - 1) Optimal Robotics making the U-Scans, 2) NCR and 3) PSI-Inc., with Optimal Robotics having the largest market share 'till now. Food chains, including Kroger's, Food Lion, Publix and Harris Teeter, and retail stores, including K-Mart and Wal-Mart, have started installing significant quantities of these systems. Profiles of the major manufacturers of the SCO system are given below:

Table 1: **Profiles of major manufacturers of SCO**

	Models	Dimensions	Bag Capacity	Screen Size	Estimated Stores	Some key Customers
OPMR	U-Scan Solo	62"X34"X58"	1	14"	1200	Harris Teeter
	U-Scan Express	69"X34"X58"	3	14"		Kroger
	U-Scan Carousel	86"X34"X58"	6	14"		Harris Teeter Kroger
NCR	A-Series	162"X29"X60"	3	12.1"	425	K-Mart
	C-Series	158"X50"X60"	2	12.1"		Publix
	E-Series	90"X29"X60"	2	12.1"		
PSI-Inc	ACM 750	130"X29"X60"	Unlimited	15"	400	Lowe's Foods
	ACM Mini	57"X28"X60"	2	15"		Food Lion

Following, are pictures of the SCO models of the above-mentioned manufacturers.

Figure 1: U-Scan Express

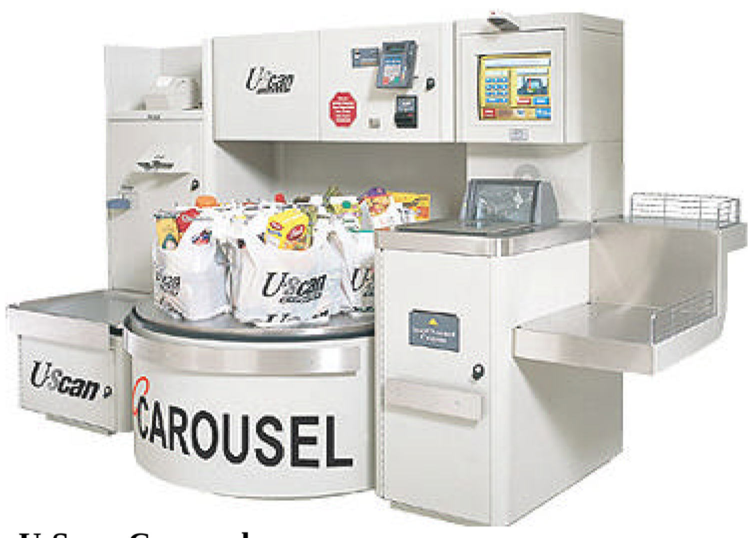

Figure 2: U-Scan Carousel

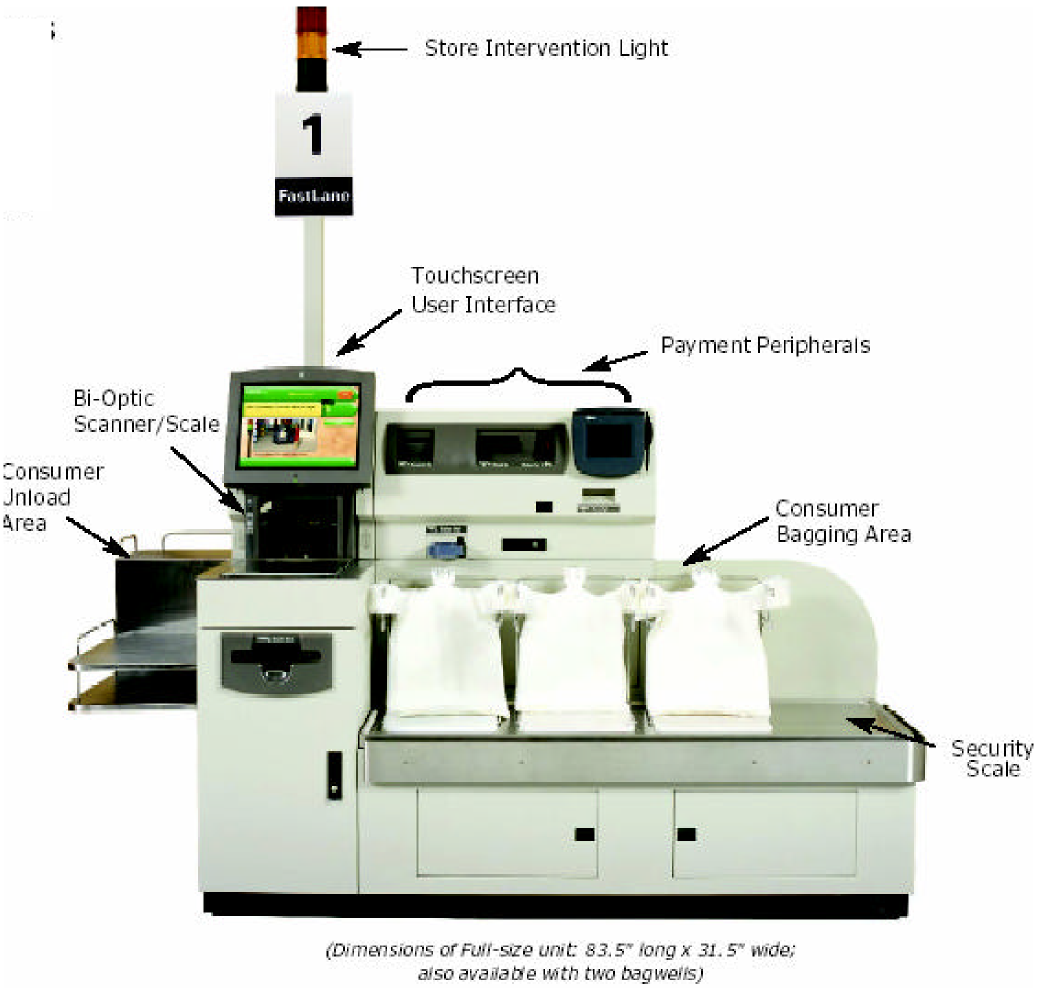

Figure 3: A NCR SCO model

Figure 4: A PSI-Inc SCO model

According to a market study done by IBM in 2001, the estimated market share of the SCO manufacturers is: Optimal Robotics (manufacturer of the U-Scan) OPMR-60%, NCR-21%, and PSI-19%. A focus group study of the U-Scans done with disabled people in real grocery store setting revealed that the SCO systems are far from the concept of Universal Design. They were found to present both perceptual as well as physical obstructions in their use by people with different abilities.

1.8.1.1 Perceptual Issues in SCO

Visual Interface – All the existing SCO systems use a touch screen for information input. The screen is typically 14”-15” wide. Thus, people who have **low vision** have to get too close to the screen in order to be able to see what is on it. At times, there are also a number of icons appearing on the screen, e.g. when the user has to select his/her produce item from the option on the screen. In such a situation, it becomes even more difficult for people with low vision to identify their items from the small icons on the screen. To exacerbate the problem, the screen is not adjustable for angle or height. Therefore, if someone is in a wheelchair or is shorter than the screen height and is looking up at the screen, his/her vision is obstructed by the **glare** that the overhead lights throw on the screen.

One **solution** to this problem could be to make the screen size bigger and the screen adjustable for angle inclination. This would accommodate people with different heights and vision and eliminate the effect of glare too. The angle adjustment should be easy to make and require negligible time and effort on the part of the user.

Audio Cues, Feedback and Warnings – Most SCO systems provide audio feedback to the user, some more than others, but none to the extent that can help minimize or eliminate errors that users inadvertently make in doing their transactions. For example, if a person forgets to take his/her money back from the machine, there is **no warning** to alert him/her about it. The touch screen interface does provide audio feedback about what the person has keyed in, but there is no way to tell if the person has keyed in the right information or not.

Another problem of the existing systems is illustrated by the fact that the system often gives the user audio cues of what to do next, but does not tell him/her how to do it. So the information dissemination in audio form is **not complete**. For example, the system tells the user to swipe his/her card, but it does not tell him/her where the card reader is located and how or in which orientation he/she has to swipe the card. This sometimes baffles the user who is left searching for the card reader wondering which way to swipe his/her card.

Yet another problem with audio cues is that the system stops giving any audio cues once the user leaves the scanner/screen area and proceeds to the bagging area to checkout, i.e. the **audio cuing stops abruptly** not following the sequence of the checkout process. Once the user has finished his/her grocery scanning and proceeds to pay, he/she has no way of knowing what to do next or where to go from there. Even if he/she walks away without taking his/her cash/change back or forgetting some of his/her grocery bags, the system has no way of alerting the him/her about this. Including audio feedback is a good way to accommodate people with disabilities but the cuing and warning of the systems should be improved to minimize the tolerance for error in the systems.

Human Computer Interaction (HCI) Issues – For a user who is using the SCO for the first time, the system is not very friendly in walking him/her through the process of checkout. That makes the system **intimidating** to a first time user. Even the aesthetic appearance of the system is not very inviting to an amateur user.

To complicate matters, the **interface hangs up** on the user, for no reason at all, asking him/her to seek help from a cashier. Then a cashier has to come, inspect the user's item and key it in from the cashier station. This wastes the user's time and leaves him/her feeling frustrated, especially if he/she has been using the system quite often and yet doesn't know what goes wrong and where.

The interface has **no tolerance for inadvertent human errors** (violates the fifth principle of Universal Design: Tolerance for error). For example, if the user places a scanned item in the cart instead of in the bagging area, the system will not instruct him/her to do what is required; instead it will simply hang up and ask the user to seek cashier's assistance. Thus, the HCI needs a lot of attention in the SCO systems. The existing systems do not respond adequately to the user's needs. This can drive a user away forcing them to go back to the age-old method of standing in queues for grocery checkout.

1.8.1.2. Physical Issues in SCO

<u>Reach</u> - The various components of the SCO – namely the scanner, screen, card reader, cash acceptor, coin acceptor, cash dispenser, coin dispenser and receipt dispenser are often out of the reach of seated users, children or short statured people. According to the ADA standards, the maximum high forward reach for wheelchair access should be 48" (ADAAG, latest amended 2002). The current systems have one or more of their components placed higher than 48" (details of U-Scan given in methods section). Because of the high reach, people in wheelchairs are not able to use the SCO systems. If they do, it is with a lot of difficulty. A solution to this is to place all the components within the reach of 'all' people. The reach distances should be designed seeking a compromise between the lowest reaches for tallest people and the highest reaches for wheelchair access. Another alternative could be to provide handheld devices for seated users so that they can perform all the various functions of the checkout without having to reach all the components (Principle 1 and 2 of Universal Design: Equitable Use and Flexibility in Use)

Clearance – None of the SCO provide clearances/cuts for accommodating seated people in a forward approach. All of them are designed with a solid metal frame in covering the front panel that obstructs the knees in forward approach. According to the ADA guidelines, the minimum knee clearance for forward approach should be 24” (ADAAG, 2002). Providing knee clearance for seated users can help in their being able to reach most of the components on the SCO system. Also, technically, the scanner only needs to be 6” thick (NCR Corp.). So, practically, the SCO designers can actually do away with the redundant metal front panel that blocks the forward access in the current systems.

Space/Maneuverability - The SCO systems should provide for adequate space for maneuverability of assistive technology devices.

Right Handed/Left Handed Access – The way in which some of the current SCO stations are installed provides for easy access only with one hand, especially if someone is using the side approach. This issue can be easily solved by locating the workstations in lanes accessible to both right side and left side approaches.

Based on the above observations and ideas from my pilot study, I decided to test the hypothesis that a redesigned SCO would corroborate to the principles of Universal Design more than the existing system.

1.9 Specific Aims of the Study

The specific aims of the study undertaken were:

- To redesign a SCO system (the U-Scan Express) that would accommodate seated as well as standing users –seated access especially for wheelchair users – focusing only on the physical issues in the design.
- To develop a prototype of the existing U-Scan Express and the redesigned version in lab.

- To simulate the process of grocery checkout on both the workstations.
- To test the primary hypothesis that if the existing U-Scan Express is redesigned from universal design perspectives then the redesigned workstation would prove to be better in terms of productivity, accessibility and users' subjective preference, not only for wheelchair users, but also for non-wheelchair users. This would, in effect, increase the acceptance of Self-Checkout Systems by the masses, thereby making them more user-friendly. Following are the specific **hypotheses** tested through experimentation and user feedback:

Hypothesis1: For the seated user, the time to complete a transaction will be lesser in the redesigned workstation than in the conventional design workstation.

Hypothesis 2: For the standing user, the time to complete will not be comparatively more in the redesigned workstation.

Hypothesis 3: For the seated user, the shoulder posture and the trunk posture will improve with the redesigned workstation.

Hypothesis 4: For the standing user, the shoulder posture and the trunk posture will not deteriorate with the redesigned workstation.

Hypothesis 5: For a seated user, the subjective response after using both the workstations would be better for the redesigned workstation.

Hypothesis 6: For the standing user, the subjective response after using both the workstations would not be worse for the redesigned workstation.

With these aims in consideration, the following methodology was developed for conducting the study.

2 Methodology

This section will cover the details of the experiment, including recruitment of the subjects, experimental set-up, independent, dependent variables and the statistical model used for the process of data collection and analysis.

2.1 Subjects

Fifteen subjects – 10 non-wheelchair and 5 wheelchair users – voluntarily consented to participate in the study. The wheelchair users were recruited by contacting the Center for Universal Design, the Students' Disability Services at NCSU, Wake County's wheelchair basketball team called the Wake Wheelers and personal contacts. The non-wheelchair subjects were recruited by word of mouth and personal contacts. Subjects were required to be 18 years of age or over and not have any cognitive disabilities. A deliberate attempt was made to choose subjects of varying strength and anthropometry. Before the beginning of the experiment, the subjects were asked to give their written consent by signing an 'Informed Consent Form' (shown in Appendix A) which described the nature of the study and their right to withdraw from testing at any point of time. Also, the subjects' structural anthropometric measurements were taken before the start of the experiment. The subjects were asked to come for the experiment wearing clothing which would allow for easy palpation of underlying bony landmarks. A total of 11 structural anthropometric dimensions for the wheelchair users, and 8 for the non-wheelchair subjects, were measured. Tables 2 and 3 below, show information about the anthropometric data collected.

