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Title: Customer Needs Elicitation and Disability Simulation Suit Validation to benefit Knowledge and Methods for Inclusive Product Design

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Current product design methodologies are not conducive to creating inclusive products (products that meet the needs of persons with and without disabilities). In order to reduce the effort and expense involved in creating inclusive products, empathic design principles are applied to discover whether customer needs for people with disabilities can be reliably gathered from people without disabilities using disability simulation. This data collection methodology both increases the safety and ease by which customer needs can be gathered and gives designers an empathic design experience with the products they develop. A disability simulation suit is validated with respect to both its perceptual and physical effects. As part of larger research, this data will be used to make generalizations about the customer needs for inclusive products within the context of modular product design to create inclusive design guidelines. This paper presents the techniques involved in, and the data regarding the collection of customer needs on known product pairs. These product pairs perform the same function, but one is designed inclusively and one is not. Prior work on the identification of modules from customer need statements is extended to more closely address the design of inclusive products.

Customer Needs Elicitation and Disability Simulation Suit Validation to benefit Knowledge and Methods for Inclusive Product Design

by
Jessica Armstrong

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Jessica L. Armstrong, Author

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CONTRIBUTION OF AUTHORS

Latane Cox assisted with the Customer Needs statement interpretation for the study. She also conducted the preliminary peg test analysis and compiled the background information on the disability simulation suit.

Dr. Rob Stone assisted with editing and background content for the Design Engineering Technical Conference paper and editing and content selection for the Journal of Mechanical Design paper. He also helped with analysis decisions for the final results.

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CHAPTER ONE: GENERAL INTRODUCTION

The Big Picture

The overall objective of the KINdReD project (Knowledge and Methods for Inclusive Product Design) is to create fundamental engineering design theory and methods to enable engineers to better perform inclusive design through the design of product families that contain both products for persons with and without a disability. Rather than attempt to design an entire product for a fully able user, a user with a disability, or both, the goal of this methodology is to intelligently identify the base platform for a product, which will satisfy all users' needed functionality as well as the differentiating modules that address specific needs. This makes it possible to create a product family that supports both typical and inclusive designs.

When complete, the KINdReD research will allow designers to leverage the economies of scale provided by a typical product family, to provide products for persons with disabilities. Inclusive product platforms offer economic viability that is expected to lead to more inclusive product offerings. KINdReD recognizes that both users and producers must be included as inclusive design stakeholders in order to achieve widespread adoption of inclusive design practice. Therefore, the research works to create knowledge which will lead to an improved ability to serve a currently underserved population.

Broader impacts are immediately achieved through integrated research activities that include working directly with persons with disabilities through collaborators at both the Texas A&M and Oregon State University sites. This collaborative activity provides immediate impact and extension of the research to a community with limited exposure to engineering research.

One primary contribution of the research is the validation of a disability simulation suit that supports empathic design of inclusive products. One significant advantage of a disability simulation suit is the ability to gather needs from a wider set of customers (rather than solely from persons with disabilities). Another advantage is the opportunity for designers to have an experience matching that of a person with a disability, to better support inclusive design activities. Through their use of and experience in a disability simulation suit, designers can gain exposure to the “human quality of life improvement” aspect of engineering often not emphasized in product design.

Research Motivation

In 2008, 49 million Americans over the age of 15 were recorded as having a physical disability [1]. Based on current demographic trends, the numbers of people with disabilities is expected to increase.

The rights of people with disabilities have been examined and advanced several times since the 1964 passage of the Civil Rights Act [2]. Apart from the ethical and legal rationale for inclusion, the economic benefit of inclusion has been repeatedly shown. Inclusive design should be viewed as a useful marketing strategy because it provides the broadest market segment [3]. Additionally, inclusive design practice often improves performance for all users. A void for an elevator shaft included in residential construction serves as one example. The shaft serves nicely as closet space until the residents find stair climbing too challenging. Another example is the OXO Good Grips product line. Though initially targeted at users with an agility limitation in their hands, the line is now highly popular with typical users [4]. The motivation and interest in achieving inclusive design is in place. The challenge that must now be addressed is how to best perform inclusive design.

Research Specifics

This thesis paper speaks to work done as a subset of the KINdReD project. It takes the form of two publications. The first discusses preliminary results, while the second presents the final results. It concludes with a discussion of additional findings and suggested changes for when collaborators perform confirming research, which will ease some of the issues with the methods that were discovered.

There are three specific hypotheses being addressed by this thesis:

H1: Users with disabilities will identify a common module through the correlation of high weight, high frequency Customer Needs (CNs).

H2: Participants wearing the disability simulation suit will generate a comparable set of CNs as people with disabilities.

H3: Participants wearing the suit will exhibit similar dexterity measures as people with disabilities.

H1 addresses the relationship between customer needs' weight and frequency and how to leverage modular product design methods for use in inclusive design. The gathering and formulation of the data required for this is a major part of this research. The goal is to fill the graph shown in Figure 1.1 with real data and confirm the proposed shape of the Customer Needs space.

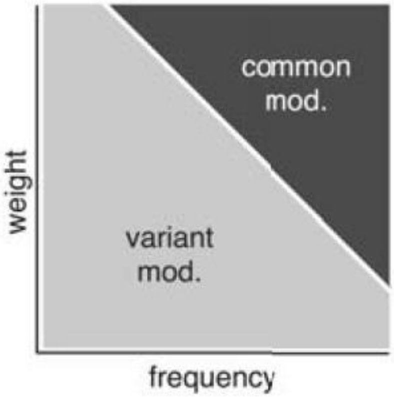

Figure 1.1: Proposed Inclusive Customer Needs space by module region. [5]

H2 and H3 address the validation of the current OSU Disability Simulation Suit. Validation of this mechanism as a tool for customer needs gathering is required before large-scale use can commence. H2 examines the effect of the suit on participants' perceptions of product interactions, while H3 examines a physical aspect of the suit’s restrictions. Simulation has many advantages, such as education of designers and a widening of potential participant pools. But if the suit does not accurately simulating disabilities, CNs collected through this method would not be useful for inclusive design.

Results for the hypotheses tested by the research contained in this thesis are mostly positive. Initial analysis indicates that H1 is likely to be true, but the way the KINdReD project plans to prove this requires a comparison with previous works that is outside the scope of this research. H2 has been proved true with three separate but related indicators of success. However, H3 shows indications of being disproved for the current iteration of the suit.

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Customer Needs Extraction using Disability Simulation for Purposes of Inclusive Design

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CHAPTER TWO: Customer Needs Extraction using Disability Simulation for Purposes of Inclusive Design

ABSTRACT

Current product design methodologies are not conducive to creating inclusive products (products that meet the needs of persons with and without disabilities). In this paper, empathic design principles and modular product design strategies are explored as part of a novel approach to inclusive design. A disability simulation suit is used to test if empathically derived customer needs from persons without disabilities can serve as a proxy for the customer needs of persons with disabilities. This data collection methodology both increases the safety and ease by which customer needs can be gathered and gives designers an empathic design experience with the products they develop. This paper presents the techniques involved in and the preliminary data regarding the collection of customer needs on known product pairs. These product pairs perform the same function, but one is designed inclusively and one is not. Prior work on module identification from customer need statements is extended to specifically address the design of inclusive products. As part of larger research, this data will be used to make generalizations about the customer needs for inclusive products within the context of modular product design to create inclusive design guidelines, which will reduce the effort and expense involved in creating inclusively designed products.

INTRODUCTION

The goal of the overall research is to create inclusive design guidelines for product design by utilizing emphatic design techniques in the context of modular design. The motivation for this is that there are millions of people with physical disabilities not being served by current products on the market.

The British Standards Institute [1] defines inclusive design as "The design of mainstream products and/or services that are accessible to, and usable by, as many people as reasonably possible ... without the need for special adaptation or specialized design." This research is focused on the latter part of this statement by working to create a way for engineers to design inclusive products using more standard techniques.

The current design process for products is not conducive to making inclusive products. Inclusive products are typically niche products that are made in low volume production runs at high cost. The extra time and money required tends to limit their footprint in the market. Therefore, it will be beneficial to develop a methodology that can take into account the needs of persons with disabilities from the beginning of the design process so that products will be made inclusive with less effort and cost.

This is accomplished by drawing on modular product design principles, which lends itself well to meeting the needs of several different groups of customers. The common module can cover the needs of the majority of users and the needs of some users by variant modules. Previous work with these concepts has developed some hypotheses about the relationship between customer needs (CNs) and common modules in terms of the CNs weight and frequency. This research is producing the necessary data to test one of these hypotheses.

H1: Users with disabilities will identify a common module through the correlation of high weight, high frequency CNs.

Since CNs for products for people with disabilities have not been collected, this is the current aim of the project and the subject of this paper.

The secondary goal of the research is to validate a disability simulation suit as a means of soliciting customer needs statements from the larger pool of persons without disabilities, as well as validating the functionality of the specific suit being used. For the suit to be valid it has to change the way participants move (the physical aspect), as well as their mindset (the perceptual aspect). The research will address the perceptual aspect with H2 and the physical aspect with H3.

H2: Participants wearing the disability simulation suit will generate a comparable set of CNs as people with disabilities.

H3: Participants wearing the suit will exhibit similar dexterity measures as people with disabilities.

The preliminary results indicate that there is initial validity to the methods and the suit used in the research. The suit is providing significant, measurable restrictions to the participants, though not the right amount to match the sample of persons with disabilities. Its current iteration provides too much physical restriction. Also, the research was able to produce results for the correlation of weight and frequency of customer need statements to the common module. Preliminary data indicates that the right information is being observed, but more extensive data is needed before the main hypothesis can be tested.

BACKGROUND

Inclusive Design

Recently in the design field, the issue of inclusive design has been rising in prominence. Details on the goals of inclusive design can be found at the University of Cambridge website, The Inclusive Design Toolkit [2]. The work of Clarkson et al. [4,5] has generally set the standard in the inclusive design field. A closely related term found in engineering design is universal design. The Universal Design Handbook [3] provides an overview of the field. The Center for Universal Design at North Carolina State University has compiled seven principles of universal design [6], which have been well received by a variety of designers. However, these principles only provide high-level guidance and are more useful as an evaluation tool than a specific aid for design. The team also recognized that the principles provide only part of the picture by stating, "…the practice of design involves more than consideration for usability. Designers must also incorporate other considerations…" [6]. They use the term universal design to refer to their work. Universal design and inclusive design have closely related meaning and they are often used interchangeably in the engineering design field – even though there are subtle differences.

There has been extensive research on universal design applied to the field of architecture and computer interaction (see examples at [7,8]) and specific guidelines exist for these fields. However, as of yet, these guidelines have not been specifically applied to the product design field. Furthermore, there are ADA (Americans with Disabilities Act) guidelines that inform design for disabilities in the United States, though they primarily address building and infrastructure design [9]. Introductory work in mapping these guidelines into product design has been done in [10,11]. Inclusive design is different from design for disabilities in that it attempts to accommodate both people with disabilities and those without.

Many current product design methodologies are not explicit in their support for creating inclusive products for two main reasons. One, the consideration of customer needs of people with disabilities requires a large pool of potential customers with disabilities. Two, inclusive considerations are made as part of the late stages of design instead of the beginning.

The goal of an engineer during design is to create a product that meets the needs of their customers. In the case of inclusive design this means ALL potential customers. Data describing the needs of persons with disabilities in a readily usable form for designers is sparse. This means that engineers designing inclusive products have to put in extra effort to collect the needs of this hard to reach group for their specific product, essentially starting from scratch every time. This extra effort does not always guarantee success in making the product accessible or appealing.

Furthermore, many product design processes tends to consider issues of accessibility and inclusivity at a late stage or as an alteration to an existing product. Currently, inclusive design is generally done near the end of the design cycle. Figure 2.1 illustrates one example of the engineering design cycle [12]. There are many examples of this design cycle containing different terms and divisions but the underlying structure remains the same.

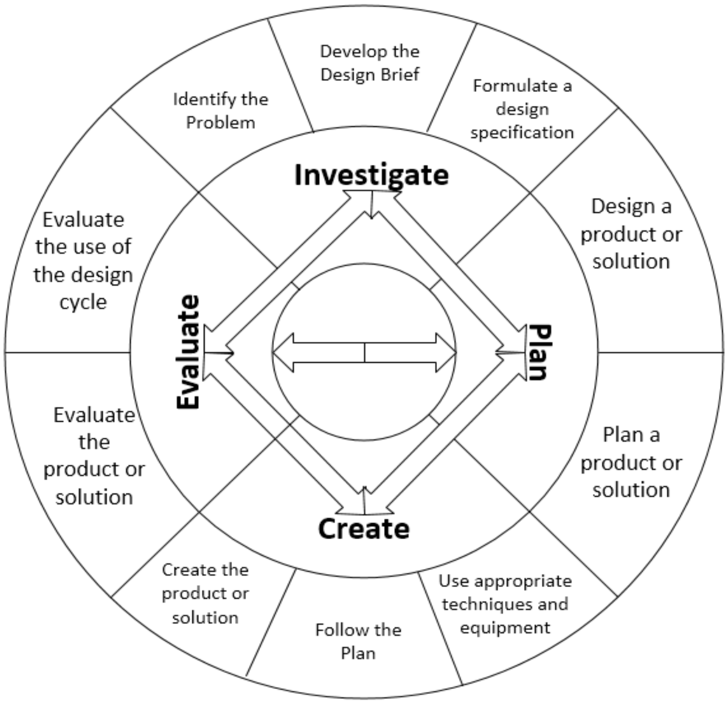

Figure 2.1: The Design Cycle. [12]

The first steps in the “Investigate” stage, are important in making sure that the effort expended in the rest of the design process, here called "Plan", "Create" and "Evaluate" stages, is not wasted by solving the wrong problem. The investigation tasks are there to make sure that the proper issues are identified before work begins on solving them. One of the main aspects of the "Investigate" portion of the design cycle is the collection of customer needs. The lack of information on CNs for people with disabilities as previously mentioned, might be contributing to the choice to perform inclusive design in the later stages.