Table 2: Anthropometric data of wheelchair users

Wheelchair subjects:	five in number			
	Mean(cm)	Std. dev(cm)	Max (cm)	Min (cm)
Seated stature	128.3	11.5	143.5	113.1
Eye height	116.6	10.9	131.0	103.4
Shoulder height	101.3	6.7	110.1	93.7
Knee height	62.4	2.9	65.5	58.4
Toe height*	23.7	10.4	38.2	16.1
Max reach height	107.2	10.3	122.2	99.4
Overhead reach	161.7	17.1	177.3	135.4
Max. reach	65.5	6.3	73.9	59.5
Arms span	209.7	109.1	403.4	144.8
Seat pan height	53.3	4.0	57.2	46.6
Wheelchair width	102.8	56.6	174.8	59.7

Table 3: Anthropometric data of non-wheelchair users

Non wheelchair subjects:	ten in number			
	Mean (cm)	Std. dev (cm)	Max (cm)	Min (cm)
Standing stature	171.7	7.6	178.9	157.8
Eye height	160.4	7.7	168.1	145.5
Shoulder height	142.8	7.0	151.8	128.9
Knee height	52.6	3.2	57.0	46.0
Max reach height	130.4	25.6	147.2	62.1
Overhead reach	213.9	9.0	226.1	199.4
Max. reach	68.5	2.4	71.6	62.8
Arms span	159.5	5.6	167.6	151.1

The definitions of the anthropometric dimensions taken are provided in Tables 5 and 6.

2.2 Experimental Apparatus and Instruments

This section includes information about the testing apparatus, data collection instruments and surveys used in the experiment for data collection.

2.2.1 Testing Apparatus

The testing apparatus consisted of two workstations – one, a dimensionally accurate prototype of the conventional self check-out system (the U-Scan Express) and second, a prototype of a proposed ***redesign*** of the conventional self check-out system (SCO). The subjects were not told which station was the redesigned one and which one the conventional, in order to eliminate any personal biases in using the systems. To the subjects, the systems were simply referred to as Workstation A (for the conventional type model of SCO) and Workstation B (for the redesigned model of SCO). The workstations were constructed with a 2" X 4" frame covered with 3/16" thick sheets of pegboard. The various components were simulated as below:

- For the touch screen, a normal computer screen, 14" wide was taken and the icons on it were developed using articles from the clipboard in Microsoft PowerPoint
- North Carolina State University's student ID card reader or the University Graphics' card reader was used to simulate the real-life card reader in U-Scans
- For the cash and coin acceptor, slots were cut into the peg board and a cup was placed behind the board as a receptacle for cash and coins
- For the bagging station, a bagging hanger was placed in the bagging area
- For the cash dispenser, a small plastic oval tray was screwed to the back panel of the peg-board at a small forward inclined angle.
- For the coin dispenser, a small plastic round cup was screwed to the back panel of the peg-board
- For the receipt dispenser, a rectangular plastic tray was screwed to the peg board

Five common grocery items namely, a gallon of water, one box of cereal, a two liter bottle of soda, one box of jello and one can of soup were provided to the subject in a real-life grocery basket for the process of checkout.

The pictures and drawings of the two workstations are shown in Figure 5 through Figure 8. The table below summarizes the major differences in the two workstations:

Table 4: Physical differences between Conventional (A) vs. Redesigned (B) workstations

Conventional (Workstation **A**)	Redesigned (Workstation **B**)
No knee clearance provided for forward reach on scanner	A knee **clearance** space of 27"high by 17"wide was provided
Height of the **scanner** – 36"	Height of the **scanner** – 33"
Position of **screen** – 54"high by 10.5"deep	Position of **screen** – 46.5"high by 12.5"deep. ADA recommends 48" as maximum high forward reach and less than or equal to 25" of depth over an obstruction (28 CFR 36, 2002)
No **knee clearance** provided for forward reach in bagging area	A **knee clearance** of 27"high by 42"wide by 18"deep was provided for forward reach in bagging area. ADA recommends at least 27" high, 30" wide and 17"-19" deep clear knee space wall or panel mounted units to allow a person in a wheelchair to approach the unit facing forward (28 CFR 26)
Position of **card reader** – 54.5"high by 17"deep	Position of **card reader** – 45.5"high by 14"deep

Conventional (Workstation **A**)	Redesigned (Workstation **B**)
Placement of the card reader – **high up** on the back panel of the bagging area	Placement of the card reader – **attached on the side** of computer screen
Position of the **cash acceptor slot**–50.5"high by 22"deep	Position of the **cash acceptor slot** – 39"high by 18"deep
Position of the **coin acceptor slot** – 49"high by 22"deep	Position of the **coin acceptor slot** -38"high by 18"deep
Orientation of the coin acceptor slot - **horizontal**	Orientation of the coin acceptor slot - **vertical**
Position of the **cash dispenser tray** – 47.5"high by 17"deep	Position of the **cash dispenser tray** – 37.5"high by 13"deep
Position of the **coin dispenser tray** – 42"high by 20"deep	Position of the **coin dispenser tray** – 39"high by 16"deep
Coin and cash dispenser are **not 'see-through'**	Coin and cash dispenser are '**see-through'** so the customer can see if there is any coin/cash left in it
Position of the **receipt dispenser** – 53"high by 21"deep	Position of the **receipt dispenser**– 30.5"high by 9"deep

The dimensions of the redesigned workstation were made in accordance with the ADA (Americans with Disabilities Act) accessibility guidelines for buildings and facilities provided in the Code of Federal Regulations (28 CFR Part 36, latest revised-2002). The specific guidelines used are mentioned in the table above at the relevant places.

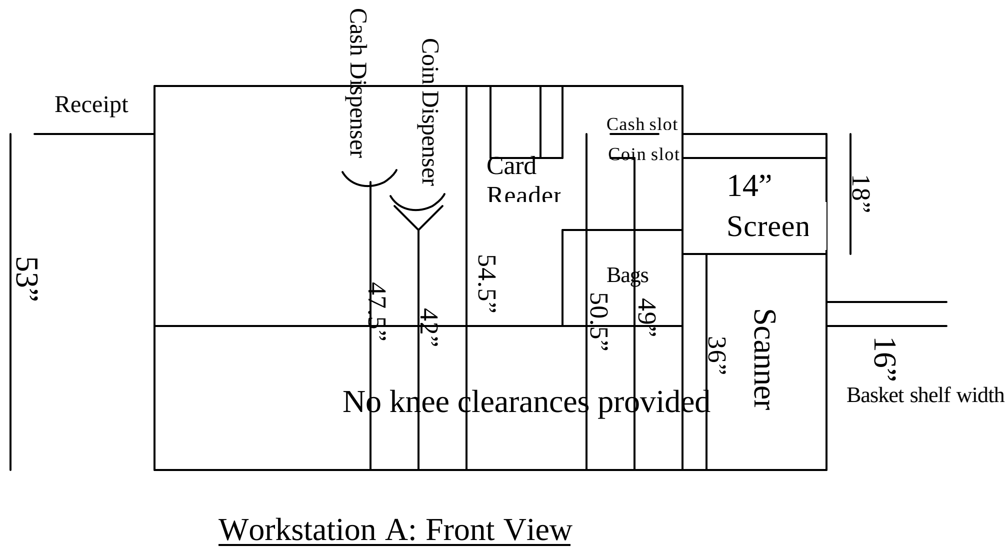

Figure 5: Front view of Workstation A

Figure 6: Front view of Workstation A (conventional SCO prototype)

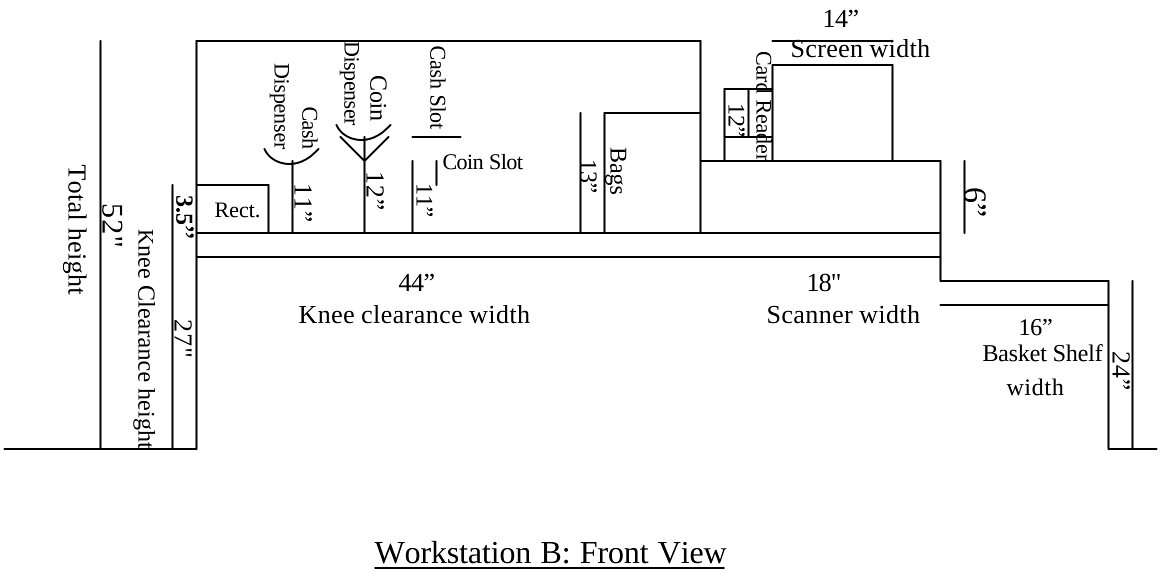

Figure 7: Front View of the redesigned workstation

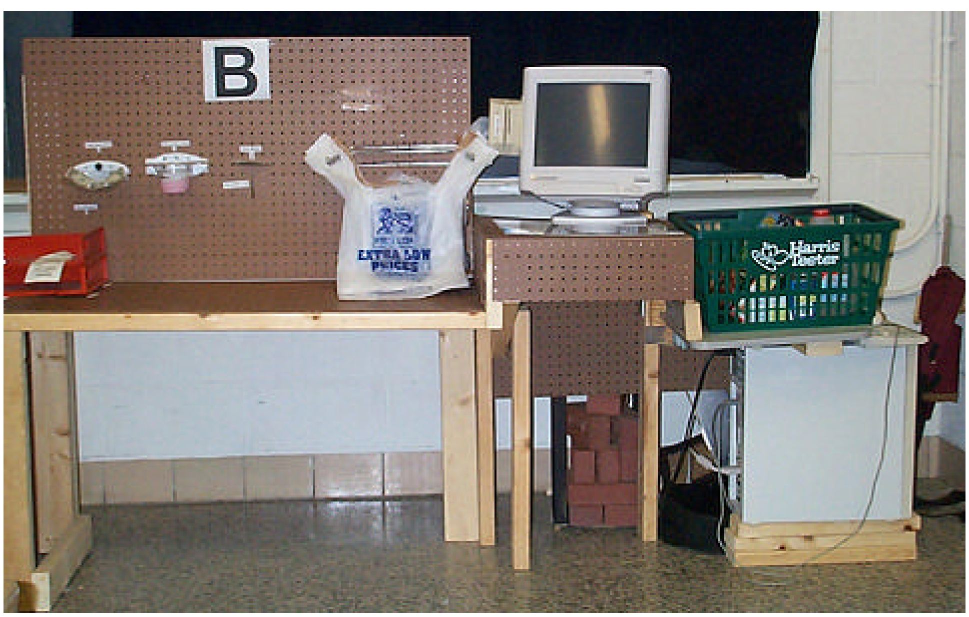

Figure 8a: Front view of the Redesigned Workstation

Figure 8b: Concept design of the Redesigned Workstation

2.2.2 Data Collection Instrumentation

An **anthropometer** was used to measure 11 structural dimensions for wheelchair users and 8 for non-wheelchair users. A list of the dimensions and the standardized anatomical landmarks which were used for these dimensions are presented in Tables 5 and 6

Table 5: Structural anthropometric dimensions and landmarks used for their determination for wheelchair-user subjects:

Dimensions	View	Definitions
Seated Height	Sagittal	Floor to top of head
Eye Height	Sagittal	Floor to center of eye
Shoulder Height	Sagittal	Floor to acromion
Knee Height	Sagittal	Floor to anterior surface of thigh (distal end)
Toe Height	Sagittal	Floor to superior-distal end of foot
Maximum Reach Height	Sagittal	Floor to proximal interphalangeal joint of middle finger with arm extended in front
Overhead Reach	Sagittal	Floor to proximal interphalangeal joint of middle finger with arm extended overhead
Maximum Reach	Sagittal	Shoulder joint to proximal interphalangeal joint
Arm Span	Sagittal	Proximal interphalangeal joint of right middle finger to proximal interphalangeal joint of left middle finger with arms stretched out on both sides
Seat pan Height	Sagittal	Floor to anterior surface seat
Wheelchair Width	Sagittal	Distance between the axis of two wheels of wheelchair

Table 6: Structural anthropometric dimensions and landmarks used for their determination for non-wheelchair subjects:

Dimensions	View	Definitions
Standing Height	Sagittal	Floor to top of head
Eye Height	Sagittal	Floor to center of eye
Shoulder Height	Sagittal	Floor to acromion
Knee Height	Sagittal	Floor to anterior surface of thigh (distal end)
Maximum Reach Height	Sagittal	Floor to proximal interphalangeal joint of middle finger with arm extended in front
Overhead Reach	Sagittal	Floor to proximal interphalangeal joint of middle finger with arm extended overhead
Maximum Reach	Sagittal	Shoulder joint to proximal interphalangeal joint
Arm Span	Sagittal	Proximal interphalangeal joint of right middle finger to proximal interphalangeal joint of left middle finger with arms stretched out on both sides

The subject was recorded on video with the camera oriented to capture video in the sagittal plane. Two 150x/26x **camcorders** (VHS compatible) were positioned on two separate tripods to operate from two separate remote positions. The video recording was used for analyzing posture while performing the task. During post-experimental data collection, a **television** and **videocassette recorder/player** were used to analyze the trunk and shoulder postures assumed while performing the task. A simple **goniometer** was also used to assess the posture angles from the video recording of subjects simulating the task of grocery checkout. Two crucial posture angles measured from the video were: Trunk angle and Shoulder angle (defined later in Section 2.4.2). A **stop watch** for recording minutes and seconds was used to monitor the time to complete a transaction in order to assess productivity measures.