Consider Figure 2.2 [13]. Under the current practice, a product’s inclusive design might be considered only at the “design for x” stage, near the very end of the process. Other examples of "design for x" include design for manufacture and design for sustainability.

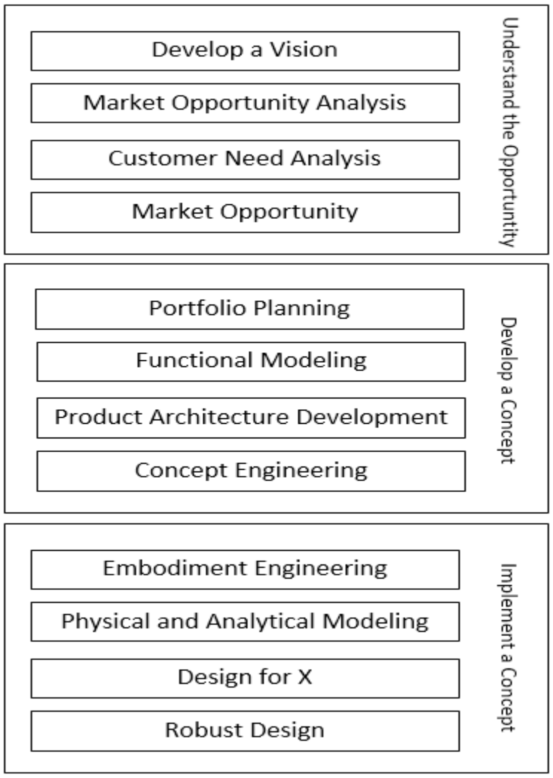

Figure 2.2: A typical product development process. [13]

Other scenarios include a company going through their design cycle with a standard product and reaching their "Evaluate" stage and realizing that the product will not work for persons with disabilities and needing to alter it. Or, someone could reach the "Plan a product or solution" step and decide to create a separate product or an add-on to an existing product to sell specifically to people with disabilities. These types of choices and attitudes mean that accessible products are created at much higher cost than standard products.

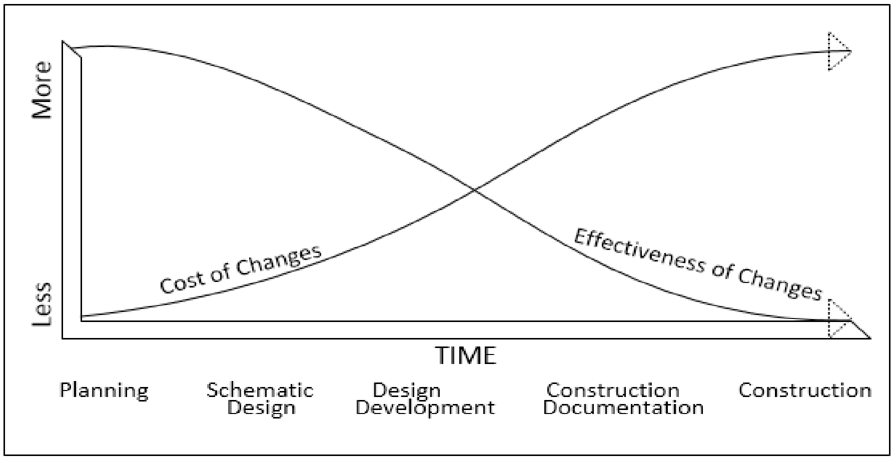

Figure 2.3: The Cost of Change vs. Time. [14]

As illustrated by Figure 2.3 [14], the farther one goes into the design cycle the more any change in design costs. This concept is well known in the design field and similar graphs are found in [15,16]. Since inclusive design tends to be done either as a separate cycle or a late stage change, it tends to cost much more than standard design. Because of this cost few companies are able or willing to do inclusive design. There is a very small subset of the product market currently designated as inclusive. An example of this is the OXO good grips [17] product line.

In order to correct these issues and make a larger percentage of the market accessible to people with disabilities it has been proposed to integrate inclusive design and engineering design. This is a large and complex undertaking that has been given the designation KINdReD (Knowledge and Methods for Inclusive Product Design). [27]

Modular Products

Modular product design methods are an attempt to leverage a common module or platform for multiple iterations (or a family) of a product. In general, this approach drives down product cost by increasing the scale of production of the common module. An important element of these methods is to illustrate the way in which function-based representations allow different criteria to be considered in module-based product family design [18-26]. Specifically, modules for inclusive design can be categorized into 1) common, 2) variant, 3) conditional, and 4) unique. Common modules are based on a function and an associated form solution that is common to both the exclusive and inclusive product. Common modules are used to build the product family platform. Variant modules solve functions that are common to both exclusive and inclusive products but differ in form. Unique modules have differing (or perhaps additional) functions for exclusive and inclusive products. Conditional modules are used to connect exclusive modules to inclusive modules if needed. [27]

Of specific interest to this research is prior work that identifies sets of customer needs that map to the common, variant, conditional and unique modules [28,29]. This work found a relationship between CN weight and frequency for non-inclusive products and persons without disabilities. They found that high weight and low frequency CNs defined the common module for these products as shown in Figure 2.4. In the work, grouped customer needs statements matched the known common and variant modules in a set of existing products.

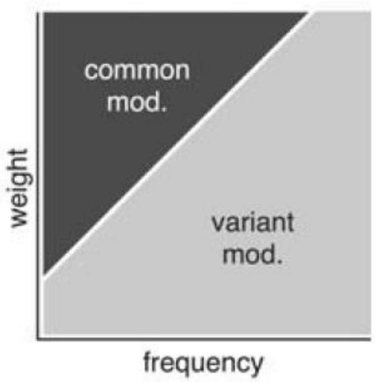

Figure 2.4: Exclusive Customer Needs space separated into module regions. [27]

If the above modular product techniques translate to, or can be extended to, inclusive product design, then any company who wishes to provide products to people with disabilities, can do so more easily and for less money. They will be able to sell a single product (or family of products) to everyone instead of one to able-bodied persons and one to persons with disabilities. This would end the current practice of making accessible products in smaller batches because people with disabilities represent a smaller segment of the market. This practice, while logical, is not optimal because creating products in smaller batches causes a higher cost per item to manufacture, which means accessible products have a higher MSRP (manufacturer suggested retail price). If a company can create a more socially conscious product without expending extra effort, then they are more likely to do so. Therefore, more inclusive products will go to market and they will cost less.

In order to extend the modular product technique, a Customer Needs space similar to Figure 2.4 must be created for persons with disabilities.

Empathic Design and Disability Simulation

The basic premise of empathic design is to expose a designer or customer to experiences with a product in challenging usage contexts or environments [30-32]. This process helps designers empathize with differing sets of customers under differing conditions. It can also expose latent customer needs that otherwise go unnoticed by pushing customers to experience a product in extreme conditions. Empathic design is an extension of ethnographic studies that puts designers and users more directly into challenging usage contexts and can increase the pool of customer from which needs may be solicited.

In order to collect the necessary data about the needs of persons with disabilities, cues from empathic design have been utilized to create disability simulation suits to solicit needs from persons without disabilities in addition to testing with the target population. Disability simulation is useful because it provides researchers a way to expand the potential participant pool. Collecting needs from people with disabilities is difficult due to a variety of factors. Using only persons with disabilities, the needs collection could take a long time. Also, since there are a variety of types and severities of disabilities, the data collected with one sample might be different from that of another sample. Having a suit that accurately simulates disability removes some of the variability in the data since it is always the same type of restrictions. It also allows everyone with the time and willingness to participate to be a useful research subject for studies into the needs of people with disabilities.

Due to the usefulness of disability simulation, it was decided that the KINdReD team would create a new disability simulation suit to match the needs of this research.

The first substantial disability simulation suit is the “Third Age Suit” developed in 1990 by Ford Motor Company [33]. This apparatus’ main goal is to offer engineers a deeper and more accurate understanding of the difficulties the elderly face while driving. Two other relevant full body disability simulation suits were also examined, which focused on recreating the adversities that the elderly face.

Several generations of the age simulation suits created by the AGNES team at MIT [34] were examined as well as the GERT suit by Produkt + Projekt Design [35].

Unfortunately, there were several shortcomings with each of these designs. The main issue is the fact that they provide no restriction for the fingers. Additionally, they are not form fitting, which makes them difficult for smaller subjects to use.

Since these suits did not provide sufficient finger function loss simulation, other products were investigated that concentrated on this area.

Cambridge University constructed a pair of simulation gloves [36] that used plastic strips to impede movement while people flex and extend their fingers. Velcro is attached in order to make this feature adjustable. Georgia Tech University also has attempted to establish an adequate prototype through their Arthritis simulation gloves [37]. Dexterity is reduced in this device through wiring placed on the fingers, however in this product the feature is not adjustable.

While these options are better, both still have several drawbacks such as being uncomfortable or too large for practical use. They would illicit sympathy well, but would not accommodate the actions participants need to do in the studies that the new suit is intended for with KINdReD.

Finally, the Third-Age Simulation Suit utilized by Boeing was examined before the current generation was conceived. It was determined that modifications to the finger, elbow, and shoulder mechanisms were essential in order to provide proper resistance. Several possibilities were considered before the suit was finalized [38].

The current KINdReD suit design is unique for several reasons. Firstly, it is much more adjustable to the participant. Secondly, it utilizes hinged rigid metal mechanisms along the finger joint that limit mobility. Third, it applies a significantly improved amount of resistance to the elbow through a modified arm brace joint.

Overall, the suit provides resistance to motion of all the upper extremity joints to various degrees. Shoulder, wrist, elbow, finger, and a bit of back restrictions are provided through wearable devices. It does not limit range of motion, but it makes every movement more difficult by providing resistance, often in both flexion and extension.

Once validated, the suit can be used to educate designers and others about the problems faced by people with disabilities. This will help them design tools useful for this demographic more specifically.

Figure 2.5: Picture of current KINdReD disability simulation suit.

RESEARCH METHODOLOGY

The research approach is to first investigate the correlation between customer need frequency and weight for persons with disabilities. The underlying belief is that data from persons with disabilities will indicate a different relationship between the customer needs and the modular product than that of persons without disabilities. Examine the difference between Figure 2.4 and Figure 2.6. The needs common to all types of people with disabilities is hypothesized to be the top right corner of the need space instead of the top left corner as is common between all non-disabled users. This research is trying to confirm the relationship in Figure 2.6. Stated formally:

- H1: Users with disabilities will identify a common module through the correlation of high weight, high frequency CNs.

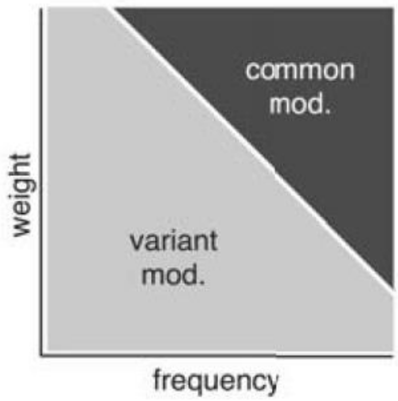

Figure 2.6: Proposed Inclusive Customer Needs space by module region. [27]

The focus of this subset of the research is in gathering the customer needs from people with disabilities in order to create this graph with real data and test H1. The common module, as described by people with disabilities, will include high weight needs and high frequency needs. The interaction of these factors is the most important and high F and high W needs should certainly be considered as part of the common module when designing inclusive products. This interaction is what the study is investigating. Finding a logical set of needs in the upper right corner and matching them to the known functions of the products will confirm the hypothesis.

The second objective of this research concerns testing a hypothesis that empathic design strategies in the form of a disability suit can allow non-disabled persons to identify customer needs that closely approximate those made by persons with disabilities. The disability suit developed by KINdReD is used to simulate, for able-bodied individuals, the experience of functioning with physical impairments. Stated more formally, the hypothesis is:

- H2: Participants wearing the disability simulation suit will generate a comparable set of CNs as participants with disabilities.

If subjects wearing the suit are noticing the same issues with the products as the subjects with disabilities then the restrictions that the suit are providing support an adequate simulation of these disabilities. This measure of similarity is delicate and somewhat subjective. Therefore, a quantitative measure of suit performance is also desired from the study, to speak to the logistics and validity of the data. If the suit is simulating disabilities properly, then H3 will prove true.

- H3: Participants wearing the suit will exhibit similar dexterity measures as persons with disabilities.

Data Collection

Products: In order to collect the customer needs, interviews/protocol analysis was performed using previously studied product pairs. The product pairs consist of two kitchen products that perform the same overall function and require manipulation by a user's upper extremities, one of which is designed inclusively, one of which is not. Initially the proposed method uses products for which the module information is already known from previous research [25,26]. If similar customer needs lists for each module match the lists that are already known for the products then the proposed method is accurate and can be used to investigate the modules of unknown products. The products under investigation for this portion of research are pairs of can openers, jar openers, garlic presses, and ice cube trays. Provided in Figure 2.7 and 2.8 are two example of product pairs. Visual observation reveals obvious differences in the form of these products. This research is concerned with their functionality and usability.