2.2.3 Surveys

The remaining data collected during the experiment was via self-reported paper surveys. All surveys used can be found in Appendices B and C. The subjects completed two post-test surveys administered at the end of the experiment. The first was "SCO Redesign Evaluation Survey". This survey asked the subjects to compare (by rating on a five point Likert Scale) the following five categories: ease of use, comfort, accuracy, productivity and overall preference. The five points of the scale were: strongly disagree, disagree, neutral, agree and strongly agree, with rating scales of 1, 2, 3, 4 and 5 respectively. For example, one statement read: "Workstation B allowed me to *more easily* complete the task than Workstation A". They were instructed to give their level of agreement to the question by circling one of the five choices, answering according to their experience of performing the task using the two different workstations. According to the scales defined, a score of 3 meant neutrality (i.e. A=B); > 3, preference for B and <3, preference for A.

The subjects were then asked to fill out a “Final Comparison Survey,” which queried the subjects on their preference of workstation setup and design, also based on the same five categories as the first survey. This survey, however, was constructed differently. It had six questions. The first five questions asked the subjects to pick their preference between Workstation A and Workstation B based upon ease, comfort, accuracy, productivity and overall preference. For example, one question read “It was *easier* to complete the task using the workstation (**B** / **A**)”. The subject had to circle his/her preference for B or A. If the subject was neutral, he/she would have to circle both B and A. A score of 1 was given for preference to A, 2 for neutral (i.e. A=B) and 3 for preference to B. In the final question, the subjects were asked to answer one comprehensive question: whether they would be willing to use the Workstation B configuration, imagining that it was built to be installed in an actual grocery store environment. They were to provide their subjective rating to this question on a scale from 1 to 10, 1 meaning not willing at all, 5 meaning neutral and 10 meaning very willing.

2.3 Experimental Procedure

Each session lasted between one to two hours, varying depending on the subject’s speed to perform the task and fill out the post-test surveys. Below is a protocol checklist that lists each activity performed, listed in brief below:

1. The subject filled out the Informed Consent Form.
2. Anthropometric data was collected.

3. Training was provided to the subject for four to six trials depending upon his/her ability to get accustomed to the sequence of operations involved in the checkout process. The purpose of training was to control the effect of learning and enable him/her to perform the checkout process at a constant speed in the actual trials.
4. The subject performed the task simulating grocery self check-out on the two different workstations (task explained in detail below), randomly being told to perform on Workstation A or B and making either cash or card transaction. In all, the subject performed the task 16 times (four repetitions of each transaction type (cash and card) and workstation design (A/B)). The time to complete each transaction was noted by a stop-watch.
5. The subject filled out post-test surveys after completion of the task.
6. The subject was thanked for participating in the study.

Upon arriving at the laboratory, the procedures of the experiment were briefly explained to the participant, and she or he was shown the workstations A and B The subject was told to perform the task in the following manner by way of an informal speech (no written script of the following was made).

"Imagine that you are a customer doing your grocery shopping at a major grocery store with the provision of Self Check-Out. You have five common grocery items to buy. Your task is to simulate the process of grocery check-out on two different workstations. The workstations are labeled 'A' and 'B'. The experiment administrator will instruct you which workstation to use when, before you start the process of check-out. You will be asked to go through each of the workstations a number of times (in random order), making the transaction by either cash or card. The experiment administrator will instruct you about the type of tender transaction and the workstation by saying one of the four cues – “Cash A”, “Card A”, “Cash B” or “Card B”. For example “Cash A” would mean you have to checkout on Workstation A using cash, “Card B” would mean you have to checkout on Workstation B using card, so on and so forth. There is a set sequence in which you will be required to perform each transaction. The sequence is explained below. Please remember to perform the task in that same sequence. Please complete the task at a pace you feel comfortable and feel free to quit any time you feel you cannot go any further. Since the task is quite simple and repetitive, you might want to hasten the process somewhere in the middle of the trials, but please take care not to do so. If you want, you can take a break whenever you want to if such a need arises.”

A written script of the following was made available to the subject for his/her reference.

“On each workstation, the sequence of your task should be as below

1. Touch screen to start
2. Then scan your items on the scanner one by one and keep putting them in bags as you scan them. When you scan the items, make sure you make the bar code pass over the designated scanning area (marked by a pink tape). Please use only three bags for bagging (this was to control any variance in time occurring due to the varying number of bags a person might use for bagging the same number of items)
3. After you have scanned and bagged all items, touch the screen to select all options appearing on it
4. Then touch the screen to select ‘finish and pay’

5. Then touch the screen to select 'method of payment' 'card' or 'cash'. This will be told to you by the experiment administrator before you start the process of check-out. So please select the option as instructed to you by the experiment administrator

6. If paying by <u>cash</u> then:

   - Put coins in the coin acceptor and bills in the bill acceptor. The coins and bills will be provided to you (a dollar bill and fifty-five cents (two quarters and a five cent) were given to the subject for making the cash transaction)
   - Leave your bagged items on the workstation itself
   - Get your change and any bills refunded back from the respective bill or coin dispensers

   If paying by <u>card</u> then:

   - Swipe your card through the card reader (an NCSU identity card was provided to the subject for this)
   - Leave your bagged items on the workstation itself

7. Finally, touch the receipt (do not tear it off) and pretend to leave."

The participant was subsequently asked to read the Informed Consent form. Those who wished to continue signed and dated it and provided it to the test administrator. If the participant wished to retain a copy of the unsigned consent form she or he was provided one to keep. The next preliminary activity was the compilation of anthropometric measurements. The Tables 5 and 6 show the dimensions taken and landmarks used for their measurement. The subject was then asked to perform the task as explained above for four to six times (depending upon his/her ability to attain a steady time to complete the task), to get him/her accustomed to the sequence of the process. This was done in order to control for any learning effects that might occur in the experiment. After the experimenter saw that the subject was accustomed to the task and was performing at a fairly constant speed, the subject was asked to actually perform the sixteen random trials. The video recorders were switched on to record the subject's activity.

After the completion of the experiment, the subject was asked to fill out two survey forms – the 'SCO Redesign Evaluation Survey' and the 'Final Comparison Survey'. The SCO Redesign Evaluation Survey asked the subject to compare his or her perceptions of the workstations A and B. The "Final Comparison Survey" asked about his or her preference of workstation setup. The culminating question on this survey asked the participant how willing he or she would be to use the Workstation B configuration, imagining that it was built to be installed in an actual grocery store environment. Finally, the subject was thanked for participating in the experiment.

2.4 Experimental Variables

This section contains information about the independent and the dependent variables used in the study. Independent variables are those which are varied by the experimenter and that can cause change in other variables. Dependent variables are those which are affected by change in the independent variables.

2.4.1 Independent variables

Workstation type was the primary independent variable in this experiment. Workstation A represented the conventional self check-out system (specifically, the U-Scan Express) and Workstation B represented the redesigned self check-out system taking into consideration the accessibility for wheelchair users. The effect of the type of workstation in the process of checkout was observed separately for two groups - wheelchair users and non-wheelchair users. For each of the two groups, this effect was quantified for each of the two tender types– cash and card. Transaction type (i.e. card vs. cash) was also considered an independent variable because it strongly influenced time to completion of the task (a cash transaction, having more number of steps in the sequence, took longer than a card transaction).

2.4.2 Dependent Variables

Three types of dependent variables were collected during the study. The *first* dependent variable quantified **productivity** on the workstations. "Time-to-completion" data was recorded for each workstation and each transaction. Since there were four trials for each type of transaction (i.e. four for Cash A, four for Card A, four for Cash B and four for Card B), there were sixteen measures in all for each subject.

The *second* variable was **posture** of the subject assumed while performing the task on each workstation. This was analyzed by conducting a post-test video analysis of the video recording of the subject while performing the task. Subjects' trunk and shoulder angles were measured in the sagittal plane as they reached the various components on the workstations. The definitions of the two angles measured are as below:

Trunk angle: Angle between a line perpendicular to the ground and passing through the hip rotation point and a line joining the hip rotation point to the top of the shoulder.

Shoulder angle: Angle between a line perpendicular to the ground and passing through the top of the shoulder at the acromium and a line joining the top of the shoulder to the lateral epicondyle at the elbow.

All the trunk and shoulder angles were measured in the sagittal plane and at the peak value of their occurrence, i.e. when the maximum angle was observed. Since the trunk and shoulder angles were measured as the subjects reached for the various components on the two workstations, their measurements were divided into the following categories as described below:

1. Basket Trunk: The trunk postural angle assumed as the subject reached into the basket to get an item out of it. Since the subject had to reach for five items in the basket, therefore the video frame when the subject was observed to bend the maximum was used to measure the 'basket trunk' angle.
2. Basket Shoulder: The shoulder postural angle assumed as the subject reached into the basket to get an item out of it. Since the subject had to reach for five items in the basket, therefore the video frame when the subject was observed to move his shoulder the maximum was used to measure the 'basket shoulder' angle.
3. Bag Trunk: The trunk postural angle assumed as the subject bagged the item on the bagging station. In this case again, since the subject bagged five items, therefore, the video frame in which the subject was observed to bend the maximum while bagging was used to measure the 'bag trunk' angle.
4. Bag Shoulder: The shoulder postural angle assumed as the subject bagged the item on the bagging station. Here again, since the subject bagged five items, therefore, the video frame in which the subject was observed to move his shoulder the maximum while bagging was used to measure the 'bag shoulder' angle.
5. Screen Trunk: The trunk postural angle assumed as the subject reached to touch the highest point on the computer screen.

6. Screen Shoulder: The shoulder postural angle assumed as the subject reached to touch the highest point on the computer screen.
7. Card Swipe Trunk: The trunk postural angle assumed as the subject reached the highest point on the card reader. This angle was observed in only eight of the sixteen trials when the subject performed the card tender type.
8. Card Swipe Shoulder: The shoulder posture angle assumed as the subject reached the highest point on the card reader. This angle was again observed in only eight of the sixteen trials when the subject performed the card tender type.
9. Cash Acceptor Trunk: The trunk postural angle assumed as the subject reached the cash slot on the workstation to put the bill in it. This angle was observed in only cash type transactions i.e. in eight out of the sixteen trials.
10. Cash Acceptor Shoulder: The shoulder postural angle assumed as the subject reached the cash slot on the workstation to put the bill in it. This angle too, was observed in only cash type transactions i.e. in eight out of the sixteen trials.
11. Coin Acceptor Trunk: The trunk postural angle assumed as the subject reached the coin slot on the workstation to put coins in it. This too was observed in only cash type transactions i.e. in eight out of the sixteen trials.
12. Coin Acceptor Shoulder: The shoulder postural angle assumed as the subject reached the coin slot on the workstation to put coins in it. This too was observed in only cash type transactions i.e. in eight out of the sixteen trials.
13. Cash Dispenser Trunk: The trunk postural angle assumed as the subject reached the cash dispenser tray to get his cash back. This too was observed in only cash type transactions i.e. in eight out of the sixteen trials.

14. Coin Dispenser Shoulder: The shoulder postural angle assumed as the subject reached the cash dispenser tray to get his cash back. This too was observed in only cash type transactions i.e. in eight out of the sixteen trials.
15. Receipt Trunk: The trunk postural angle assumed as the subject reached to get the receipt.
16. Receipt Shoulder: The shoulder postural angle assumed as the subject reached to get the receipt.

The following pictures depict the posture angles on Workstations A and B.

Figure 9: A wheelchair user reaching for screen on Workstation A (conventional)

Figure 10: A wheelchair user reaching for screen on Workstation B (redesigned)

Figure 11: A non-wheelchair user reaching for the card swipe on Workstation A (conventional)

Figure 12: A non-wheelchair user reaching for the card swipe on Workstation B (redesigned)

The *third* type of dependent variable was subjects' **subjective response** on the two surveys administered, consisting of the 'SCO Redesign Evaluation Survey' and the 'Final Comparison Survey'.

The 'SCO Redesign Evaluation Survey' asked five questions requiring the subjects to rate their level of agreement to a statement on the basis of ease of use, comfort, accuracy, productivity and overall preference. Answers ranged from "strongly disagree" to "strongly agree," which produced scores on each question ranging from 1 to 5, with a score of 3 implying neutrality, >3, a preference for B (redesigned) and <3, a preference for A (conventional).

The "Final Comparison Survey" asked the subjects about their preference to a workstation – A or B – by means of six questions. For the first five questions on preference, scores ranged from 1 to 3, with a score of 2 implying neutrality, >2, a preference for B (redesigned) and <2, a preference for A (conventional). The final sixth question concerning willingness varied in score from 1 to 10, with a score of 5 implying neutrality, >5, a willingness for using B (redesigned) and <5, a willingness for using A (conventional). All data were collected and stored with a unique identifier number for each subject.

2.5 Statistical Analysis

To see the effect of workstation type (conventional vs. redesigned, i.e. A vs. B) on the three dependent variables – productivity, posture and users' subjective responses on the two surveys - the data was analyzed using ANOVA procedures. Because of differences in the data types being analyzed, slightly different analyses were performed. Throughout, the analysis, a probability of less than .05 indicated a significant effect.

2.5.1 Assumptions for performing the ANOVA

Before performing the ANOVA, the assumptions of the procedure were tested. The following three assumptions were tested:

1. Normality: The residuals from the statistical model were normally distributed.
2. Homogeneity of variances: The residuals had constant variance.
3. Independence or randomness of data: The data collected from each subject was unique. The data from one subject was unrelated to the data from any other subject.

1. Test for normality: The normality assumption was tested using graphical assessment for the distribution of residuals. Quartile plots of the residuals were plotted. If the underlying error distribution is normal, then the plots will resemble a straight line. Moderate skewedness in the plots is acceptable. In fact, with small samples, considerable fluctuation often occurs, so the appearance of moderate departures from the straight line does not necessarily imply a serious violation of the normality assumption (Montgomery, 1984). In general, moderate departures from normality are of little concern in the ANOVA. Since the F-test is only slightly affected, the ANOVA is robust to the normality assumption (Montgomery, 1984).
2. Test for homogeneity of variances: If the model is correct and if the assumptions are satisfied, the residuals should be structureless; in particular, they should be unrelated to any other variable including the response (Montgomery, 1984). Therefore, as a simple check for this, the residuals were plotted as a function of the predicted values, Y, to see if any systematic changes occurred in the variability of the residuals as a function of Y. To satisfy this assumption, the plot should not reveal any obvious pattern, e.g. residuals should not increase as Y increases resulting in a bugle shape or

an outward opening funnel. However, if this assumption is slightly violated, the F-test is not considerably affected, because of the robustness of the model (Montgomery, 1984). Therefore, slight departure from the assumption is acceptable.

3. Independence or randomness of data: This was assumed by random subject recruitment.

2.5.2 Analysis of Productivity Data

General Linear Model described by the equation below (Equation 1) was used for analysis of the productivity data. An ANOVA was performed separately for each user group-wheelchair users and non-wheelchair users. The goal of this study was not to compare wheelchair vs. non-wheelchair users and the data from wheelchair users was also not comparable to the data from non-wheelchair users. So the two groups were analyzed separately. Transaction type was considered in the analysis of productivity because of its strong effect on the time to complete a transaction.

$y_{ijk} = \mu + \tau_i + \beta_j + \varepsilon_{ijk}$ (i = 1-2, j = 1-2, k=1-4)……………………………...(Equation 1)

where, y = time to complete the task (in seconds)

μ = expected mean value of time to complete

τ represents workstation type (A or B)

β represents transaction type (cash or card)

ε represents error term

2.5.3 Analysis of Postural Data

General Linear Model described by the equation below (Equation 2) was used for the analysis of posture data. An ANOVA was performed separately for each user group-wheelchair users and non-wheelchair users. The reason for this, as explained above, was that the goal of this study was not to compare wheelchair vs. non-wheelchair users and the data from wheelchair users was also not comparable to the data from non-wheelchair users. So the two groups were analyzed separately.

Because a number of the dependent variables were not the same in the two transaction types (e.g. card swipe trunk and card swipe shoulder were there in card but not in cash transactions and cash acceptor trunk and cash acceptor shoulder were there in cash but not in card transactions), transaction type was not analyzed as an independent variable for the posture data.

$y_{ij} = \mu + \tau_i + \varepsilon_{ij}$ $(i = 1\text{-}2,\ j = 1\text{-}8)$……………………………………………..(Equation 2)

where, y = postural angle while reaching a component (in degrees)

μ = expected mean value of the postural angle

τ represents workstation type (A or B)

ε represents error term

2.5.4 Survey Data

As the surveys were subjective and could be classified as ordinal scales, a nonparametric ANOVA was performed. The Kruskal-Wallis test (Kruskal and Wallis, 1952) was used for the analysis. Since the survey responses depended on the user's personal preference for any workstation (A or B), and since the purpose of this study was to see whether or not both the user groups would prefer the redesigned workstation (B) in comparison to the conventional one (A), the survey responses were analyzed for each user group – wheelchair vs. non wheelchair users. Because the surveys were not designed to see the user's preference for transaction type, transaction type was not analyzed as an independent variable for the survey data. The following equation represents the model used for survey data analysis:

$y_{ij} = \mu + \tau_i + \varepsilon_{ij}$ (i = 1-2, j = 1-5)……………………………………………..(Equation 3)

where, y = user's response score

μ = expected mean value of the response score

τ represents user type (wheelchair user or non-wheelchair user)

ε represents error term

3 Results

The results are presented in four sections. Section 3.1 covers the results from the test of ANOVA assumptions. Section 3.2 contains the productivity results. Section 3.3 presents the data on posture angles, namely trunk and shoulder posture angles. Finally, Section 3.4 explains the users' survey response data. For all the variables, the results are divided into two major groups – the results for wheelchair users and the results for non-wheelchair users.

3.1 Test of ANOVA Assumptions

3.1.1 Test for Normality of Residuals

Figures 13 – 16 show examples of the graphical analysis performed to test the normality of residuals. In order to satisfy this assumption, the quartile plots should approximate straight lines.

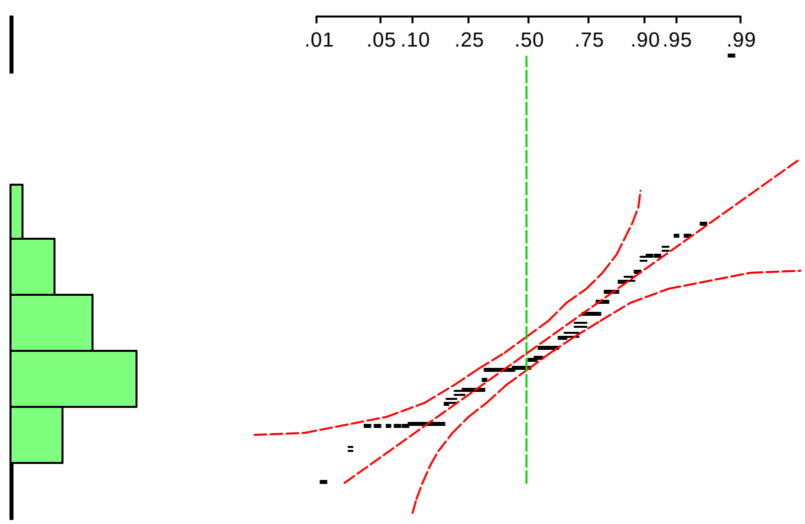

Figure 13: Quartile plot of Residuals for Cash Acceptor Shoulder Angle in Wheelchair users

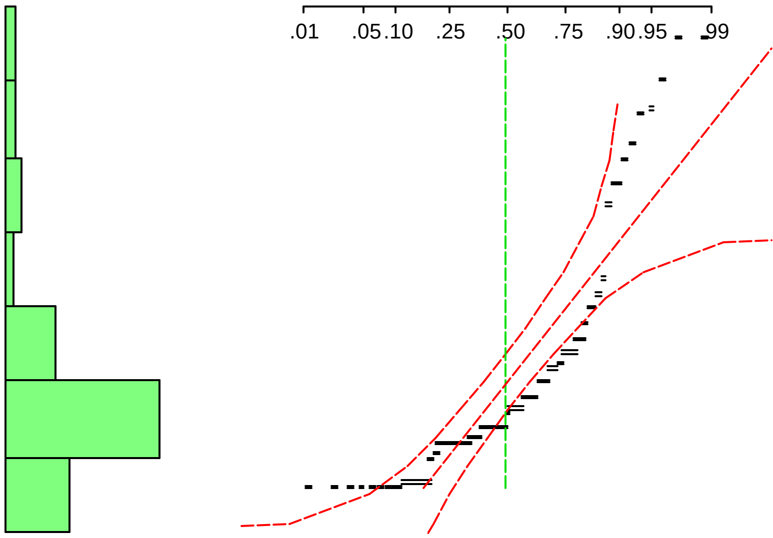

Figure 14: Quartile plot of Residuals for Basket Shoulder Angle in Wheelchair users

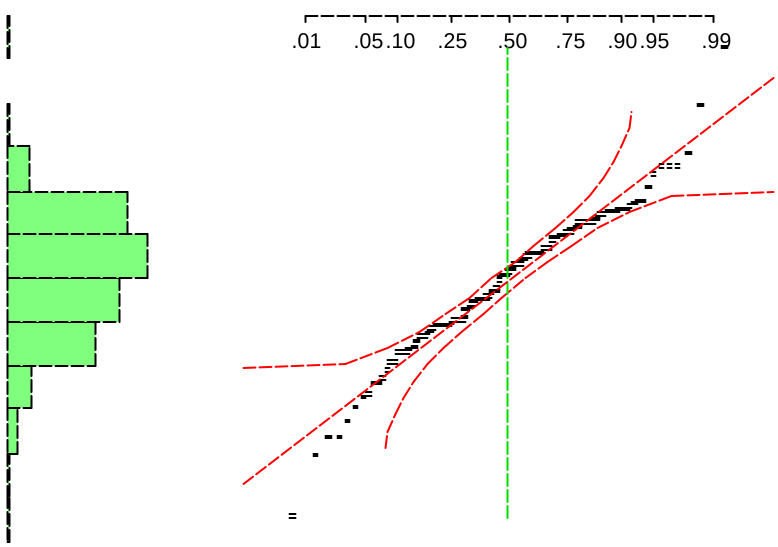

Figure 15: Quartile plot of Residuals for Basket Trunk Angle in Non-Wheelchair users

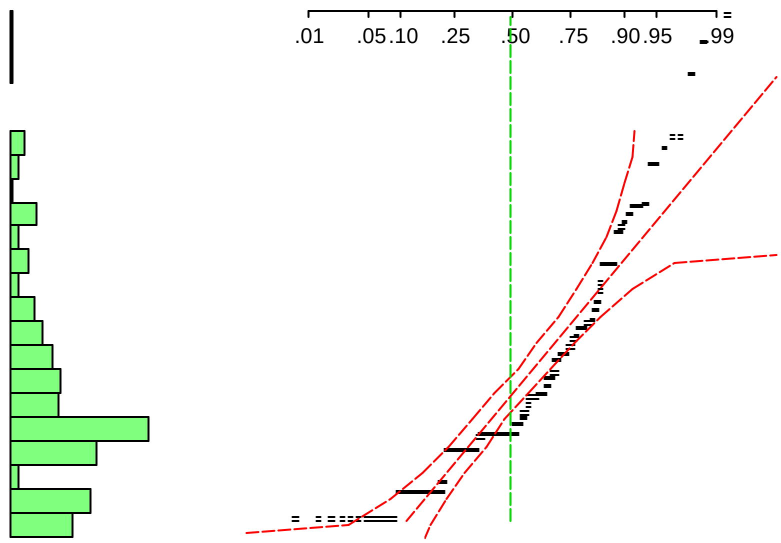

Figure 16: Quartile plot of Residuals for Receipt Shoulder Angle in Non-Wheelchair users

From the plots, it can be seen that they are not exactly straight lines, as should be the case if residuals are perfectly normally distributed, but this does not imply that our assumption test failed. According to Montgomery (1984), moderate skewedness in the plots, especially with small samples, is acceptable. In general, moderate departures from normality are of little concern in the ANOVA. Since the F-test is only slightly affected, the ANOVA is robust to the normality assumption (Montgomery, 1984).

3.1.2 Test of Homogeneity of Variances

Figures 17-18 show examples of scatter plots of the residual plotted as a function of the predicted value, Y. In order to satisfy this assumption, the scatter plots should be structureless and not depict any trends in the residuals as function of the predicted values.

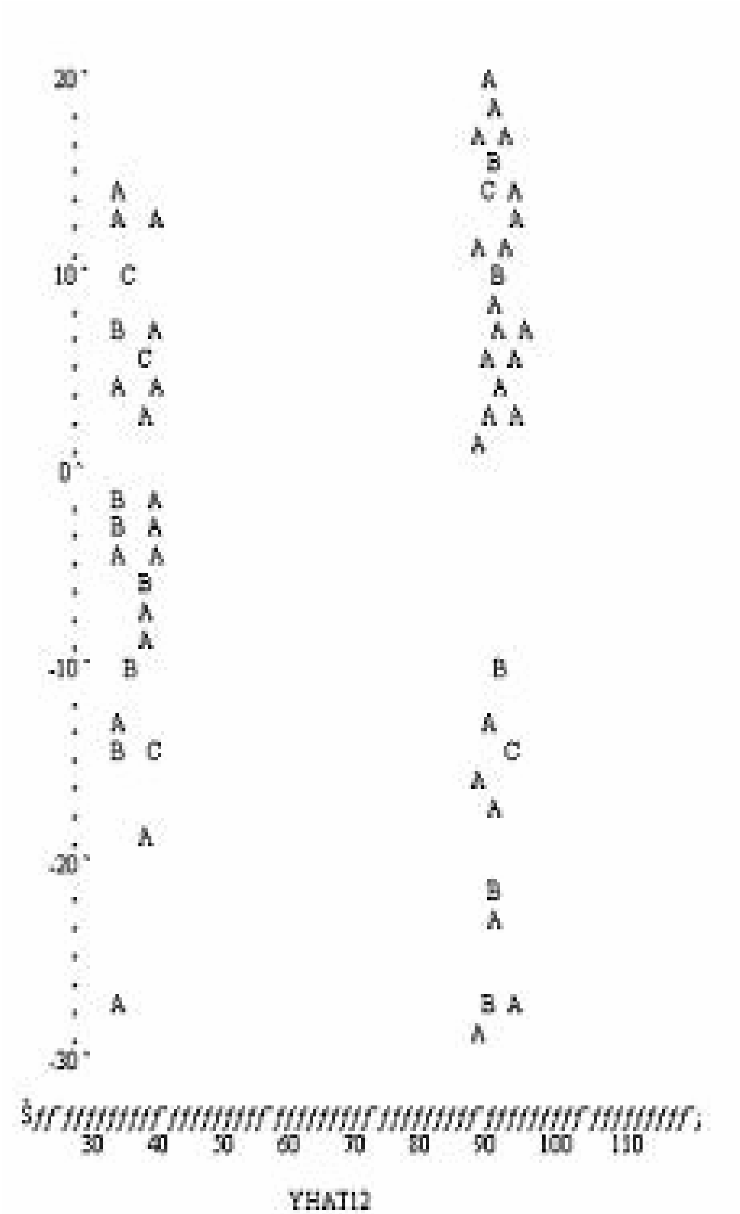

Figure 17: Scatter Plot of Residuals as a function of the Predicted values (YHAT) for Receipt Shoulder Angle in Wheelchair users