Figure 2.7: Ice cube tray product pair. The inclusive product is the mastrad® ice cube tray with orka® patented Technologies on the left and the standard product is the Rubbermaid® easy release ice cube tray on the right.

Figure 2.8: Can opener product pair: The Zyliss Swiss Innovation® can opener on the left is the inclusive product and the Swing-A-Way® Portable Can opener on the right is the standard product.

<u>Participants</u>: The participant pool was chosen to best represent the entire population. There were no limitations on the able-bodied participants other than their willingness to be recorded and placed in the disability simulation suit. It was important to interview a wide variety of perspectives since different backgrounds yield different statements and perspectives of need importance. The participants with disabilities were limited to those with upper extremity physical disabilities because the upper extremities are what are needed with these products and what the suit is restricting. These participants were asked to describe their physical restrictions so that

ICF classification [39] data will be available for use in later stages of KINdReD research. This will be helpful in considering the effects of specific disabilities.

This research deals with three sets of data. Group 1 data is the statements from persons with disabilities. Group 2A data is the statements from people with no disabilities. Group 2B data is the statements from the same able-bodied people going through the test while wearing the disability simulation suit. These will be referred to throughout this paper as Gr1 and Gr2A and Gr2B.

Test situation: Tests were performed in a laboratory conference room at Oregon State University. The participant always sat at a table during the test in order to give a common situation and not allow any participant to gain extra leverage by standing. The participants were requested to use all of the products and talk through their thoughts and experiences with each. They were given an explanation and example of a protocol analysis and directed to follow that format. The interviewer did not conduct direct questioning or inject any biasing information, only asking for clarification and expansion when needed. For example, a participant could say, “that was hard” and the interviewer would ask, “hard in what manner” to try and illicit a more descriptive statement.

The participants were video recorded in order to capture every detail of their responses as well as their actions. The video camera was set up to capture all the motions and manipulation of the products clearly without seeing the participants’ faces. It was anticipated that many of the responses would be of the sort "well this (point to feature) right here is not very good at this (demonstrate task)" and it would be an important component of the research to know what "this" was. Therefore, video recording was helpful in limiting the data loss that is often problematic in interview data collection.

Suit Validation Data: In order to test the restriction imposed by the suit in a quantitative manner, the 9-hole peg test [40] was employed. This test is used by occupational therapists to measure manual dexterity. This is a simple test in which participants insert pegs into a board and then remove them, as fast as they can, and are timed as to how long it takes. It involves movement of most of the restricted joints. It is designed to give a measure of dexterity and the normal population distribution data from the test is a useful baseline for comparison. It also addresses the difference in functioning of the dominant and non-dominant hand. This is the only feasible quantitative measurement available that applies to this suit.

The participants were also asked to provide opinions on how well the disability simulation suit works. These will be helpful for the team to know where the strengths and weaknesses of the suit occur from the perspective of the user.

Data Analysis

A large part of the data analysis process was being able to translate the various phrases used by the participants into a common meaning. For example, if Participant Four says, "I cannot grip this" and Participant Seven says, "This is too slippery" they both mean the same thing, and this can be translated into the CN of "Product should have a good gripping surface". This analysis was performed by two researchers, watching and listing separately, in order to catch any inconsistencies in the interpretation. The fact that there were only 3 out of 53 statements that differed between the lists proved that this interpretation method works well.

After all interviews are translated, the CNs can be aggregated in terms of weight (W) and frequency (F) in order to test hypotheses about the relation between W and F and modular product design. The frequency data is achieved through statement tracking and manual clustering. For the finished research, the same participants who were interviewed will provide the weights for the CNs. They will be given the completed list of customer needs (with NO frequency data) and asked to rate each CN by importance on a scale of 1-5, 5 being the most important. However, the preliminary data in this paper contains weights provided by members of the OSU Design Engineering Lab, who were instructed to imagine themselves as disabled when ranking the list. This was done since letting the participants view an incomplete list before presenting them with the final list of CNs would bias their rankings and skew the final data.

Tracking the number of participants versus the number of unique (i.e. not previously mentioned) needs identified by that participant will yield an asymptotic curve which will assist in deciding when data collection is sufficient. This is standard practice in design studies in showing when an investigation has received most of the available information. When the number of unique statements per person drops off significantly, the study can be considered to encompass the majority of the possible statements. This exercise corresponds with findings from Griffen and Hauser [41].

RESULTS AND DISCUSSION

The customer needs based results presented in this paper are limited to statements from a subset of Group 1 (the persons with disabilities). The customer needs presented represent an aggregated set of statements made for all four product pairs made by Group 1 participants. However, the suit validation results are based on the test measurements of the final participant set.

Module Identification

Figure 2.9 shows the knowledge content graph created for the initial study results, which shows the rate at which product knowledge is being collected. The shape of the curves indicates that the study data is following the expected trend and that the new information obtained by each new customer is decreasing. A few more samples with little or no additional information will prove that an asymptote has been reached and collection can stop.

Only information from the interviews with persons with disabilities is included in the results, as it has not yet been proven that the statements from Gr2B can be considered equivalent to Gr1.

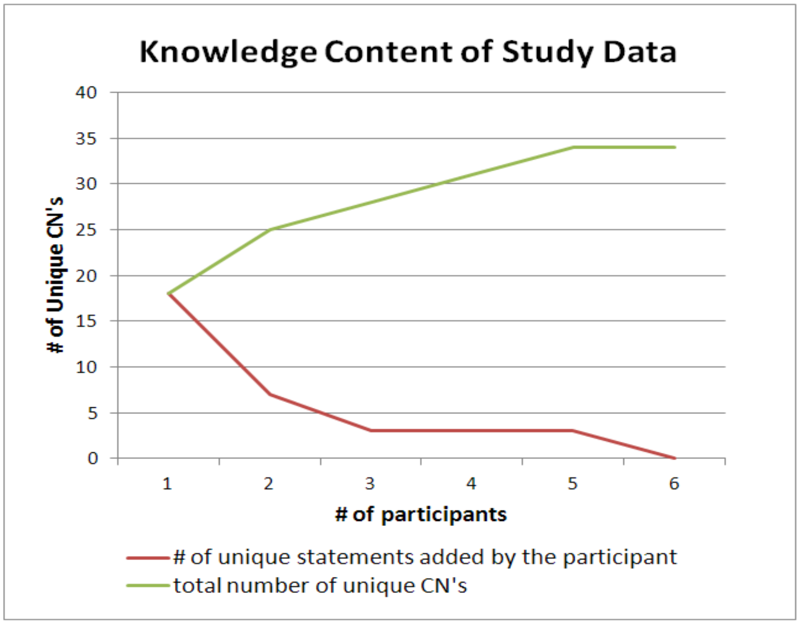

Figure 2.9: Example of knowledge tracking graph using preliminary results.

For the initial results, six interviews from participants in Group 1 were examined. CNs were developed and their frequency tracked. The presented weights are from lab members and not from the participants in order to not influence participants before all data is collected. The participants will not see these weights or this list. The values are the average rating for each need based on the response of 5 people. This number was chosen to simulate the expected response rate (80%) to the final questionnaires.

Even with only 6 participants, the list of CNs contains 34 unique entries. The customer needs presented in this paper are a compilation of all the statements for every product used in the study. While the functionality of the products pairs is similar, they are not exactly the same. For example, “easy to twist” is not a need that would accompany the garlic press, but is important to the products that have twisting as part of their functionality. Future analyses will avoid this applicability issue by separating statements by product and creating a list and graph of CNs for each product pair.

In order to test the hypothesis, the weight vs. frequency graph is created and the module separation line is drawn based on the form hypothesized in H1 (i.e., to match Figure 2.6) to designate a common module space in the upper right corner. The customer needs falling in the common module region will be evaluated at a later stage to determine if they relate to the common modules of the four product pairs used. A cut-off line was chosen for the initial data so that the common module includes frequencies alone of 3 and higher. This represents the needs that are mentioned by half the participants sampled. The cut-off chosen for weight alone is anything with an average rating of 4 and higher. However, the interaction/combination of these factors is the most important aspect. The common module space proposed is a triangle, not a square, meaning some needs below each cut-off can be included if they are high on the other value. This meant two CNs with a lower weight were also included since they had a high frequency (see the corner of the triangular space in Figure 2.10). If there had been a CN at (2,5) it would also be included.

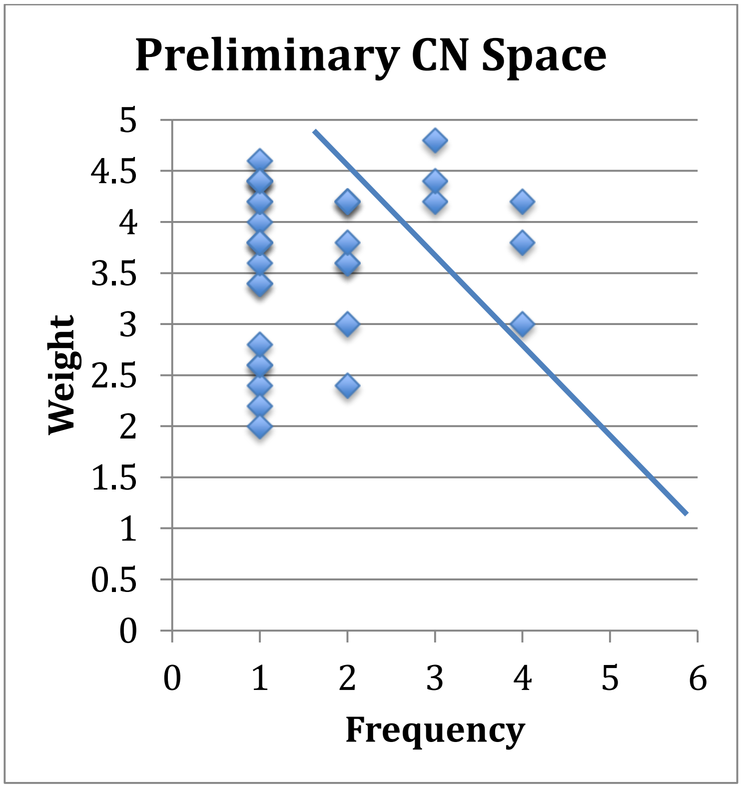

Figure 2.10: Illustration of the module separation line to match the proposed graph.

The graph in Figure 2.10 illustrates the line placement activity clearly, showing how the created graph matches the theoretical graph. The needs that have been determined to be part of the common module based only on preliminary results are listed in Table 2.1.

TABLE 2.1: CNs in the common module & their values.

Customer Need	Weight	Frequency
Product should be easy to grip	4.8	3
Product should hold items securely	4.4	3
Product should be simple	4.2	3
Product should be easy to understand	3.8	4
Product should not be heavy	3.0	4
Product should not require large forces to use	4.2	4

As the study continues to collect more data, there will likely be a wider spread in the frequency so that determining what to consider as high frequency will be more challenging. An important part of the research, once all the data is compiled, will be deciding where to place the line. Changing the cut-offs for what is considered “high” on either axis, or changing how the interaction of the effects is viewed, will place different needs in the common module.

For the final study, H1 is evaluated based on whether the customer needs in the upper right triangular region map to common modules of the actual product pairs. However, for the initial study, the authors’ evaluation of the mapping of customer needs to common module is used. The fact that the needs identified for the common module would apply to any product in the set indicates that the research methodology is on the right path.

Once the suit is validated then statements from Gr2B can be added to the graph to widen the data pool. This may result in more or less needs in the common module space. The results of the peg test measurement of suit validity hints at the likelihood of being able to include this group in the future. However, testing H2 by comparing the CN lists from Gr1 and Gr2A must be performed before a final decision can be made. If the lists are similar enough, the groups’ statements can be combined, if not, then the suit is not simulating the perceptual aspect properly and they must remain separate and the collection method of using simulation is not valid. Preliminary data does not include sufficient information to perform this comparison.

Suit Evaluation

The peg test data presented is not preliminary but final data. It includes results from all participants in the research. The study was completed with 11 subjects in Group 1 and 14 subjects in Group 2. Of the 25 total subjects, 23 also participated in the peg test. Of these participants, 14 were female and 9 were male, whose ages ranged from 18 to 64 with a mean of 30 and a median of 26. One issue with the peg test data was the largely unequal variances between sample sets. Therefore, any t-test not performed on paired data was a type 3 test, as defined by Excel.

A set of two tailed, unequal variance t-tests were used to compare the mean test times of Gr2A to the mean adult norms for the 9-hole peg test given by [40] in every subcategory (male and female, dominant and non-dominant hand and whole group averages). Since 5 out of 6 of these tests resulted in a p-value greater than .05 (p-value ranged from .043 to .963), it is apparent that they are not significantly different. This provides initial evidence that the sample population is a valid representation of all people.

A one tailed, type 3 t-test was used to compare the peg test times from Gr1 (people with disabilities) to the times of Gr2A (people with no disability). Given that this yielded p-values less than .01 (p-value = .0008 for dominant hand and .004 for non-dominant), the conclusion is that the peg hole test times for subjects from Gr1 are statistically significantly slower than those times for Gr2A. This mean the sample of people with disabilities is exhibiting an appropriate reduction in effectiveness for the purposes of comparison.

Using a one tailed, paired t-test, it can also be determined that the mean test times from Gr2B (persons with no disability wearing the disability simulation suit) are significantly slower than the mean test times of Gr2A (p-value = 2E-5 and 2E-7). This means the slowing effect of the suit on participants is measurable and statistically significant.