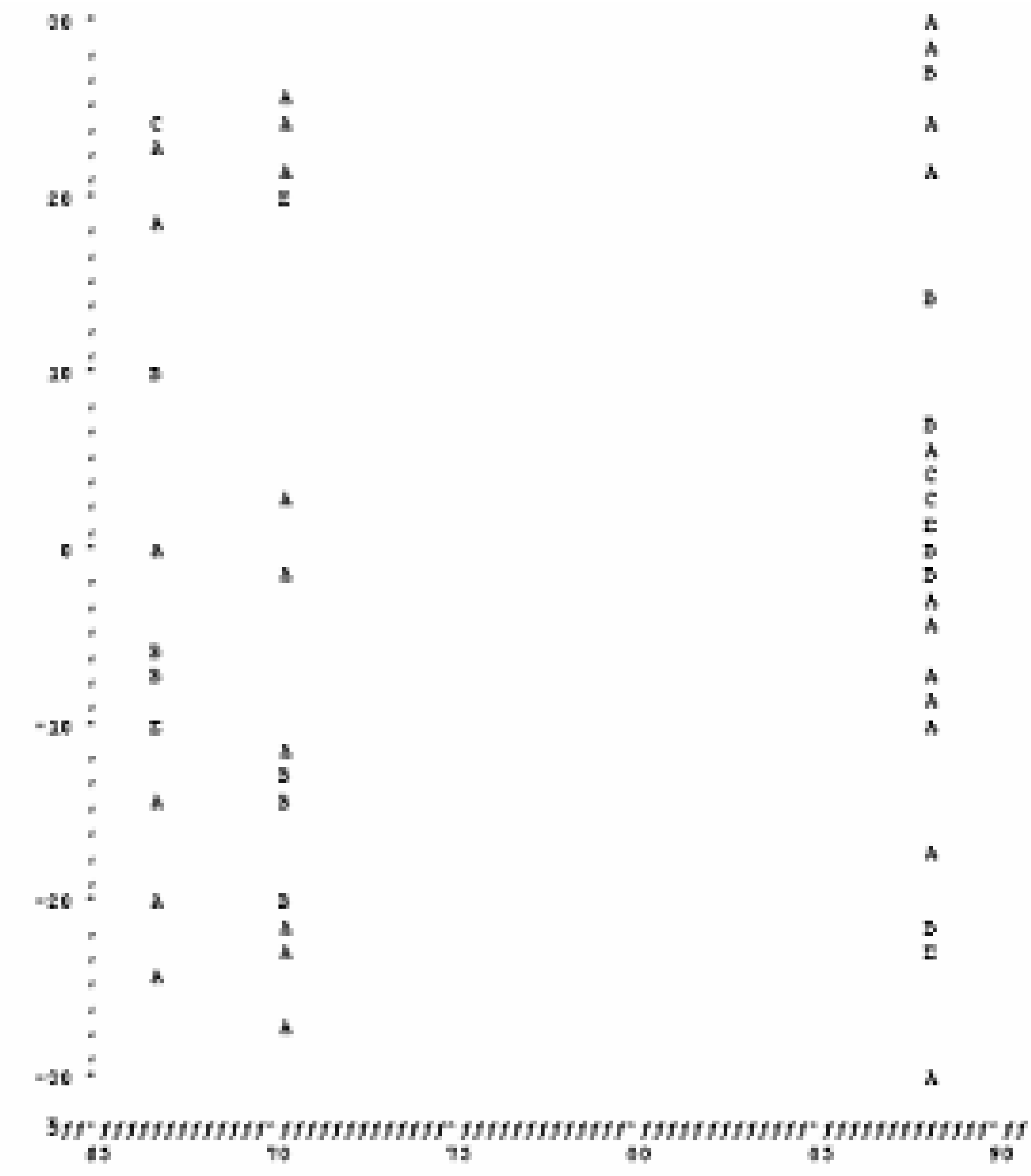

Figure 18: Scatter Plot of Residuals as a function of the Predicted values (YHAT) for Screen Shoulder Trunk Angle in Non-Wheelchair users

Looking at the plots, since the residuals appear structureless and no systematic changes in the spread of the data are seen to occur, therefore they satisfy the 'homogeneity of variances' assumption.

3.2 Productivity

The productivity or the time to complete a transaction was affected by the type of transaction (cash or card) but not by the type of workstation (A or B), nor the interaction between transaction type and workstation type, in the case of both wheelchair as well as non-wheelchair users (Tables 7 and 8).

Table 7: ANOVA interactions between Transaction type and Workstation type affecting Productivity for Wheelchair users

Wheelchair Users	F-value	P-value
Transaction	9.30	0.0031*
Workstation	0.25	0.6193
Transaction*Workstation	0.40	0.5281
*represents statistically significant results (P<.05)		

Table 8: ANOVA interactions between Transaction type and Workstation type affecting Productivity for Non-wheelchair users

Non-wheelchair Users	F-value	P-value
Transaction	63.04	0.0001*
Workstation	2.59	0.1092
Transaction*Workstation	0.00	0.9839
*represents statistically significant results (P<.05)		

The following graphs show the effect of transaction type (cash or card) on productivity, for wheelchair users and non-wheelchair users. For both the user groups, cash transaction takes longer than card transaction.

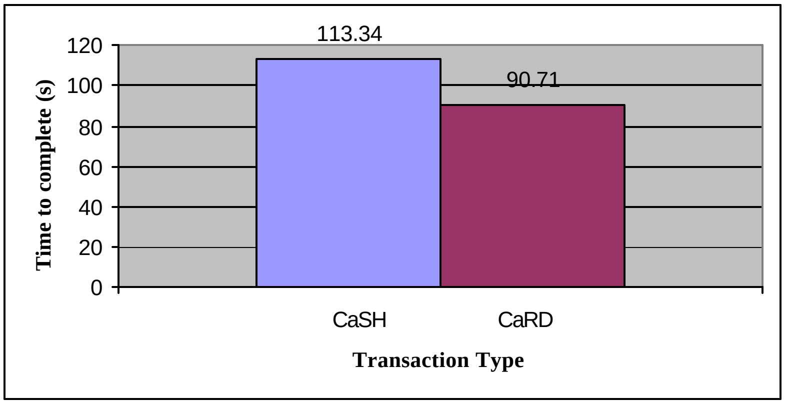

Figure 19: Comparison of Productivity between Transaction types for Wheelchair users

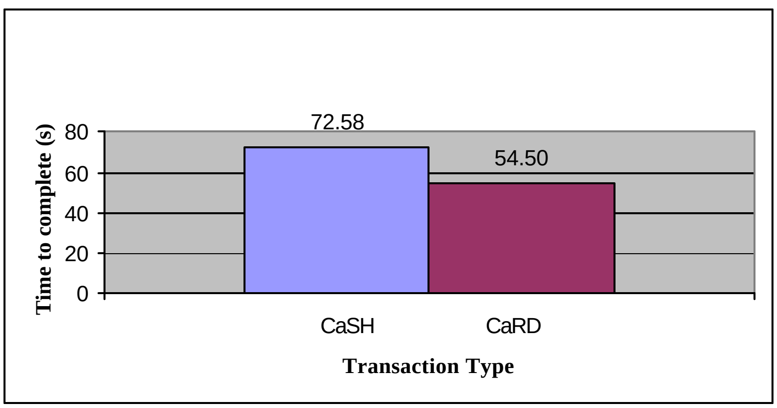

Figure 20: Comparison of Productivity between Transaction types for Non-wheelchair users

For the wheelchair users, the difference in productivity between cash and card transactions is ~20%. For the non-wheelchair users, the difference in productivity between cash and card transactions is ~25%.

3.3 Posture

For the posture data, under the primary division into wheelchair and non-wheelchair users, the results have also been sub-divided into trunk and shoulder posture angles.

Table 9: Mean Trunk Angle (in degrees) as the Wheelchair users reached each of the following components

Components Reached	Workstation A	Workstation B	F-value	P-value	
Card Swipe	15.7	5.3	14.67	0.0005	*
Cash Acceptor	16.1	9.4	7.67	0.0086	*
Coin Acceptor	15.7	9.2	7.09	0.0113	*
Cash Dispenser	6.6	6.7	0.00	0.9586	
Coin Dispenser	7.6	5.0	2.55	0.1187	
Receipt	9.8	2.2	47.99	<.0001	*
Bagging	12.6	6.7	20.68	<.0001	*
Basket	13.5	10.4	2.21	0.1408	
Screen	7.0	3.6	4.00	0.0491	*

* represents statistically significant results (P<.05)

Table 10: Mean Trunk Angle (in degrees) as the Non-wheelchair users reached the following components

Components Reached	Workstation A	Workstation B	F-value	P-value	
Card Swipe	1.0	0.6	0.95	0.3324	
Cash Acceptor	6.3	6.9	0.26	0.6103	
Coin Acceptor	5.7	6.2	0.14	0.7106	
Cash Dispenser	3.4	2.5	1.17	0.2837	
Coin Dispenser	4.9	3.2	2.62	0.1094	
Receipt	2.5	5.8	14.92	0.0002	*
Bagging	13.8	8.3	31.26	<.0001	*
Basket	12.0	11.4	0.49	0.4844	
Screen	1.6	0.2	21.60	<.0001	*

* represents statistically significant results (P<.05)

Table 11: Percent reductions in Trunk Angle of Wheelchair users for significantly affected components

Card Swipe	66.56
Cash Acceptor	41.43
Coin Acceptor	41.72
Receipt	78.01
Bagging	47.33
Screen	48.20

Table 12: Percent reductions in Trunk Angle of Non-wheelchair users for significantly affected components

Receipt	-57.39
Bagging	39.73
Screen	87.60

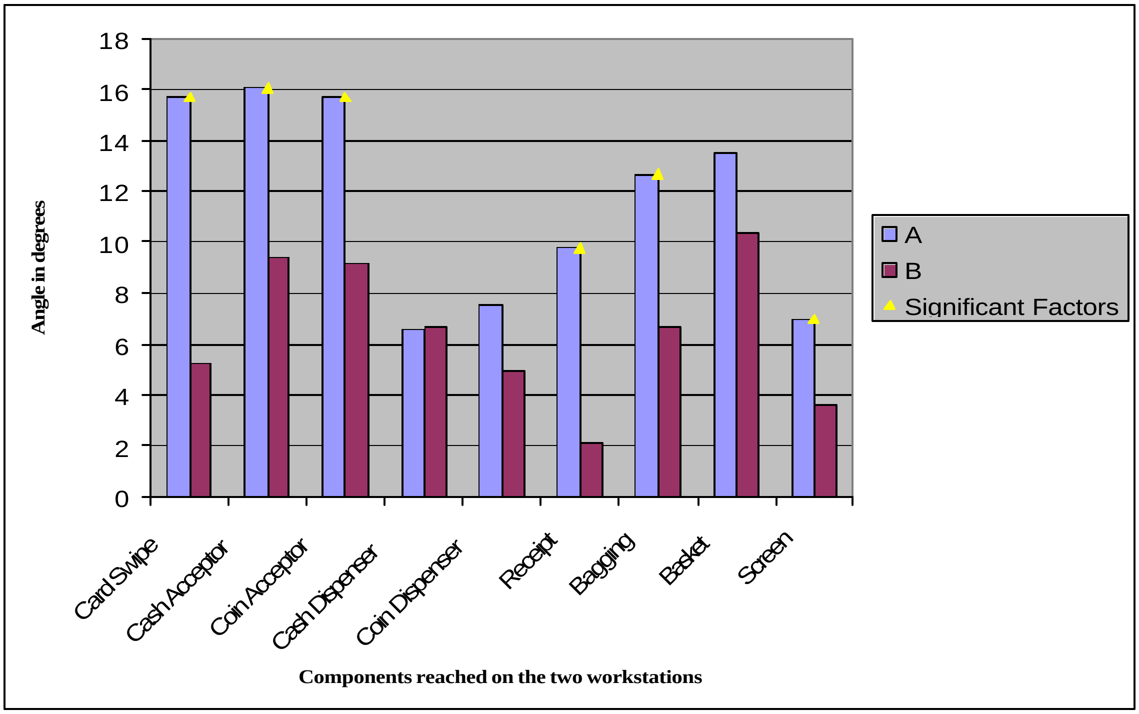

Figure 21: Comparison of Trunk Angle between Workstations A and B for Wheelchair users

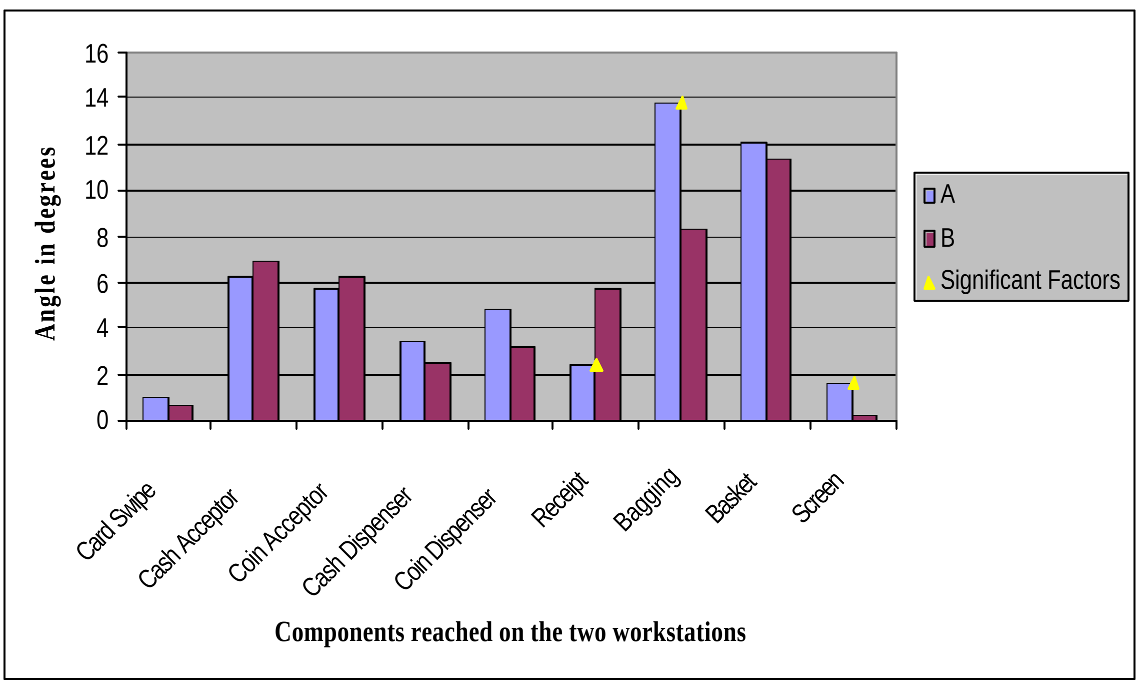

Figure 22: Comparison of Trunk Angle between Workstations A and B for Non-wheelchair users