An unpaired, unequal variance t-test between Gr1 and Gr2B yields a p-value less than 0.01 (p-value = .005 and .0003) indicating that they are significantly different results. This means that even though the samples are good and behaving as expected in terms of directions of change, H3 must still be rejected.

TABLE 2.2: Peg test results for ALL subjects (in seconds).

Group	Dominant Hand Speed (avg)	Non-Dominant Hand Speed (avg)
Gr1	23.3	24
Gr2A	19.9	21.3
Gr2B	30.1	36.5

The average speed for the peg test of subjects from Gr2B using their dominant hand is 6.4 seconds slower than that of Gr1 subjects using their dominant hand. The average speed for the peg test of subjects from Gr2B using their non-dominant hand is 12.5 seconds slower than that of the Gr1 subjects using their non-dominant hand. The suit slows the test times of Gr2A subjects' dominant hands on average by 51.26% and their non-dominant hands by 71.36%. This is a larger effect than is desired if the goal is to match the Gr1 data.

Due to these observations, the suit can be said to do a sufficient job of slowing down the reaction time of the subjects with no disabilities. However it does not appear that it slows the times to ones that accurately represent those of the subjects with upper extremity disabilities.

This could be due to the specific people in the Gr1 sample. It is a small sample and might not contain an accurate range of impairments. Enlarging the sample of people with disabilities might bring the numbers closer. Alternatively, it could indicate that the suit is working well and simply requires adjustment in future to tone down or change the finger impedance mechanisms to a more accurate degree of restriction.

CONCLUSIONS AND FUTURE WORK

H1 is showing initial indications of being true, based on the location of logical and general CNs in the common module space. H3 has proven false based on the peg test measurements for the suit under these experimental conditions.

The first step in the continuation of this research will be to create the separate CN graphs for Group 1 and 2. This will yield Gr2A and Gr2B data to use for the planned statement comparisons for H2 as well as the ability to move forward with confirming H1.

It is necessary to create separate weight vs. frequency graphs for each product in order to compare the CNs placed in the common module using this research methodology and the CNs in the common module found from previous research. This will be done on the final study date as part of future work.

If the comparison reveals only a small difference, then that difference will be examined to inform the line placement decisions. However, if this comparison shows a very large difference, then the validity of the hypothesis H1 will be challenged.

If the hypothesis holds, and the collection methods are sound, then the research can move forward to integrating the study findings into the larger KINdReD context and creating the inclusive design guidelines that are the ultimate goal.

Testing H2 is a qualitative analysis of suit performance. This is achieved by comparing the data from the Gr1 and Gr2B. If the need statements are very similar then the group's experiences are equivalent and can both be used to draw conclusions. Comparing the lists of needs extracted from each group will also identify if there are conflicting needs that the inclusive design guidelines have to address specifically.

Another piece of work that should be done is comparing the conclusions about the validity of the suit drawn from peg test data with that drawn directly from participant comments about the suit and the change in their product preferences. The difference between these comparisons and the interaction of conclusions from H2, H3 and H1 will help to inform future research direction. If the conclusion stands that the suit is too restrictive, effort can focus on modifying it to add adjustability to make it capable of simulating a wider range of disabilities, and not just the extreme cases. If the conclusion is conflicting, the focus can be on widening the participant pool for Group 1 in order to get a more representative population and using the ICF classification information to analyze the validity for certain subpopulations

After the specifics of this research are validated, then work can begin on integrating these findings into the larger KINdReD research to create the inclusive product design guidelines. Then, examining another set of products, using the same methods, will confirm the general usefulness of the KINdReD research.

One possible avenue of interest in the future is in combining the results from KINdReD with the developing natural language processing (NLP) field. Using NLP software to examine the videos and develop the same graphs and then comparing the results would provide a commentary on both the KINdReD methodology and the effectiveness of the software.

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A Validation Study of Disability Simulation Suit Usage as a Proxy for Customer Need Statements from Persons with Disabilities

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CHAPTER THREE: A Validation Study of Disability Simulation Suit Usage as a Proxy for Customer Need Statements from Persons with Disabilities

ABSTRACT

Current product design methodologies do not typically address the creation of inclusive products (products that meet the needs of persons with and without disabilities). In this paper, empathic design principles and modular product design strategies are explored as part of a novel approach to inclusive design. The use of disability simulation as a data collection methodology both increases the safety and ease by which customer needs can be gathered and gives designers an empathic design experience with the products they develop. Before use, it is necessary to determine if the suit accurately mimics physical behaviors of persons with disabilities in users of the suit, and also if empathically derived customer needs from persons without disabilities can serve as a proxy for the customer needs of persons with disabilities. Two key hypotheses were tested regarding the validity of the current disability simulation suit design.

INTRODUCTION

In 2008, 49 million Americans over the age of 15 were recorded as having a physical disability [1]. Based on current demographic trends, especially the aging population, the number of people with disabilities is expected to increase.

The proliferation of activist groups and government regulations regarding the rights of people with disabilities has increased the importance of creating products that integrate their needs into all facets of living [2]. Apart from the ethical and legal rationales for inclusion of people with disabilities, there is the additional economic benefit of targeting a wider consumer base.

Inclusive design is advantageous in that it not only addresses the needs of a specific population, but should also provide a product that can improve performance for all users. It is not the addition of requirements for specialized design, but rather a new way to approach the design task. It also provides an excellent marketing strategy [3]. A good example of effective inclusive design is the OXO Good Grips product line. Originally targeted at users with hand use limitations, the line is now popular with typical users as well [4].

The new challenge for inclusive design is implementation. The motivation and interest in producing inclusive product is there. It is simply hard for people to know where to start and what to do. Inclusive design is defined by the British Standards Institute [5] as "The design of mainstream products and/or services that are accessible to, and usable by, as many people as reasonably possible ... without the need for special adaptation or specialized design." Focusing on the second part of this statement, this research is working to create methods whereby engineers can use common techniques to create inclusive products.

In order to provide the information necessary for the practice of inclusive design at an early stage of product development, and allow for products to be developed with more cost effective, function-based, modular product techniques, integration of standard engineering design and inclusive design principles is needed. This new approach would serve to make a larger percentage of the product market accessible to people with disabilities.

The results reported in this paper are part of a multifaceted, long-term project that has been given the designation KINdReD (Knowledge and Methods for Inclusive Product Design) [6]. Its goal is the creation of Inclusive Product Design Guidelines that provide designers with knowledge and techniques that will make the inclusive product design process cheaper and easier to perform.

The specific scope of the project covered by this paper is the collection and formulation of customer needs for people with disabilities. As part of this activity, a disability simulation suit is used, and evaluated for validity. This research is testing two hypotheses about the functionality of the suit. HA tests the perceptual effect of the suit and has three component contributions. HB tests the suit’s physical effect.

HA: Participants wearing the disability simulation suit will generate a comparable set of CNs as participants with disabilities.

HB: Participants wearing the suit will exhibit similar dexterity measures as persons with disabilities.

BACKGROUND

Inclusive Design

Inclusive design has been a rising field in recent history and there are many movements and programs across the world dedicated to it. An overview of the field, and its subsections, as of 2001, is provided by the Universal Design Handbook [3]. For a history of the field in the UK see the Applied Ergonomics article by Clarkson and Coleman [7]. John Clarkson is a leader in inclusive design and has a wide array of publications on the subject. [8,9] Details on the goals of inclusive design can be found at the University of Cambridge website, The Inclusive Design Toolkit [10].

The two focus areas that have received much of the attention and research from the field are structural design and human computer interactions. However, not much has been done specifically addressing inclusive product design.

The Inclusive Design Institute [11] is an example of a focus on inclusivity in Information and Communication Technology as well as mobile and web based computing in Canada. Guidelines proposed for this area can be found in the Nicolle and Abascal publication [12]. Section 508 amendments to the Rehabilitation Act of 1973 specify Government accommodation of disabilities as it relates to Electronic and Information Technology [13].

In 1997, the Center for Universal Design at NC State University produced the principles of universal design [14], which have been generally well received. This center deals with housing and environment design. Other examples of inclusive design with a focus on buildings and open spaces are [15,16]. ADA guidelines address issues of accessibility for buildings and infrastructure [17]. Mapping of these guidelines into the product design realm has begun in the works of Sangelkar and McAdams [18,19].

The terms inclusive and universal design are used largely interchangeably, though there are subtle differences in their definitions, which tend to vary by region. The Norwegian Design Council provides simple definitions of these terms that illustrates the difference [20]. The main difference between the two subfields is the fact that inclusive design makes efforts to reduce the blatancy of the inclusivity, while universal design is much more obvious about the accommodations in the products. If inclusive design is done well then the persons using the product should not even realize that it is inclusive.

Empathic Design and Disability Simulation

In order to collect data on the needs of persons with disabilities, empathic design concepts have been used to create disability simulation suits, which can be used to solicit these needs from persons without disabilities. Though testing with the target population is still important, disability simulation is a useful way to expand the potential participant pool. Collecting customer needs from people with disabilities can be logistically difficult and time consuming. Disability simulation allows any motivated individual to be a useful research subject for studies into the needs of people with disabilities. Another area where disability simulation is useful is in the removal of data variability. Since there are many types and severities of disabilities, the data collected will vary from one sample to the next. However, a working suit will provide the same restrictions to every person.

It was determined that the KINdReD team should create a new disability simulation suit to match the needs of this research and add the benefits of simulation to the data collection options. It was determined that modifications to the finger, elbow, and shoulder mechanisms were essential in order to provide proper resistance. Several possibilities, including the Third-Age Simulation Suit used by Boeing, were considered before the current suit design was finalized [21].

In order to do this, four relevant full body disability simulation suits were examined. Several generations of the AGNES age simulation suits created by the AgeLab team at MIT [22] were examined as well as the GERT suit by Produkt + Projekt Design [23]. These focused on recreating the hardships of elderly persons. The first substantial disability simulation suit is the “Third Age Suit” developed in 1990 by Ford Motor Company [24]. The main goal of this suit is to offer engineers a deeper and more accurate understanding of the difficulties encountered by elderly people during driving tasks.

Several shortcomings were discovered with each of these designs. Since they are not form fitting, use of these suits by smaller participants is difficult and unreliable. Also, the fact that no finger restriction is provided is their main disadvantage. Other products were investigated that concentrated on the area of loss of finger function.

Simulation gloves from Cambridge University [25] used plastic strips to impede movement while people flex and extend their fingers, with Velcro attachments adding adjustability. The Arthritis simulation glove from Georgia Tech University [26] was another prototype for finger restriction. These reduce dexterity through wiring placed on the fingers; however, this is not an adjustable feature. These options also contained drawbacks. They were too large or too uncomfortable to be reasonable for use on study participants. They would not allow the actions that participants need to perform as part of the KINdReD study.

The KINdReD suit design is unique in three main ways. One is its adjustability, achieved by having each part of the suit attach separately. Another is the original finger restriction mechanisms, which place stiffened hinges in line with the lower finger joint, making it difficult to move when both opening and closing the joint. The next is the largely improved amount of resistance to the elbow, provided by a modification of the joint in a standard arm brace, which increases the amount of force required to adjust the position of the arm in either direction. The suit provides shoulder restriction with resistance bands attached between waist and arm brace in a way that restrains the movement of the arms away from the body in any direction.

The back brace provides a platform for attachment of parts as well as a slight restriction to the movement of the back so that participants cannot use their back to assist with extremity movements. The wearable devices are designed so that there are no hard limits on range of motion. Rather, resistance to both flexion and extension increases the difficulty of movements of the upper extremities. The suit is pictured in Figure 3.1 to provide a visual description.

Figure 3.1: Picture of current KINdReD disability simulation suit.

Once validated, the suit can be used for data collection as well as education. Designers and others will be able to easily experience and understand the issues faced by people with disabilities. The basic principle of empathic design is to expose people to experiences with a product in difficult situations. This will facilitate designers' understanding of different sets of customers and different use conditions. It can also bring out customer needs that would otherwise go unnoticed by pushing customers to experience products under extreme conditions. Empathic design is an extension of ethnographic studies that connects designers and users more directly with challenging usage contexts [27-29].

Modular Products

Modular product design methods leverage a common module or platform for multiple iterations of a product. This drives down cost of the product by increasing the scale of production of the common module. Modular product techniques are adapted well to the consideration of different sets of users. One key to these methods is illustrating the way in which function-based representations allow different criteria to be considered [30-38].

Modules for inclusive design can be categorized into common, variant, conditional, and unique. Common modules are based on an associated form and function solution that is common to both the exclusive and inclusive product. Common modules are used to build the product family platform. Variant modules address functions that are common to both exclusive and inclusive products but different in form. Unique modules have differing (or additional) functions for exclusive and inclusive products. Conditional modules can be used to connect exclusive modules to inclusive modules as needed [6].

As an example of this, the fact that users must hold a device, dictates that it has a handle. However, the type of handle needed is different depending on the type of customer. A larger handle would be better for some people, while a different user base might find this inconvenient. From a modular product perspective the handle's presence and placement in relation to the device can be a common module. The type of handle is the variant module and can differ by device. Alternatively, the product could come with an attachment, a conditional module, which will widen the handle for those who want or need that feature.

This research builds on prior work [39,40], which identifies sets of customer needs that map to these modules. These works found that high weight and low frequency CNs defined the common module for non-inclusive products and persons without disabilities. This is illustrated on the left side of Figure 3.2. The grouped customer needs statements were found to match the known common and variant modules in a set of existing products. In order to extend the modular product technique, a customer needs space similar to the right side of Figure 3.2 must be created for persons with disabilities.