Table 13: Mean Shoulder Angle (in degrees) as the Wheelchair users reached each of the following components

Components Reached	Workstation A	Workstation B	F-value	P-value	
Card Swipe	107.0	75.9	17.15	0.0002	*
Cash Acceptor	99.2	71.4	30.69	<.0001	*
Coin Acceptor	99.2	68.8	39.58	<.0001	*
Cash Dispenser	95.8	78.0	15.88	0.0003	*
Coin Dispenser	89.6	79.3	6.11	0.0180	*
Receipt	101.5	36.5	411.01	<.0001	*
Bagging	57.4	64.1	3.21	0.0772	
Basket	70.2	47.4	41.27	<.0001	*
Screen	87.2	67.5	27.73	<.0001	*

* represents statistically significant results (P<.05)

Table 14: Mean Shoulder Angle (in degrees) as the Non-wheelchair users reached each of the following components

Components Reached	Workstation A	Workstation B	F-value	P-value	
Card Swipe	47.5	22.8	53.58	<.0001	*
Cash Acceptor	43.6	21.4	111.41	<.0001	*
Coin Acceptor	39.8	19.7	90.16	<.0001	*
Cash Dispenser	36.3	24.6	29.70	<.0001	*
Coin Dispenser	43.7	29.2	63.23	<.0001	*
Receipt	45.0	13.6	206.48	<.0001	*
Bagging	26.6	23.6	6.18	0.0139	*
Basket	24.5	17.4	16.80	<.0001	*
Screen	21.8	13.7	44.66	<.0001	*

* represents statistically significant results (P<.05)

Table 15: Percent reductions in Shoulder Angle of Wheelchair users for significantly affected components

Card Swipe	29.08
Cash Acceptor	28.07
Coin Acceptor	30.65
Cash Dispenser	18.58
Coin Dispenser	11.55
Receipt	64.05
Bagging	32.49
Screen	22.67

It is interesting to note that except for the 'Basket' component, all the components were significantly improved for shoulder posture in going from A to B, for wheelchair users.

Table 16: Percent reductions in Shoulder Angle of Non-wheelchair users for significantly affected components

Card Swipe	52.13
Cash Acceptor	50.89
Coin Acceptor	50.60
Cash Dispenser	32.42
Coin Dispenser	33.10
Receipt	69.85
Bagging	11.32
Basket	29.20
Screen	37.19

It is interesting to note that the shoulder angle was significantly reduced for all the components going from A to B, for non-wheelchair users.

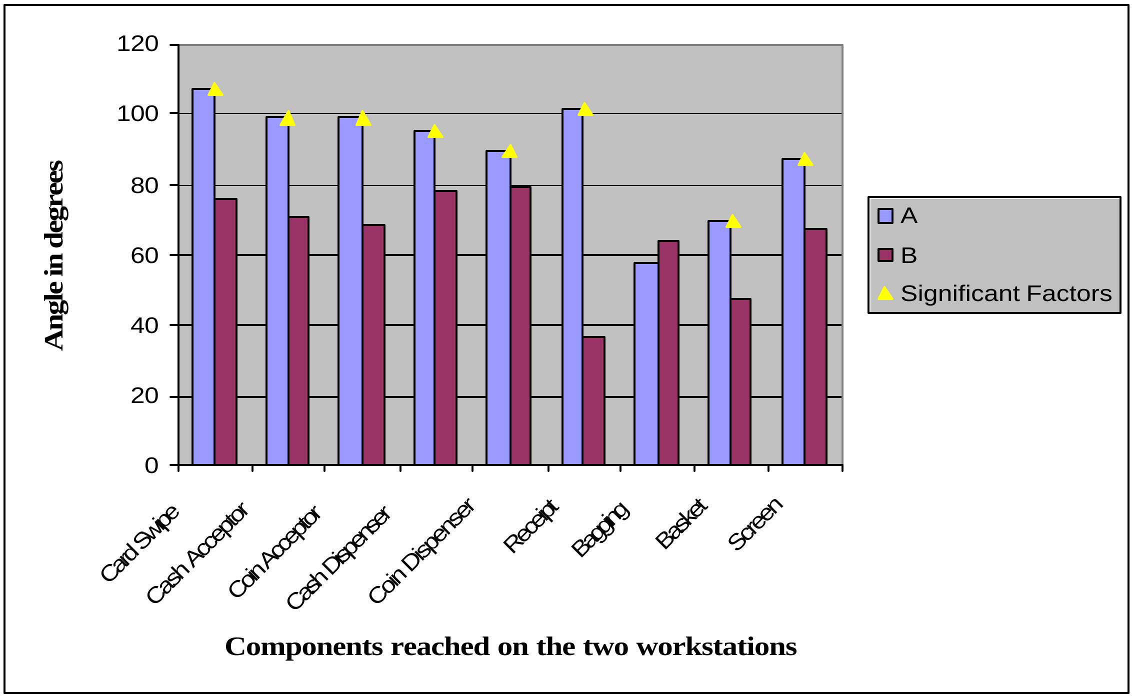

Figure 23: Comparison of Shoulder Angle between Workstations A and B for Wheelchair users

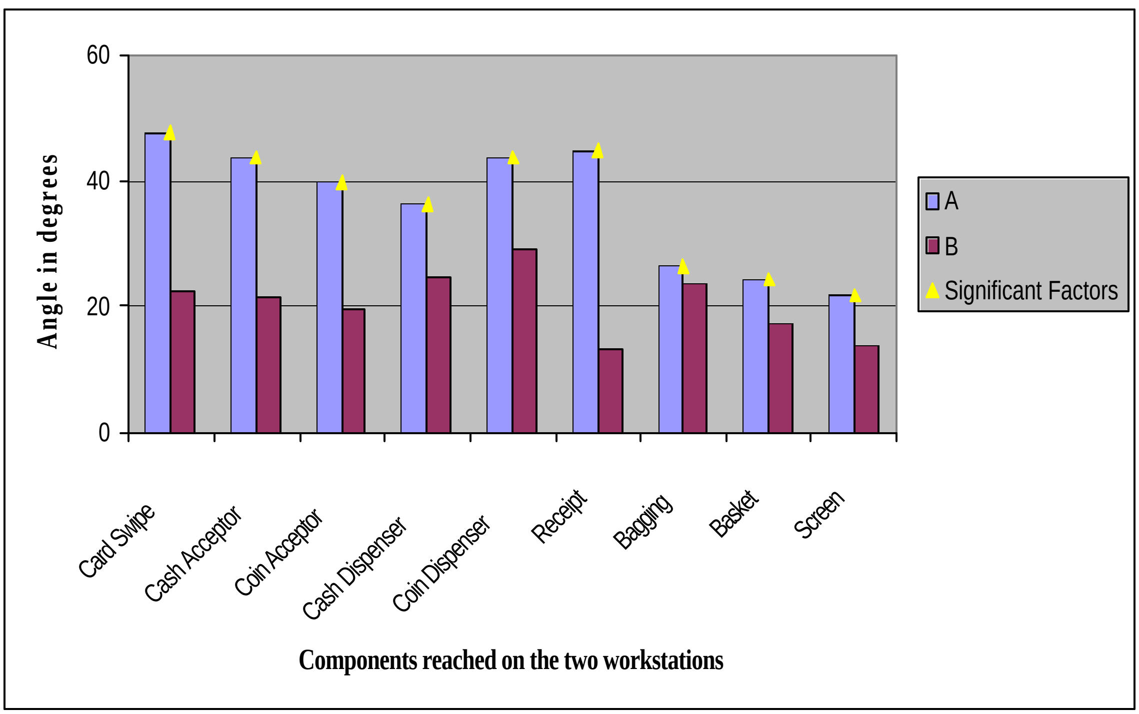

Figure 24: Comparison of Shoulder Angle between Workstations A and B for Non-wheelchair users

3.4 Survey Response

In the 'SCO Redesign Evaluation Survey', a score of 3 means neutrality (i.e. A=B), >3, a preference towards B. From the actual responses, it was seen that all of the five wheelchair subjects responded with a >3 score on 'ease', 'comfort' and 'overall preference'. In 'accuracy' and 'quickness', all of the five wheelchair users responded with a = 3 score. For the non-wheelchair users, it was seen that out of the ten non-wheelchair users, eight responded with a = 3 score on 'ease', seven responded with a = 3 score on 'comfort', nine responded with an = 3 score on 'accuracy', one responded with a > 3 score on 'accuracy', nine responded with a = 3 score on 'quickness' and seven responded with a = 3 score on 'overall preference'. Results show that the average scores for wheelchair users on 'ease', 'comfort', 'accuracy', 'quickness' and 'overall preference' are >3, indicating a preference towards the redesigned workstation (B) among the wheelchair users. For the non-wheelchair users, the average scores on 'ease', 'accuracy', 'quickness' and 'overall preference' are slightly >3 and the average score on 'comfort' is slightly <3.

Table 17: Comparison of SCO Redesign Evaluation Survey Scores between Wheelchair and Non-wheelchair users; Results from the Kruskal-Wallis Test

Variable	Wheel Chair Users	Non Wheelchair Users	Chi-Square	Pr>Chi Square	
Ease	5	3.2	10.1744	0.0014	*
Comfort	4.6	2.9	7.7440	0.0054	*
Accuracy	4.6	3.1	8.2964	0.0040	*
Quickness	3.8	3.4	0.3479	0.5553	
Overall preference	4.8	3.1	8.2895	0.0040	*

* represents significant difference between the two user groups

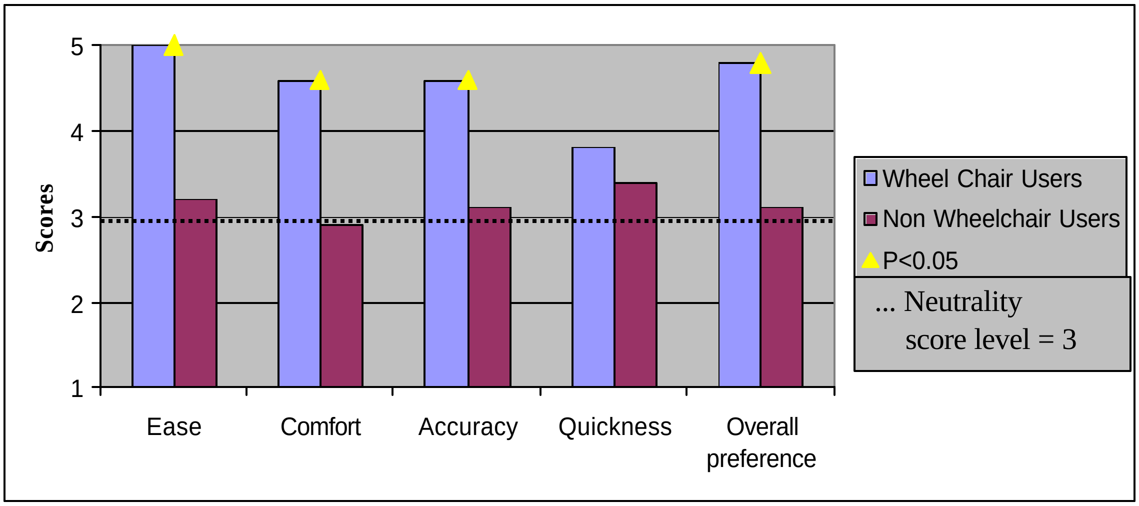

Figure 24: Graph showing difference between the Responses of Wheelchair and Non-wheelchair users on the SCO Redesign Evaluation Survey

For the 'Final Comparison Survey', a score of 2 implied neutrality (i.e. A=B) and >2, a preference towards B. From the actual responses, it was seen that all of the five wheelchair users responded with a score of 3 (preference for B) on 'ease', 'comfort', 'accuracy' and 'overall preference'. On 'quickness', two out of the five wheelchair users were neutral (A=B) and the rest three were in preference towards B. For the non-wheelchair users, it was seen that out of the ten non-wheelchair users, eight responded with a = 2 score on 'ease', five responded with a = 2 score on 'comfort', all ten responded with a = 2 score on 'accuracy', eight responded with a = 2 score on 'quickness' and seven responded with a = 2 score on 'overall preference'. Results show that the average scores for wheelchair users on 'ease', 'comfort', 'accuracy', 'quickness' and 'overall preference' are >2, indicating a preference towards the redesigned workstation among the wheelchair users. For the non-wheelchair users, average scores on 'ease', 'accuracy', 'quickness' and 'overall preference' are slightly >2 (indicating a slight preference for B), while the average score on 'comfort' is slightly <2..

Table 18: Comparison of Final Comparison Survey Scores between Wheelchair and Non-wheelchair users; Results from the Kruskal-Wallis Test

Variable	Mean Scores Wheelchair	Mean Scores Non wheelchair	Chi Square	Pr>Chi-Square	
ease	3	2.2	4.4056	0.0358	*
comfort	3	1.9	4.5000	0.0339	*
accuracy	3	2.1	10.5000	0.0012	*
quickness	2.6	2.3	0.3738	0.5409	
Overall performance	3	2.1	4.3750	0.0365	*
Willingness to use B in preference to A	9.4	6.7	6.5251	0.0106	*

* represents significant difference between the two user groups

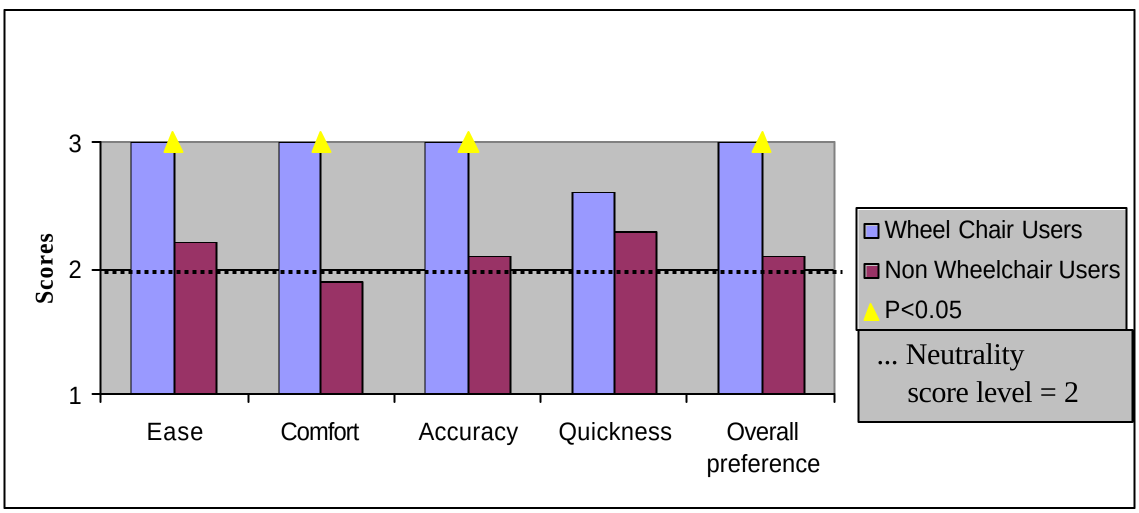

Figure 25: Graph showing difference between the Responses of Wheelchair and Non-wheelchair users on the Final Comparison Survey

For the 'willingness' question on the 'Final Comparison Survey', a score of 5 meant neutrality (i.e. A=B), <5, an unwillingness to use B in preference to A and >5, a willingness to use B in preference to A. From the actual responses, it was seen that all of the five wheelchair subjects gave a 'willingness score' of > 5 (three gave a score of perfect 10; one gave a score of 9 and one, a score of 8). Of the ten non-wheelchair users, eight gave a score of >5, one gave = 5 and one gave much <5 (gave a score of 1, not willing at all to use B in preference to A). Results show that the average score for the wheelchair users on 'willingness' was 9.4 (Table 18), indicating a very high willingness to use the redesigned workstation in preference to the conventional one. For the non-wheelchair users, the average 'willingness' score was 6.7 (Table 18), again indicating a willingness to use the redesigned workstation.

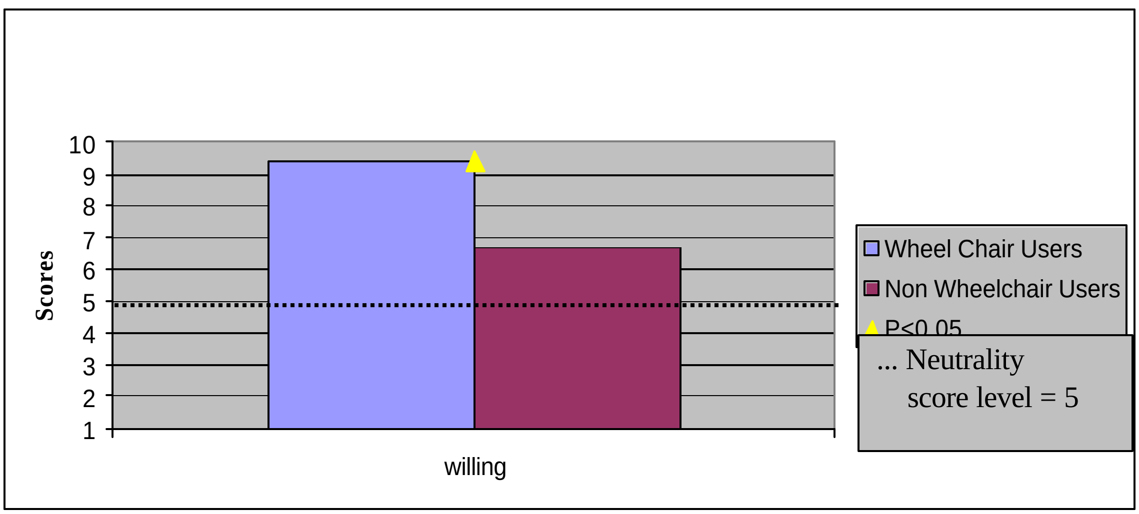

Figure 26: Graph showing difference between the Responses of Wheelchair and Non-wheelchair users on the 'Willingness to use B' question

In the following section, a discussion of these results is presented.

4 Discussion

The over-arching hypothesis of the current study was that a universally designed workstation like that of the redesigned workstation would be better than a workstation which does not conform to the principles of Universal Design, in terms of productivity, accessibility and users' subjective preference. Thus, the sections that follow discuss the significance of the results, what they imply and so in essence, whether the results corroborated the hypothesis or not.

Results from the productivity data revealed that, for both the user groups, there was no significant difference in productivity in changing from one workstation to another. This can be explained by the fact that the sequence of operations was the same on both workstations and the length of the two stations was also not significantly different. One can think the process of checkout analogous to a simplified assembly line. There are two ways of reducing the cycle time (or increasing the productivity) of the assembly line: 1) eliminate, rearrange or combine certain steps in the sequence, and 2) change the method of operation so that the operation now takes lesser time. Now, in case of our workstation redesign, we definitely did not adopt the first strategy of eliminating, rearranging or combining any operations from the sequence. The sequence was kept exactly the same. Though the method of operation was affected, its focus was more on making the task easier than quicker; and there too, since the task is so simple for a non-disabled person, it can't be made much easier for him (or her), but for a person in wheelchair, it did get easier (as seen from the results) and in their case, a very small improvement (a mere mean of 4 s) in productivity was also seen.

The significant effect in productivity was seen across transaction types for both groups. This is very obvious because of the fact that a cash transaction involves more number of steps than a card transaction. The mean value of the cash transaction was 42.8 seconds more for the wheelchair users than for the non-wheelchair users; for the card transaction, the mean of wheelchair users was 36.2 seconds more than the non-wheelchair users. This can help us appreciate the fact that needs of the disabled people are different than the able-bodied. Tasks which require no time for the able-bodied can require considerable time and effort for the disabled people. There was motion economy because of reduced reach distances, but since these were small changes (in reach distances) in small components of the whole process, the overall cycle time was not significantly affected.

In considering the posture data for the wheelchair users, the trunk posture was significantly improved for card swipe, cash/coin acceptor, bagging, receipt and screen. Among these, the most noteworthy are the improvements for card swipe (which reduced the trunk bending from ~16 deg to ~5 deg) and cash/coin acceptor (which reduced the trunk bending from ~16 deg to ~9 deg). For understanding the effects on trunk posture of wheelchair people, it is crucial to know the ways in which they approach systems. Most wheelchair users adopt a sideways approach in reaching components which have no knee clearances under them. In doing so, their trunks don't bend much in the sagittal plane but do so in the lateral plane, thereby generating asymmetric loading in the spine and high shoulder moments. They try to reach out as much as possible with their arm because the sides of the wheelchair restrict their trunks from hanging out over to the side. When there are knee clearances available for them, they use the forward approach to reach where they need to reach. In this case, care should be taken to design components within their maximum overhead reach, so that they don't have to bend over excessively in the sagittal plane and face the risk of tipping out of their chair. That is why the ADA has different reach distances specified for side approach (44" maximum) and forward approach (48" maximum) (28 CFR 36, 2001).

As for the non-wheelchair users, they used the forward approach on both the workstations and all the components on both the workstations were always within easy reach of them. Therefore, their trunk posture did not improve for as many components or in as significant a magnitude as the wheelchair users. What matters is that their posture was not compromised at the cost of improvement in posture among the wheelchair users Although results show that the non-wheelchair subjects' posture deteriorated in the receipt component of B, a little attention to the data will reveal that it deteriorated from an angle of 2.5 deg to 5.6 deg only which does not pose any serious threats to their trunk posture. This conforms to the concept of Universal Design according to which there should be one solution that can accommodate people with disabilities, as well as the rest of the population (Steinfeld, 1994).

Considering the shoulder postures of the two user groups (wheelchair users vs. non-wheelchair users) on the two workstations (A vs. B), the results show a significant improvement for eight out of nine components in the wheelchair user group and all the nine components for the non-wheelchair group. The maximum reduction in angle is for the 'receipt' (~64% for wheelchairs users and ~69% for non-wheelchair users), followed by card swipe (~29% for wheelchair, ~52% for non), coin acceptor (~31% and ~50.5%) and cash acceptor (~28% and ~51%). The results are consistent across groups in that they show the same effect (of improvement in posture) in both the groups. These results again corroborate the hypothesis that the Workstation B provided a more Universal Design, specifically it conforms to the equitable use (Principle 1 of Universal Design, CUD), low physical effort (Principle 6 of Universal Design, CUD) and size and space for approach and use (Principle 7 of Universal Design, CUD).

The importance of these results becomes particularly evident when one considers the prevalence of musculoskeletal disorders in the wheelchair-user population. Previous studies on the biomechanics of wheelchair propulsion have revealed that there is a high prevalence of upper extremity complaints in the wheelchair user population. One of the possible causes for this pain might be high load on shoulder during wheelchair propulsion (Bayley et al., 1987). In a recent study of load on the shoulder in low intensity wheelchair propulsion by Veeger, et al. (2002), it was found that the peak glenohumeral contact forces were between 100-165% of body weight. On an average these forces were 500-850 N. Wheelchair users often experience upper extremity pain that interferes with essential activities of daily living (Curtis et al., 1999 and Pentland et al., 1994). These findings have implications in the current study. Since wheelchair users are more prone to upper extremity disorders, especially shoulder injuries which pose a hurdle even in their activities of daily living which are simple tasks, therefore, care should be taken while designing products so that they require as minimum a loading of the shoulder as possible. In the conventional design of the SCO, the shoulder angle is much greater than in the redesigned version. This implies lesser loading of the shoulder in the redesigned system as compared to the existing system and therefore, an improvement in design from conventional to the redesigned. As for the epidemiology of low-back pains in wheelchair users, we can draw parallels from the epidemiology of low-back pain in sedentary workers. Prolonged sitting has been identified as being associated with back pain but there has not been much research in identifying the cause of this pain associated with seated postures (Burdorf et al., 1993). When reaching sideways, the wheelchair users undergo asymmetric loads in a laterally bent trunk posture. Asymmetric material handling frequently results in lateral bending of torso. Garg and Badger (1986) found 6% to 9% reductions in maximum acceptable weight for each 30 deg increase in asymmetry. They also found that maximum isometric strength decreased by 12%, 21% and 31% for asymmetric lift angles of 30, 60 and 90 deg respectively. Mital and Fard (1986) compared lifting in a 90 deg asymmetric position and found that subjects were willing to lift 8.5% less weight asymmetrically. Each of these factors has been linked via epidemiological investigations to the incidence of low back disorders (Marras and Mirka, 1989). Since wheelchair users remain seated perpetually all the time and since they perform all their activities of daily living in that seated posture only therefore it can be speculated that they are more at risk of low back injuries than the non-disabled people. Also, since they bend laterally in absence of any clearances (as in the conventional design), their strength is reduced which can result in making even a simple task like grocery checkout cumbersome for them. In light of this fact, the reduction in trunk angle of wheelchair users in using the redesigned system is an important aspect.

From results of the SCO Redesign Evaluation Survey, it can be seen that both the user groups' average scores on 'ease', accuracy', 'quickness' and 'overall preference', are above neutrality. It is noteworthy here to know that two non-wheelchair users disagreed that the workstation B allowed them to more easily complete the task – one gave the reason that the space in the bagging area was lesser than in workstation A ("less space to put items after scanning them") and the other found workstation B too low ("too low, my purse slipped off my shoulder when I had to reach down"). Similarly for comfort, one non-wheelchair user found the screen on B too low to be read comfortably ("it was difficult to read the screen because I had to bend my head down") while another found the height of the card reader, coin acceptor, bill acceptor more comfortable on A ("Workstation A more comfortable because of the height of the swiping, coins, bills etc. components"). The standing height of these subjects was less than the average standing height of the non-wheelchair subject group, so their extreme responses cannot be related to extreme heights or to any other extreme anthropometric dimensions. Although such responses were in minority, they became the outliers and affected the mean scores. Thus, it is important to consider them while making future improvements in the design of such systems. It is interesting to note that quickness is not perceived significantly different by both the groups and the mean scores of quickness for both groups are above neutrality. This means that, although in reality productivity was not affected across workstations, both the groups' perceived impression was that Workstation B allowed them to more quickly complete the task. Probably the ease of use on the redesigned system made all the users feel that they were performing the task more quickly on it. The results also show that the magnitude of preference for B is higher for wheelchair users than non-wheelchair users. This again seems obvious because the conventional system offers more challenges to the wheelchair users than to the non-wheelchair users; therefore, the greater the dissatisfaction with A, the more the inclination towards B.

The Final Comparison Survey corroborates all these aspects of subjects' perception of the redesigned system again. The 'Final Comparison Survey', too, shows that the average scores of both the user groups are above neutrality for the redesigned station in terms of ease, accuracy, quickness and overall preference. The subjects who responded in disagreement with workstation B in the 'The SCO Redesign Evaluation Survey', did not prefer it to workstation A in the 'Final Comparison Survey' also. But again the majority of subjects either preferred B to A or were neutral towards both B and A.

Comparing the 'willingness' of the subjects to use the redesigned system, when the only other option is the conventional system, it is seen that the average score for both the user groups remains above neutrality, or in other words, in preference of using the redesigned system to the conventional system. This truly confirms the growing belief in the concept of Universal Design according to which Universal Design can help gathering mass appeal for a product (Steinfeld, 1994).

Universal Design is a much better and more effective alternative to accessible design which focuses only on the needs of the disabled. Accessible design is often expensive, because it employs assistive technology. Accessible design has a medical or institutional appearance, but Universal Design has a more aesthetic appeal. Universal Design can be more generally available at lower costs (Steinfeld, 1994). The current study goes to support this fact as it showed how making simple, inexpensive changes in products, just putting a little thought into designing for all, can result in a more widespread acceptance of the product. Universal Design ensures a wide range of anthropometric fit. The redesigned workstation accommodated non-wheelchair as well as wheelchair users and was even accepted by both the groups. Thus, the study has been fruitful in proving the benefits of Universal Design.