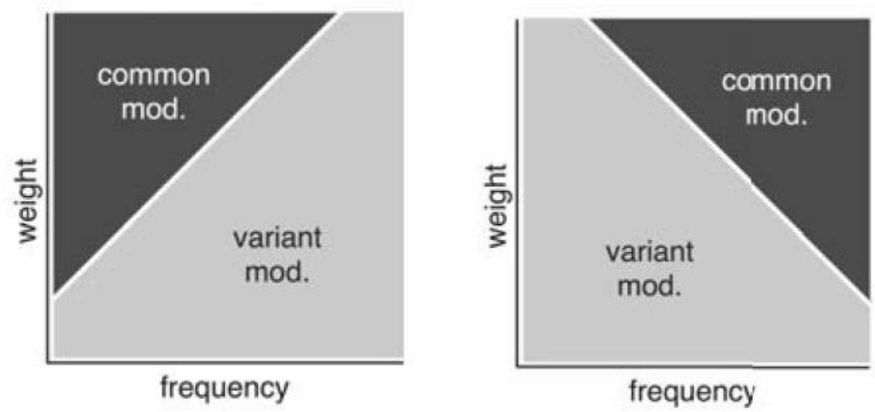


Figure 3.2: Customer Need spaces separated into module regions. Left, Discovered Exclusive CN space, Right, Proposed Inclusive CN space. [6]

If function-based modular product techniques can be extended to inclusive product design, then companies that wish to provide products to people with disabilities can do so more easily and for less money. They will be able to sell a single product to everyone, as opposed to making separate products for each user base. If companies can create a more socially conscious product without expending extra effort, it is likely that more inclusive products will go to market and at a lower cost. The current practice or producing accessible products in small batches, because of the smaller market segment of their users, causes these products to have a higher manufacturing cost and a higher MSRP. This divide between accessibility of function and accessibility of price is something inclusive design research seeks to correct.

Current Practice Issues

In engineering design there are always many factors to consider; safety, reliability, functionality, usability and many more. However, at its core, engineering design has a goal of creating a product that meets the needs of that product's customers. In the case of inclusive design, this means *all* potential customers, no matter how diverse. There are two main reasons that current product design methodology is not conducive to creating inclusive products.

Firstly, a lack of information about the needs of people with disabilities makes it difficult for this user group to be considered during design. Since little formal investigation into the customer needs of persons with disabilities has been conducted with regards to manual products, designers have insufficient reference data available. This forces designers who would like to design inclusive products to expend extra effort to collect customer needs from this hard to reach group. This extra effort does not always guarantee success in making the product accessible or appealing.

Secondly, consideration of product inclusivity tends to be made as part of the later stages of design and not near the start. Figure 3.3 [41] shows a typical product development process. A product's inclusive design might be considered only at the "design for x" stage, near the very end of the process. Other examples of "design for x" include design for manufacture and design for sustainability.

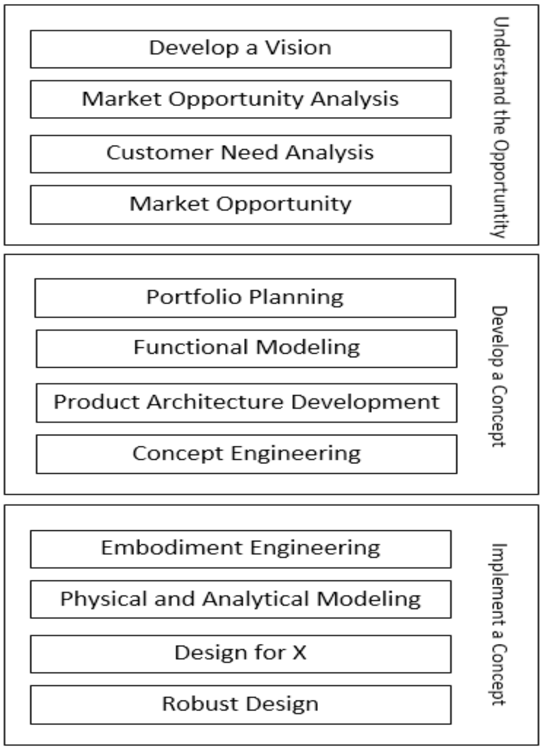


Figure 3.3: A typical product development process. [41]

Other scenarios include a designer following their design cycle with a standard product and reaching the evaluation steps in "modeling" and realizing that the product will not work for persons with disabilities, necessitating a backtrack and expensive changes. Alternatively, they could reach the detailed planning steps in "embodiment" and decide to create a separate product or an add-on to an existing product to sell specifically to people with disabilities. These types of choices cause accessible products to be designed at a higher cost than standard products.

Issues of accessibility are often dealt with as an afterthought, or as an alteration to an existing product. Being at the end of the design cycle, changes necessary to address inclusivity are less impactful and more expensive as illustrated by Figure 3.4 [42]. This relationship is a well known in the design field and similar graphs are found in [43,44]. When inclusive design is done as either a separate cycle or a late stage change, it will cost more than standard design, making many companies unwilling or unable to perform inclusive design due to budget constraints or profit margins. This causes only a small subset of the product market to be designed inclusively. It would be better if inclusive design principles were considered at the beginning of the design where they could be most effectively utilized.

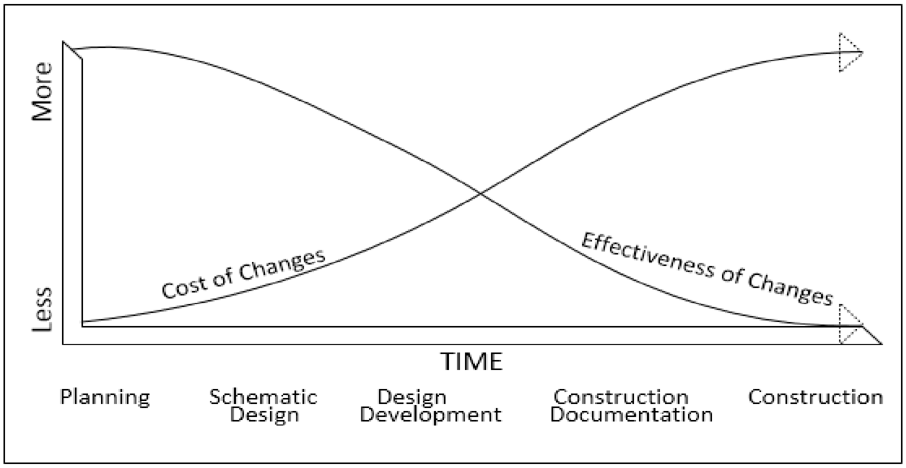


Figure 3.4: The Cost of Change vs. Time. [42]

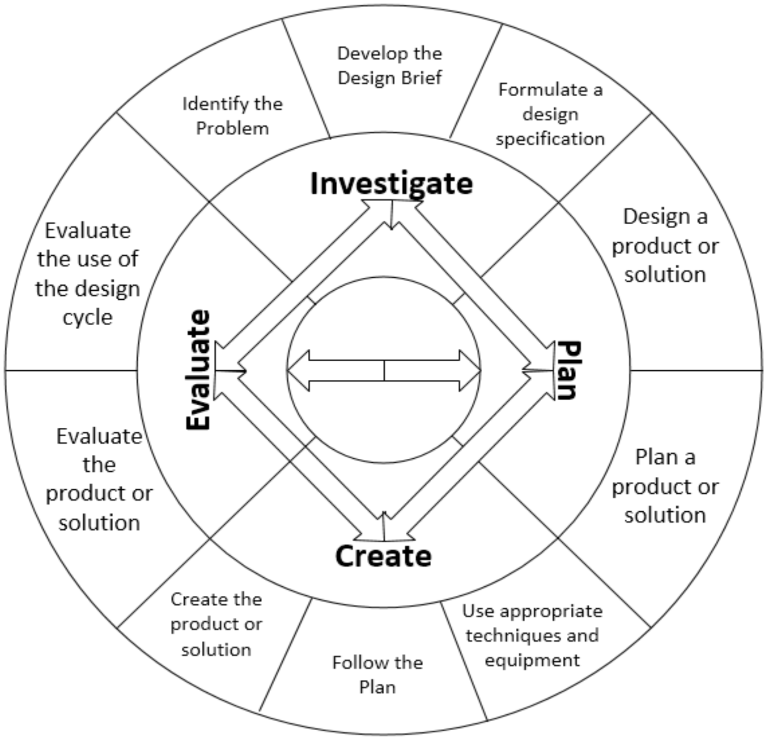


Figure 3.5: The Design Cycle. [45]

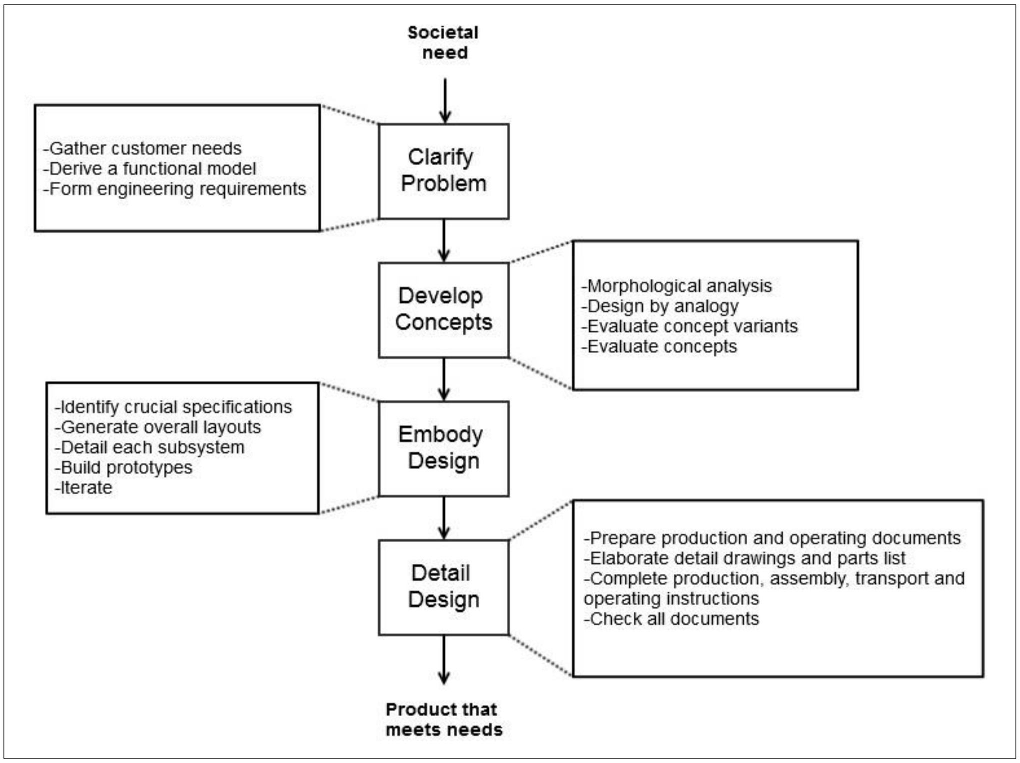


Figure 3.6: The Design Process. Derived from [46,41].

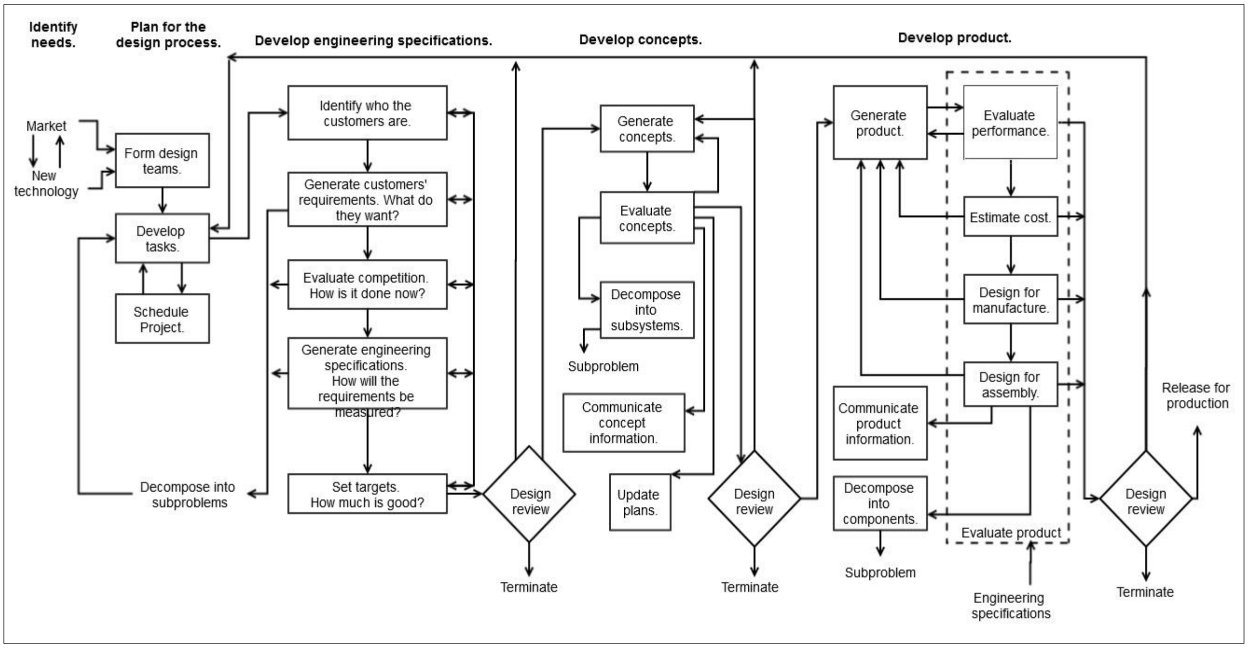


Figure 3.7: The Mechanical Design Process. [47]

Figure 3.5, 3.6 and 3.7 illustrate examples of the engineering design cycle but an untold number of specific cycles exist. The basic structure will be similar everywhere, though the terminology and detailed divisions will differ. The design cycle can be simple or complex, highly regulated with design reviews and checkpoints or more loose/suggestive. It is often highly specific to a particular institution or company and can be cyclical and iterative. The basic cycle begins with an investigation of the problem the product should solve, moving onto preliminary design activities such as concept generation and evaluation, then more detailed design, then production/prototyping, and then testing and evaluation.