In the larger realm, the study has contributed in laying the groundwork for future research in this field. Universal Design is applicable not only to including disabled people in the design criteria, but so many others with different needs including older people, children, people from different nationalities, and people with restricted abilities for a short period of time. It is estimated that by the year 2030, 20% of the population in the US will be over 65. The purchasing power of this population is very significant. Consumers over 65 have the highest discretionary income in the US. They purchase 60% of all domestic cars and own 50% of all homes. This represents a huge market to be tapped by companies to increase their profitability.

Consumer products and environments should not be designed for Peter-Pan and his friends who live in the Never-Never-Land and never grow old. This does not imply that Universal Design means that the world be fully usable by everybody at all times. It means that it should be usable by those who need to use it comfortably, easily and intuitively. There are so many products that can be designed to include more people. For example, automobiles: people with special needs get them customized according to their needs. At least some features can be improved so that they can be usable by all and not requiring customization for people with special needs. The doors of automobiles, for example, can be designed like automated electro-mechanical doors. The rear-view technology can be improved so as to facilitate the driver to reverse the automobile without having to twist the neck around and stress the cervical muscles. On a yet broader perspective, Universal Design can and should be applied to the parting of information.

For example, multilingual booths can be made at airports where people can go pick up a head-phone (as in music stores) and access information in a language they understand. Or electronic language translators can be provided in lecture halls. The technology for all these things exists today. In fact technology is so much into our lives that we have begun to stop prodding about what more could be needed or asked. Necessity is the mother of invention, true, but today we are at a stage where we need to dig deeper to find what is lacking or better still, create a need for people for something that they never thought was missing before.

4.1 Limitations

One major limitation faced during the course of this study was the limited **previous literature** available on the topic of designing workspaces for the disabled population. The product (U-Scan Express) was first launched by Optimal Robotics Inc. in late 1995 at the Louisville division of Kroger Company. So the product has been in market only for about seven years now and has not reached its maturation stage. This is one reason why no published literature is available on the design issues of Self-Checkout Systems (SCO's). Companies, which are either manufacturers of the system or see future prospects of venturing into the market, have conducted their own private research, but since they have not been published, therefore accessibility to information is difficult. Some of such information was obtained through personal contacts at IBM and NCR. Most of the companies' research at present focuses on the marketing issues of SCO, because this being such a new product, companies are first trying to penetrate the available market for saturation with their systems. So at this stage, major focus is not as much on research and design as on gaining market share with whatever has been accepted by retailers in the first pass. But as more and more of these systems are being installed, consumer feedback is becoming more and more important and in this aspect, the current study is really significant in that it can contribute in the research and design of SCO's when in a few years from now these issues will become really important.

Also, there is no comprehensive database available on the **anthropometry** of wheelchair users. This has been previously discussed in Sec.1.3 and Sec 1.5. This posed a limitation in designing the reach distances of various components on the SCO. In absence of any such database, the Americans with Disabilities Act Accessibility Guidelines (ADAAG, 2002) were used as reference. But even the U.S. Access Board is questioning the usefulness of human factors studies in determining parameters for building and facility design and is actively seeking approaches that may be more appropriate for a technological age (Thibault, 2001). Thus, the reliability of the dimensions suggested for the redesigned workstation is only limited to the present information available on the anthropometry of wheelchair users.

Another big hurdle faced in the study was the **recruitment** of wheelchair users. Several organizations and institutions were contacted – NCSU Student Disability Services, Center for Universal Design, Stalls Medical, Wake Med Rehabilitation Center, Wake Wheelers athletic association to name some - for the purpose of recruitment of wheelchair users, but due to their privacy policies, they could not give me contacts of people. All they could do was pass along the information about this study to their customers/users. Thus my communication with wheelchair users, in the recruitment stage, was not at a one on one level, but through a third party. This could have influenced the number of wheelchair users who, after learning about the study, contacted me and agreed to participate. So the sample size of wheelchair users (five) is not comparable to non-wheelchair users (ten). For the purpose of more reliable and statistically significant results, a greater sample size of wheelchair users would have been desirable.

Another limitation of the study was that it looked at only the physical factors involved in the design of SCO. **Human – machine interface** factors like vision, hearing, screen display, human computer interaction, software usability etc. were not delved into, because that required simulating the point-of-sales system used by actual SCO's. There were both time and resource constraints involved in doing that. Therefore, it was thought best to proceed with the study considering only the physical ergonomics factors – posture, reach, physical discomfort etc.

Another limitation was my ability to access postural angles for certain peculiar situations – e.g. some users used their left hand to reach the various components and the camera was set to capture sagittal view of the right arm only, then most wheelchair users used side approach to reach components on Workstation A, so their angles had to be assessed from lateral view. This could have induced a small percentage error in the postural angle measurement.

Lastly, Universal Design, in essence, should include all users of the product. But because of time and resource constraints, my study included only wheelchair users from the disabled population, ignoring people with visual, audio, perceptual or cognitive limitations. One reason why this was done was that in order to design to accommodate the visually or hearing impaired, issues like human computer interaction would also have to be considered in the design. This, as already explained above, was not thought possible with the time and resources available. Another reason was that the analysis of data obtained from such a study would be much more complicated and require much more time than the current study. So, the decision was made to focus on only wheelchair users.

4.2 Future Research

Even with the above-mentioned limitations, the study can prove to be a major contributing factor in future research studies aimed at integrating the field of ergonomics and user-centered product design.

The anthropometric data collected in the study could be useful in the efforts of making an anthropometric database for wheelchair users, a research project currently underway at the Rehabilitation and Research Center at the State University of New York at Buffalo. Also, since the landmarks for the anthropometric measurements have been properly defined, it could help in measuring and communicating critical postural information in a way that is uniformly useful to service providers, researchers, manufacturers and wheelchair users themselves (Hobson, 2001). Here, it is also noteworthy to mention that since the effects of the study were analyzed on a full-scale model of the SCO, therefore this study could be very useful in studying the anthropometry of users using a SCO and thus developing the design criteria for these systems specifically. As Steinfeld (2001) points out that full-scale modeling can be used to measure functional abilities in context – an approach to physical modeling in which functional abilities are observed as users complete tasks in an environment that has realistic dimensions, tools and fixtures.

I only focused on the static anthropometry of users while collecting data. For future research, it would be informative to look at the functional anthropometry characteristics also, e.g. reach envelopes of, strength characteristics etc. of wheelchair vs. non-wheelchair users in an environment simulating realistic dimensions, tools and fixtures.

The current study looked at the trunk and shoulder posture angles only. Some useful information might be obtained by looking at the neck angle also as some non-wheelchair users did respond in disagreement with workstation B because they found it too low. Thus, neck angles can be measured in order to see whether the neck undergoes significant loading in such operations and to find ways in which neck angle could be reduced to comfortable levels for all users.

Then a major area of future research could be the consideration of human-machine interaction factors in order to design a universally accessible Self-Checkout System. Factors such as, vision, hearing, audio cuing and feedback, screen display, glare issues, etc. play a very important role in designing the user experience with the Self-Checkout System. This would require simulating a point-of-sales system, redesigning it and testing it for different user groups. For those with hearing impairment, visual or tactile cues and feedback should be added; for those with impaired vision, tactile and audio cues should be added. Another design idea that can be tested is to make the design adaptable to the user, i.e. the screen can be made adjustable for height and angle, and the scanner bed can raise or lower depending upon the height of the person or a handheld scanner can be provided to people who cannot reach the scanner bed as it is. The more complex the function, the more a designer has an important role to play. So there is lot of potential for future research in this particular field of designing Self-Checkout Systems for ALL.

Going back to where we started - the role that technology has played in shaping our lives – the existing Self-Checkouts are at a transition stage between wonder and comfort carrier. Like every product's market cycle, this product is today at a stage where companies and brands are searching ways of market penetration and acceptance. But once that stage of market saturation starts to reach and Self-Checkout Systems become as prevalent as the ATM's or the self-service gas stations, then the companies would have to research into improving the functionality of their systems in order to help them attain a competitive edge over their rivals in the market. Therefore, this current research of mine is probably a small leap into the future when Self-Checkouts would become a way of being for the shoppers and everyone would expect it to be there at the highest level of performance. Then there would be no contention that they need to be designed to accommodate ALL users.

Fore even little things can produce tremendous consequences. The ocean is after all, an aggregation of little small streams, brooks, lakes, rivulets, rivers, only meeting at one place and going together for vast unimaginative stretches.

5 Conclusion

The specific aim of this study was to redesign an existing Self-Checkout System and evaluate it from the perspectives of Universal Design. Redesign was done and prototypes of the existing (conventional) and redesigned versions were developed and tested out in a laboratory setting at the NCSU Ergonomics Lab. It was hypothesized that the redesigned workstation would improve the productivity for wheelchair users and not reduce it for non-wheelchair users. This hypothesis was not supported by the results, as productivity was not significantly affected by the type of workstation. Another hypothesis was that the posture of wheelchair users would be improved and the posture of non-wheelchair users would not be deteriorated going from the conventional to the redesigned workstations. This hypothesis was supported by the data for shoulder postures, which resulted in a maximum shoulder angle reduction of 64% for wheelchair users and 69% for non-wheelchair users. Lastly, it was hypothesized that the redesigned workstation would be preferred by wheelchair users and would not be rejected outright by non-wheelchair users. This hypothesis too, was supported by the data. Subjective feedback from both the groups showed a preference for the new design in terms of ease, accuracy, quickness and overall preference although, the preference was higher for the wheelchair group than the non-wheelchair group. The average scores of both the user groups on 'willingness' in using the redesigned system in preference to the existing system were also above neutral – all five of the wheelchair users and 8 out of 10 of the non-wheelchair users responded with a score above neutral for willingness. Thus, it can be concluded upon evaluating the redesigned system that it is definitely better and more universally accessible than the presently existing system (the U-Scan Express) in the market.

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Appendix A

North Carolina State University
INFORMED CONSENT FORM

Title of Study: Redesign and evaluation of the grocery store self check-out systems from Universal Design perspectives.

Principal Investigator: Komal Bajaj Faculty Sponsor: Dr. Gary A. Mirka

You are invited to participate in a research study. The main purpose of this study is to evaluate and compare the usability of existing and redesigned grocery store self check-out systems from Universal Design Perspectives and focusing on the physical ergonomics aspects only.

INFORMATION
In this study, before you begin, your static anthropometric measurements will be taken. Then your dynamic anthropometric measurements will be taken, e.g. reach height, reach envelope etc Then, using the mock-up models of the Self check-out sytem set up in the laboratory, you will be required to simulate the process of grocery check-out. This would involve scanning the items (which would be provided to you), swiping the card through the card reader or putting cash in the bill acceptor, bagging the items and taking the receipt. You will be asked to do sixteen different repititions of the task. Performance of the task will be measured in terms of your subjective ratings, posture while performing and time to perform the task. You must perform at a pace you feel comfortable, take breaks whenever you want to and quit at any point you feel you cannot continue with the task.

RISKS
The task may be a bit physically exerting for you. You may encounter problem in reaching some surface or area which might make the task more difficult for you. For this, I ask you to perform the task at a pace you feel comfortable, take breaks whenever you want to and quit at any point you feel you cannot continue with the task. Also, please take careful look around the area where you have to perform the task. If you feel the clearance space is too less for you to move or you see any object in the vicinity that you think you may hit into, please let me know now.

BENEFITS TO SOCIETY
The research will be very useful in designing a Self Check-Out System that even the wheelchair bound people could use. Each one of us is physically challenged at some point in life - old age or some accident might produce conditions wherein we are unable to continue our work like we normally do. So it is in the best interests of everyone to design a product which could be used universally. This research is intended to design one such product (the self check-out system) which is becoming increasingly popular in

the market today and it is a product which everyone would definitely like to use, for everyone would like to buy their own grocery.

CONFIDENTIALITY
The information in the study records will be kept strictly confidential. Data will be stored securely and will be made available only to persons conducting the study unless you specifically give permission in writing to do otherwise. No reference will be made in oral or written reports that could link you to the study.
A video record of this session will be taken. Only the persons conducting the study, in order to review your use of the systems, will see the videotapes. The material on the videotapes will be deleted after the conclusion of the study.

COMPENSATION
None.

CONTACT
If you have questions at any time about the study or the procedures, you may contact the researcher, Komal Bajaj, at Riddick Hall room 341, or 515-7210. If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact Dr. Matthew Zingraff, Chair of the NCSU IRB for the Use of Human Subjects in Research Committee, Box 7514, NCSU Campus (919/513-1834) or Mr. Matthew Ronning, Assistant Vice Chancellor, Research Administration, Box 7514, NCSU Campus (919/513-2148)

PARTICIPATION
Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed your data will be destroyed.

CONSENT
I have read and understand the above information. I have received a copy of this form. I agree to participate in this study.

Subject's signature ________ Date______

Investigator's signature _________________ Date __________________

Appendix B

SCO Redesign Evaluation Survey

Instructions
• Read each statement
• Please indicate your *level of agreement* by circling the corresponding number.
• When answering questions, *compare* the Workstation B set-up to the Workstation A set-up

Compared to the workstation A:

1) The workstation B allowed me to *more easily* complete the task.

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

Comments:____
____

2) The workstation B allowed me to *more comfortably* complete the task.

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

Comments:____
____

3) The workstation B allowed me to *more accurately* complete the task.

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

Comments:____
____

4) The workstation B allowed me to *more quickly* complete the task.

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

Comments:____

5) *Overall*, I would prefer to work with workstation B.

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

Comments:____

Subject ____

Appendix C

Final Comparison Survey

Instructions
• Read each statement carefully
• Please circle which workstation setup (**B** or **A**) you prefer based on the italicized words.
• If you are equally satisfied with both configurations, then circle both choices.

1) It was *easier* to complete the task using the workstation (**B** / **A**)

2) I was *physically more comfortable* using the workstation (**B** / **A**).

3) I was able to *more accurately* complete the task using the workstation (**B** / **A**).

4) It was *quicker* to complete the task using the workstation (**B** / **A**).

5) *Overall*, I would prefer to work with the workstation (**B** / **A**).

For this question, circle the number corresponding to your feelings

6) Looking at all aspects of the self check-out task (ease of completion, comfort, accuracy and speed), how willing would you be to *use **Workstation B*** imagining that it was built to be installed in an actual grocery store environment. (assuming the other alternative would be the Workstation A kind of system)?

1 2 3 4 5 6 7 8 9 10

Not at all willing Very willing

Subject _____