The tasks in the "Investigate" portion of the design cycle are there to make sure that the proper issues are identified before work begins on solving them. No matter the term, the beginning stages of design are important to ensure that the effort expended in the rest of the design process is not wasted by solving the wrong problem. The main aspect of this is the collection of customer needs. In the case of inclusive design, the lack of information on CNs for people with disabilities could be contributing to the choice not to perform inclusive design at this stage, but wait until later when specific testing can be done.

If inclusive design can be moved to an earlier design stage, it can be more effective and cost less. If inclusive design and modular product design can be combined, then economy of scale and a wider marketing base will availability of inclusive products. If customer needs for people with disabilities are known, then inclusive design will be more likely to occur and succeed. If disability simulation can be used to collect these customer needs, the collection will be easier and provide the added benefit of empathic experiences. Therefore, a valid simulation and collection methodology is the first step in the production of inclusive design guidelines.

METHODOLOGY

In order to validate the disability simulation suit, two types of suit functionality were considered; the physical effects and the perceptual effects that the suit had on participants.

The hypothesis HA relates the perceptual aspect of suit performance and the hypothesis HB relates to its physical performance. If both HB and HA are proved to be true, then the suit is performing effectively, and can be used as a viable method for gaining customer needs for people with disabilities, from people with no disabilities.

- HA: Participants wearing the disability simulation suit will generate a comparable set of CNs as participants with disabilities.
- HB: Participants wearing the suit will exhibit similar dexterity measures as persons with disabilities.

How a study interprets the terms "comparable" and "similar" in the hypotheses will change the outcome. Therefore, information is provided as to how this particular study regarded these terms during its analysis.

Measurements

First, there is the physical effect of the restrictions, which can be measured more objectively. This study uses the 9 hole peg test [48] as the measure of physical restriction. This test is classified as an objective functional performance test [49] and is used widely by occupational therapists to test manual dexterity. It has also been used in the evaluation of function related to several types of disabilities [50,51]. Participants are timed while they insert pegs into a standard board and then remove them, as fast as they can. This test involves movement of most of the joints restricted by the suit, making it an acceptable measurement of suit restriction. It is very simple to administer, requiring little training and equipment [52]. It is also easy for the participant to understand, removing any confounding effects from cognitive abilities. Any potential confounding effects are removed by the fact that all participants are mentally capable and the same instructions were given to each person. Also, everyone had the same amount of practice and none had any visual impairments that could confound the hand-eye coordination factor. The peg test has data available on test performance of a normal population distribution, providing a useful baseline against which the study population can be checked. It also addresses the difference between the results for the subjects' dominant and non-dominant hand. This difference in functionality could be important for a study of this nature. In HB "similar" means the measures should not show a statistically significant difference at a 90% confidence interval.

Second, there is also the perceptual aspect of the suit's affect on participants. Is the suit placing the user in the desired mindset, matching that of users with disabilities? This is more difficult to measure, but still possible. In HA "comparable" is defined mainly as people with no disabilities making CN statements that cover at least half of those statements made by people with disabilities, though 75% would be preferable for a strong result. There are also two other observations of similarity for this hypothesis. The two groups should not show significant differences in the weight or frequencies for the CNs. Also, if both groups place similar CNs in the common module (upper right corner of the CN space) then the suit is performing adequately.

This is a logical extension of the similarity measures that compare the overall CN lists. It speaks directly to the suit's usefulness for research in the modular product design context.

Equipment and Procedures

This study involves two groups of people. Both groups were restricted to people over the age of 18 with no mental disabilities who were willing to be video recorded. Group 1 consisted of people with upper extremity physical disabilities, hereafter referred to as G1. Group 2 were people with no disabilities, and will be referred to as G2. G2 performed the study activities first without the suit, and then again while wearing the disability simulation suit. There were no additional restrictions placed on the demographics of G2 participants. This was done because gathering a wide range of perspectives is important when trying to design "inclusive" products. There were two additional requirements for people to be participants in G1. They had to have an upper extremity physical disability, since that is the focus of this study. They also had to be willing to describe their disability in enough detail so that International Classification of Functioning Disability and Health (ICF) data [53] could be created for use in a later stage of the project. There were no specific measurements of disability taken for this portion of the study. This research specifically investigates user opinions and experiences with the products, not the detailed interaction effects that would require specific movement metrics. This study was approved by the Oregon State University Institutional Review Board in regards to its interactions with human subjects.

Test situation controls were in place to make sure that each participant had an equivalent experience and that no data was lost. All tests were done in the same conference room at Oregon State University. All participants sat at the same table for the test to eliminate the leverage and movement advantage provided by standing. Each person used each product and spoke about their thoughts and experiences based on the same explanation of a protocol analysis given at the start of the test. Participants were provided with simple descriptions of the products with which they were unfamiliar, to try to limit confounding factor of subject experience. The researchers had a script, which was followed for each test. The researcher was allowed only to ask for clarification or to remind the participant to speak more when needed and not to ask any directing or potentially biasing questions. For example, a participant could say, “that was hard” and the researcher would ask, “hard in what manner?” or "could you explain why it was hard?" This method leads to more useful CN information, while avoiding leading the subject in any way.

The participants were video recorded to ensure that every detail of their responses and actions were available for analysis. The camera captured the product manipulations but not the subjects' face, for an added privacy layer. It was anticipated that many of the responses would be of the sort "well this (indicate feature) is not very good at this (demonstrate)" and it would be important for this research to know what "this" was during statement interpretation.

A product pair is two products with the same functionality and purpose, one designed inclusively, according to company claims, and one that is not. The product pairs used in the study are all kitchen implements used by the upper extremities; can openers, jar openers, garlic presses, and ice cube trays. One product pair is pictured in Figure 3.8. Examination will reveal changes to the product's form in the inclusive product that are intended to improve the ease of use of certain functions/interactions.

Figure 3.8: Jar opener product pair pictures. Right to Left: Exclusive Jar Opener top view, Exclusive Jar Opener bottom view, Inclusive Jar Opener top view, Inclusive Jar Opener bottom view.

Analysis Techniques

There were several phases of analysis. The first was statement interpretation. The second was statement aggregation and tracking. Third was surveying participants to get the weight data required, and to complete the customer needs space. The last phase was to perform the similarity calculations to make conclusions about HA. HB was also tested with statistical analysis of peg test results.

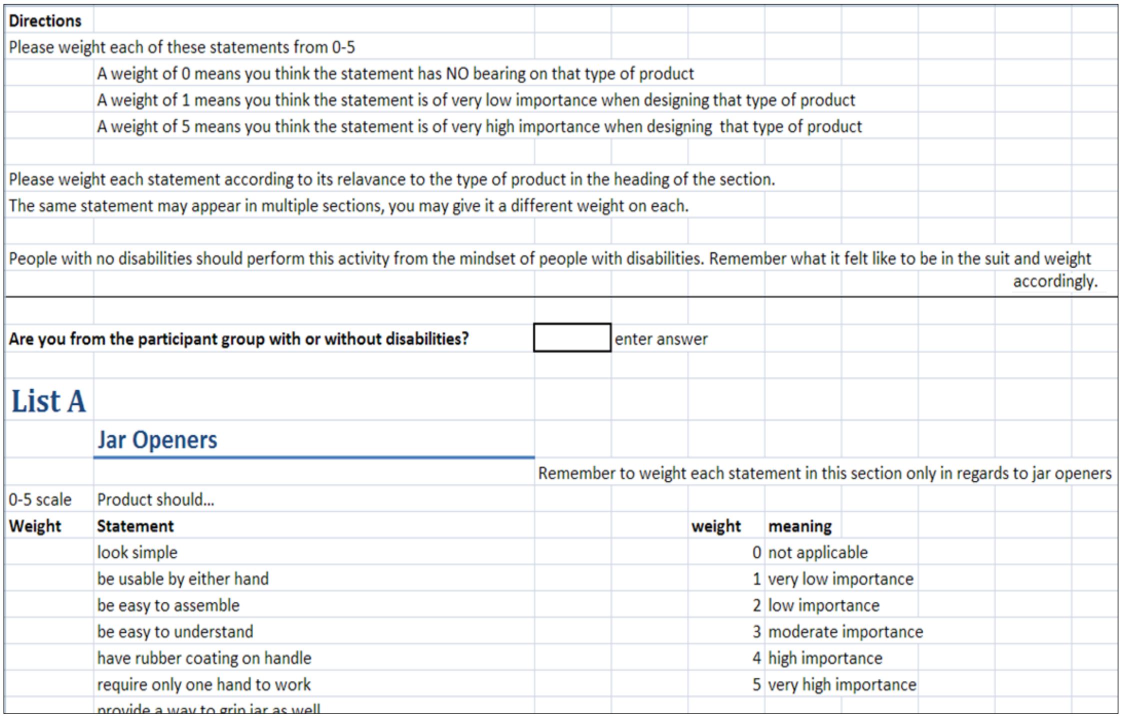
During the interpretation phase, the interviews were watched and the various participant comments were translated into the standard form customer need (CN) statements. For example, if one participant says, "It's hard to keep a hold of this" and another says, "This is quite slippery" they both mean the same thing, and this can be translated into the CN of "Product should have a nonslip grip surface". This analysis was performed by two researchers for the sake of reliability. They watched the recordings and wrote CN statement lists independently and then compared.

Two people also performed the statement matching to determine CN list similarity. The matching was not conducted independently, as in inter-rater reliability, but as a discussion. A CN pair was marked as similar only if both people agreed that it was. The second person was a neutral third party, someone who barely knew the project context, so that they would not be influenced by preconceived notions of customer needs, and could speak directly and purely to statement similarity.

After the matches were made, similarity calculations were performed. The calculation of similarity was a simplified version of vector projection. The CN statement lists were unit vectors and G2 was projected onto G1. By projecting G2 onto G1 the similarity measures how much of the G1 needs are reproduced. It was expected that the people without disabilities would not be stating *only* the needs of people with disabilities, since they still have their own experiences to draw from. Rather, the goal is simply to have the suit cause participants to produce as many of the needs of people with disabilities as possible, as well as their own.

To state it more simply, the metric is the number of statements that are found on both lists divided by the number of statements on the list produced by people with disabilities. What percentage of the needs of people with disabilities is being elicited by G2 using the suit?

Another purpose of this research is to create graphs of CN weight vs. frequency to be used later in the KINdReD study. They take the form of Figure G and are separated by product pair. The frequency data is achieved through statement tracking and manual clustering. The weights were provided through a survey of the study participants. They were given the list of customer need statements for both groups. Each list section had the CNs randomized to prevent bias due to order or category. They were not told which list was derived from which group. They were asked to rate each CN by importance on a scale of 0-5, 5 being the most important, 0 being not applicable to that product. They were provided with descriptions of what each weight means (see Figure 3.9) and told to consider each CN as applicable only to the product for which it was listed.



Directions

Please weight each of these statements from 0-5

A weight of 0 means you think the statement has NO bearing on that type of product

A weight of 1 means you think the statement is of very low importance when designing that type of product

A weight of 5 means you think the statement is of very high importance when designing that type of product

Please weight each statement according to its relavance to the type of product in the heading of the section.

The same statement may appear in multiple sections, you may give it a different weight on each.

People with no disabilities should perform this activity from the mindset of people with disabilities. Remember what it felt like to be in the suit and weight accordingly.

Are you from the participant group with or without disabilities? ☐ enter answer

List A

Jar Openers

Remember to weight each statement in this section only in regards to jar openers

0-5 scale	Product should...		
Weight	**Statement**	**weight**	**meaning**
	look simple	0	not applicable
	be usable by either hand	1	very low importance
	be easy to assemble	2	low importance
	be easy to understand	3	moderate importance
	have rubber coating on handle	4	high importance
	require only one hand to work	5	very high importance
	provide a way to grip jar as well		

Figure 3.9: Survey directions. (screen shot of Excel file sent to participants)

Knowledge tracking techniques [54] were employed to determine when data collection could stop. Tracking the number of participants versus the number of unique need statements will produce an asymptotic curve. When the graph begins to flatten out and new participants make few unique statements, the study will have reached a sufficient amount of total product knowledge and can end data collection. This is standard practice in design studies and is a good way to balance the time and effort of additional research with possible knowledge gain.

RESULTS

Subject Demographics

The final demographics for the study are now presented. The study had 11 subjects in G1 and 14 subjects in G2. Of the 25 total subjects, 23 also participated in the peg test. Of the 23 peg test subjects, 14 were female and 9 were male. The ages of these participants ranged from 18 to 64 with a mean of 30 and a median of 26. This shows a slight skew toward younger participants, which is difficult to avoid in studies based on volunteers in a college town. As expected, the mean age of people in G1 was 15 years above the mean age of participants from G2 (39 as opposed to 24) since people tend to become more disabled with age. However, there were also some young participants in G1 whose disabilities were due to injury.

It should be noted that a significant portion of the participants in G1 had some form of damage that made it painful/difficult to move their fingers, such as carpel tunnel, arthritis, and tendon damage. Only three of the participants classified their disability as severe. Due to privacy concerns, the range of disabilities tested will not be discussed in more detail.

It was decided during experimental design not to make specific measurements of the disabilities, as it would be invasive for the participants and not of immediate/extensive use to this research subset. It was felt that a description would be sufficient, since this research was concerned more with their thoughts and interactions with the products.

No measurements were taken on the people without disabilities. Looking back on the subject pool it can be noted that, while the small size of wrist and finger parts were used for the majority of participants, people on both extremes were tested. The pool included one very small female participant, approximately in the 5-10th percentile. One male participant was requested, after completion of the study, to be measured as a representative of the larger variety of participants tested. The useful measurements were determined through the FAA [55] and the measurements were matched to the database compiled by NASA [56]. In 6 out of 11 measurements taken from the upper extremities, he was at or above the 95th percentile. The suit did exhibit fit issues at both the large and small ends of the anthropomorphic data range.

TABLE 3.1: Upper range participant measurements.

Measurement	**Percentile**
functional reach	95th
elbow-grip length	75th
elbow-fingertip length	75th
index finger width	99th
index finger length	50th
hand breadth	50th
palm length	95th
hand length	75th
wrist circumference	95th
forearm circumference	99th
upper arm circumference	99th

Peg Test Results

In order view the peg test results effectively, four relationship statements are provided which illustrate the desired results. If all four statistical relationships were proved true, then HB would be true.

- Group 1 times should be significantly lower than Group 2A times, indicating that the disabilities are providing restrictions that are measurable with this testing method and that these people are a separate sample set.

- Group 2B times should be significantly lower than Group 2A times, indicating that the suit is providing restrictions that are measurable with this testing method, and they can now be considered as part of a separate sample set.
- Group 2A should not be significantly different from the normative data provided with the peg test, indicating that a representative sample in G2 has been gathered so that the results are generalizable to the entire population.
- Group 2B times should not be significantly different from Group 1 times, indicating that the suit is matching the functionality of the people with disabilities.

One important attribute of the peg test data was the largely unequal variances between sample sets. This meant that any test comparing non-paired data sets had to use the unequal variance type t-test. This was not a difficulty, but it was interesting to see how different the groups' variances were.

A set of two tailed, unequal variance t-tests were used to compare the mean test times of G2A to the mean adult norms for the 9-hole peg test given by [48] in every subcategory (male and female, dominant and non-dominant hand and whole group averages). Since 5 out of 6 of these tests resulted in a p-value greater than 0.05, it is apparent that they are not significantly different. This provides initial evidence that the sample population is a valid representation of all people.

Comparing the times of G1 (people with disabilities) to the times of G2A (people with no disability) yielded p-values less than 0.01. Therefore, the peg hole test times for subjects from G1 are statistically significantly slower than those times for G2A. This mean the sample of people with disabilities is exhibiting an appropriate reduction in effectiveness with this measurement method. It was also determined that the times from G2B (persons with no disability wearing the disability simulation suit) are significantly slower than the times of G2A (p-value less than 0.01). This indicates that physical speed reducing effect of the suit on participants is measurable and statistically significant.

The comparison of G1 and G2B yields a p-value well below 0.01 (p-values = 0.005 and 0.0003, respectively), indicating that they are significantly different results. This comparison being the crux of the hypothesis regarding the suit's physical effect, even though the samples are good and behaving as expected in terms of directions of change, the amount of change is too large and H3 must still be rejected.

TABLE 3.2: Peg Test Statistics.

Comparison	**T-test**	**P-value Dom Hand**	**P-value Non-Dom Hand**	**Result**
G1 - G2A	1 tail, type 3	.0008	.0044	Positive
G1 - G2B	1 tail, type 3	.0054	.0003	Negative
G2A - G2B	1 tail, type 1	2.5 E-5	4.1 E-7	Positive
G2A All - Norm	2 tail, type 3	.212	.443	Positive
G2A Female- Norm	2 tail, type 3	.043	.126	½ Positive
G2A Male - Norm	2 tail, type 3	.963	.830	Positive

TABLE 3.3: Peg test average results.

Group	**Dominant Hand Speed (avg) (sec)**	**Non-Dominant Hand Speed (avg) (sec)**
Group 1	23.7	26.7
Group 2 no suit	19.5	20.8
Group 2 with suit	28.9	36.0

Final Customer Needs

The Final CN lists are in Appendix B in Table form. These display the CN statement, frequency, weight and weight statistics (min, max, stdev). Each CN statement has a tag so it can be easily referenced in graphs and discussions without writing the whole statement. This tag has the form First letter of product type - Group number - CN number, so the fourth need on the garlic press list made by G2 would be tagged as G-2-4. There were a total of 202 customer needs developed during this thesis work. The distribution of the CNs are shown in Table 3.4.

TABLE 3.4: CN totals split by participant group and by product.

Category	**Number of CNs**
Group 2	111
Group 1	91
Garlic Presses	57
Can Openers	66
Jar Openers	50
Ice Trays	29

Knowledge Tracking

The knowledge tracking exercise indicated that new data collection had slowed at around 8 subjects, so that each new person added 0-3 statements not previously articulated by subjects. Since the knowledge graphs were climbing significantly slowly and 25 was exactly half or the originally proposed subject number, it was decided to cut data collection at 25 subjects. The original knowledge curves in Figure 3.10 show this effect.

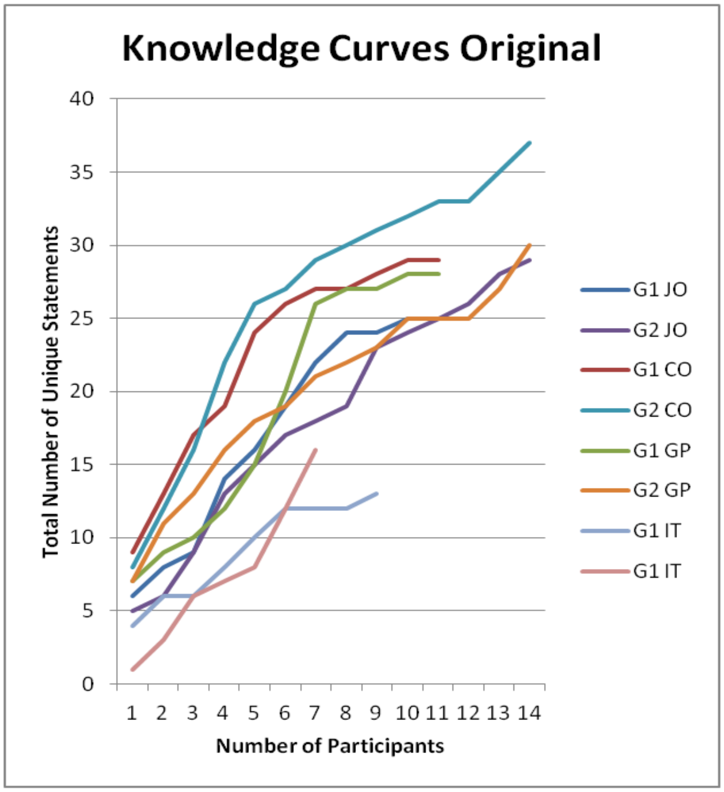


Figure 3.10: Knowledge curve for actual participant order.

However, this type of knowledge tracking is not meant to be a specific decision making tool, but more of a guide based on the trend of the curve. If the knowledge gain with each new participant is indeed slowing, then randomizing the subjects and re-tracking the uniqueness should yield a similar shaped curve. This was performed, and proved true as shown in Figure 3.11. This was an effective double check exercise to ensure that data collection could be stopped without missing out on significant information.

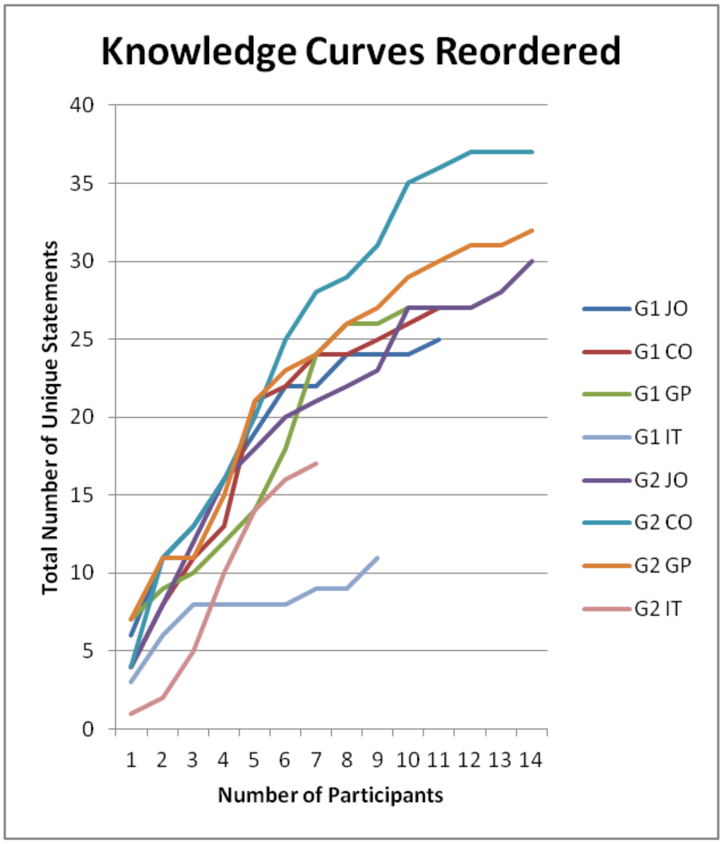


Figure 3.11: Knowledge curve for randomized participant order.

The rest of the knowledge curves for each data set, both Original and Reworked, can be found in Appendix C. It is important to note that each group and each product was tracked separately and has its own curve. Some products exhibit a better curve than others do; which is to be expected. The smaller number of subjects who used it, due to problems posed by bringing fresh ice to the testing room, and the difficulty subjects had in coming up with statements about it, made the ice cube tray a regrettable choice of CN gathering tool for this study.

Analysis Phase Reliability Results

The interpretation phase reliability results were very positive. For G1, out of 179 total statements, 2 were different between raters. For G2, out of 160 total statements, 6 were different. This represents a percentage of agreement of 98.9% for G1 and 96.25% for G2, which indicates that this manual interpretation method is acceptably reliable.

During the statement matching phase, almost all matches were made easily, with no discussion or clarification needed. The few disagreements (3 out of a possible 91 contention points) arose almost entirely from the distinction between form and function statements that relate to the same topic. It had been decided during interpretation that a statement that spoke directly to the form or feature of a product would be considered separate from a statement that generalized to product functionality only. For consistency, it was necessary to maintain this distinction in the similarity calculations as well, even though it was not as automatically recognizable to the non-engineer. The 96.7% agreement indicates that this is also an acceptable method for developing similarity measures.

Similarity Determination #1: Explicit Calculations

The results show a similarity measure of 81.8% for the Jar Openers, 60.3% for the Can Openers, 62.9% for the Garlic Presses, and 30.7% for the Ice Trays. This means that this research methodology is moving in the right direction but could stand to be a bit better before expanding to general usefulness. In order to use this collection method widely it should not show quite as much variation by product.

For the purposes of hypothesis testing HA is true since 3/4th of the products show similarity measures above 50%.

The statement matching exercises, which display the matches between CN lists, and the similarity calculations, are in Appendix D.

Similarity Determination #2: Group Interactions

While creating the Weight (W) vs. Frequency (F) relationships and assigning cutoff lines on the graphs, the difference in W and F between groups and lists were also examined. Each group weighted both lists so that we could examine the if there is a significant difference in how one group assigns weights to the CNs elicited from the other group. The difference in frequency from each group for the CNs on both lists was also of interest.

First, the weights between groups were compared manually for all the CNs in the survey. The weights from one group differ from the other group by 0.5 or more on only 24 % of the statements. This was small enough to indicate that the weight difference is not important. Then, a two tailed, type 2, t-test was performed on the weights for the whole list. This yielded p-values much higher than 0.1, (0.39 and 0.48) indicating that the weights are not significantly different statistically either. Therefore, the difference in weights between groups is considered to be negligible.

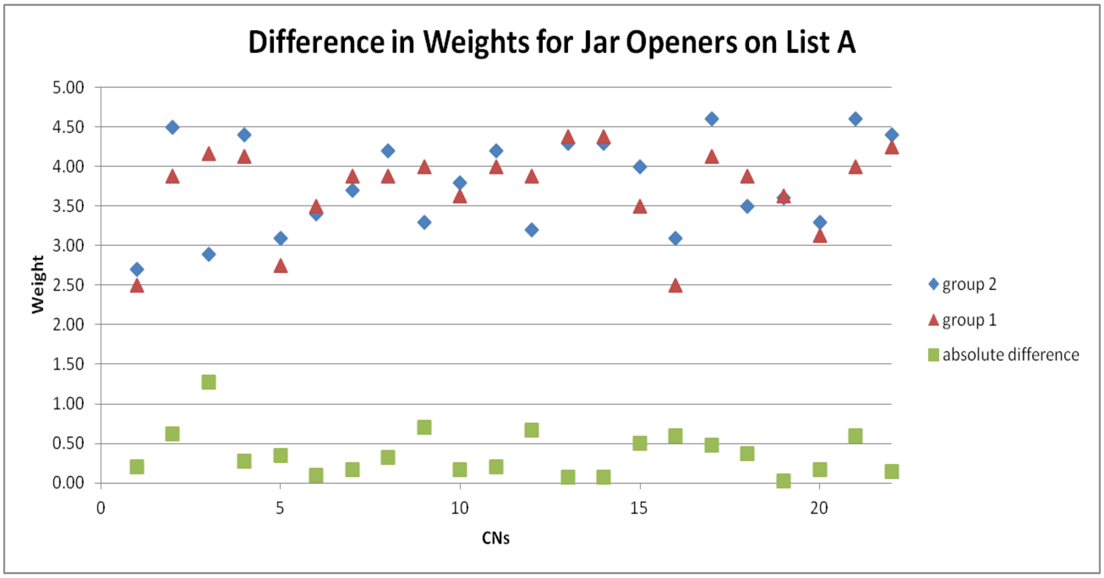


Figure 3.12: Weight Difference Graphical Example.

Comparing frequency in a similar manner, the frequency numbers were first translated into percentage of the population of the group that mentioned that statement. Then, the difference in percent was calculated for any CN statement that appeared on both lists. Any difference greater than 20% was counted as significant. The CNs with a significant difference in F were only 15% of the total duplicated CNs. This makes the difference in frequency also a negligible factor for this analysis. Tables showing the frequency difference calculation are in Appendix E.

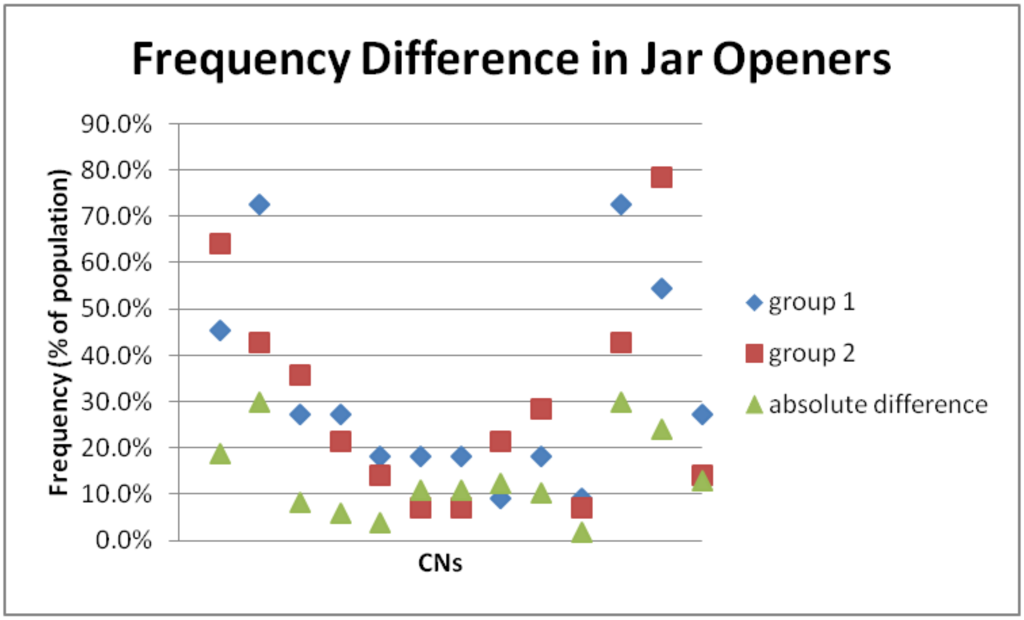


Figure 3.13: Frequency Difference Graphical Example.

Given that neither the weight nor the frequency differences between groups were significant, HA is further supported as true.

Similarity Determination #3: Common Module Comparison.

Common module cut-off lines are placed in the CN space based on the proposed formulation. For the purposes of this research "high weight" is any CN with an average weight of 3.75 or above and "high frequency" is any CN mentioned by at least half the participants in the group. The cut-off lines were placed and the common module line was drawn so that the end points were equally spaced on each axis.

Figure 3.14 shows the final modularized CN space graph for the Jar Openers for both groups. The thin red lines are the cut-offs lines, the thick red line is the module separation line, and the grey space is the common module region. The rest of the CN space graphs, both clear and marked with the common module regions are in Appendix F. Table 3.5 shows all the needs in the common module for all products and both groups.

TABLE 3.5: Common Module Customer Needs

Group 2			**Group 1**		
Statement	**Product, Weight, Frequency**	**Match**	**Statement**	**Product, Weight, Frequency**	**Match**
be easy to understand	JO, 4.10, 64.3%	1	be easy to understand	JO, 4.13, 45.%	1
grip lid securely	JO, 4.40, 78.5%	2	grip lid securely	JO, 4.00, 54.5%	2
be easy to turn	CO, 4.40, 78.5%	3	be easy to turn	CO, 4.25, 45.4%	3
pierce the can with little effort	CO, 4.40, 35.7%	4	require only minimal squeeze force to puncture can	CO, 4.25, 27.3%	4
operate with low force/strength	CO, 4.30, 42.9 %	4			
be easy to squeeze	CO, 4.40, 35.7%	na			
require only low force to close	GP, 4.40, 100%	5	require only low force to close	GP, 4.38, 72.7%	5
parts should align automatically	GP, 4.60, 57.1%	na			
accommodate any size garlic clove in compartment/holder	GP, 4.50, 42.9%	na			
require low finger strength	IT, 4.38, 57.1%	na	provide easy way to remove cubes	IT, 4.50, 33.3%	na

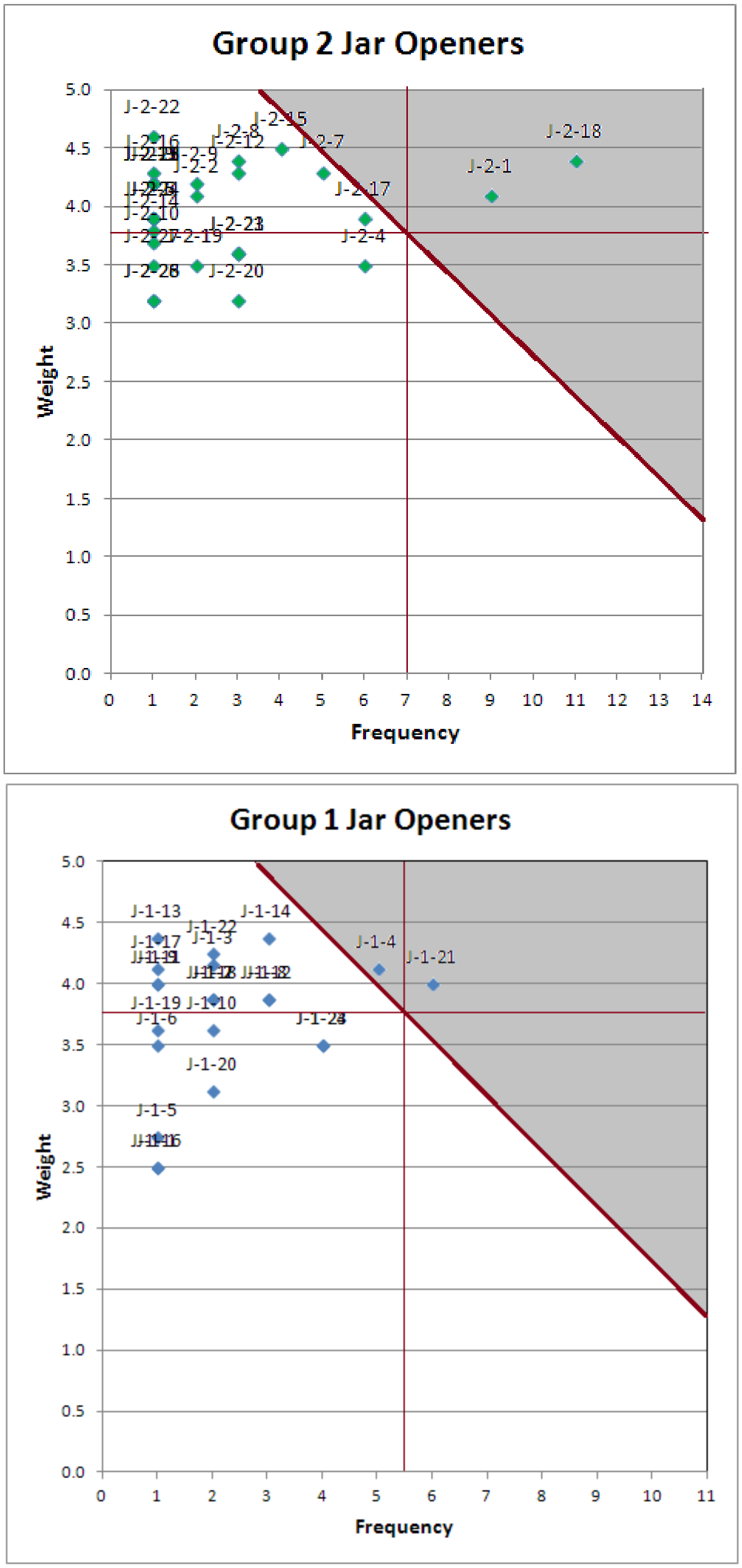


Figure 3.14: Final CN space examples. Top, G2's JO space. Bottom, G1's JO space.

A projection of the G2 common module needs onto the G1 common module needs the same way as done with the CN lists was performed to see how well the common module needs match between groups. This was done for each product pair and the total list. All product pairs apart from the Ice Trays had a 100% coverage of G1 needs, leading to a combined 85.7% of G1 CNs covered by the G2 common module space.

CONCLUSIONS AND DISCUSSION

HA has been proved true through three different considerations. This is an excellent indication that disability simulation will be useful for future research into inclusive design. HB has been proven false under the strictures of this experiment. However, the directional relationships and considerations of the reasons indicate easy methods for correcting this, either with changes to the suit or the testing methods.

Peg Test Interpretation

The average speed to perform the peg test, using their dominant hand, of subjects in the suit, is 5.2 seconds slower than that of subjects with disabilities and the average speed using their non-dominant hand, is 9.3 seconds slower. The suit slows the peg test times of subjects with no disabilities by 48.2% for their dominant hands and their non-dominant hands by 73.0%. Therefore, the suit can be said to do a sufficient job of slowing down the reaction time of the subjects with no disabilities. However, since the goal is to match the times from G2B to those of G1, this is a larger effect than is required. Therefore, the suit does not accurately represent the physical capabilities of the subjects with upper extremity disabilities.

This effect could be attributed either to a problem with the suit or an unrepresentative sample set for G1. The G1 sample is small and might not contain an accurate range of impairments. Enlarging the sample of people with disabilities might bring the numbers closer.

Alternatively, the suit may require adjustment in the future to tone down or change the finger impedance mechanisms specifically to a more accurate degree of restriction. The finger mechanisms are the main contributor to the peg test results and the participants often commented on their restrictive effects, often in undesired dimensions.

Participant comments regarding the effectiveness of the suit should be aggregated and considered as another factor in the evaluation of suit validity before a final decision is made.

In addition, only 1/3 of the non-dominant hand times showed a significant difference from the dominant hand. This may be a confounding factor that we have not yet accounted for.

Product Use Observations

Participants were not told which was the inclusive product during the test. However, the apparent visual differences made it obvious to some. Many comments were made such as, "now I will use the 'old-fashioned' or 'standard' or 'common style' product type" as opposed to comments like "the 'fancy' one is better at X".

The difference in usefulness of the data between product pairs is obvious. The ice cube trays show a slower knowledge gain as shown in the knowledge tracking graphs. Also, the number of statements made from each participant was much lower for this product, yielding one or two instead of 4-6 as is typical of the others. It may be that this product is too simple and people have never thought of how to use it explicitly. Articulating their thoughts while using this product was observed to be difficult for participants.

The jar openers were also very simple. However, almost all of the participants had zero experience with this type of device. Therefore, they could easily articulate their attempts to figure it out. In addition, one was very difficult to use, which elicited many similar statements speaking to the difficulties and design flaws.

A general observation during the interview was that when a device has a large problem, people will focus on that issue and not expand out as much into other areas of consideration, which they can do for less problematic products.

Also, the people with no disability notice the issue with the mechanism more so than those with disabilities. This could be due to the fact that people with disabilities expect things not to work well for them, so they don't comment on the "obvious" design flaw that creates a difficulty.

Group Interactions

Having both the weight and frequency difference be negligible indicates in another manner that the groups are equivalent. This speaks further to the suit’s ability to engender understanding of disabilities in participants. This is the second component of the validation of HA. If the CNs list had been similar but the W or F’s for those CNs had been significantly different, then further investigation would be called for into the psychological issues at play with this CN gathering methodology.

Common Module CNs

The fact that the common module needs are very similar between groups, as determined by the proposed CN space cutoff line, is a good initial indicator of method validity. This speaks further to the validity of HA. Since both groups are putting the same needs into the common module, they are certainly having similar perceptions of the products.

Given the conclusions on HB that the suit is too restrictive in the physical sense, it can be speculated that some of the extra CNs in the common module for Group 2 might be due to this effect. The large physical effect might be translating to the salience of certain difficulties that are not as salient for those people with disabilities since they are used to accommodating for them.

FUTURE WORK

Future work has two paths; expansion of results, and correction of methods.

- The information collected about the people with disabilities can be turned into ICF classification data, which can be examined to confirm whether representation of various types of disabilities is being achieved. Peg test data can also be reanalyzed to test whether the suit matches for a specific subset of disabilities.
- Add range of motion parameters to the experiment. Collect goniometer measurements and use these to calibrate range of motion restrictions to the suit capabilities. This opens a new avenue of research with more accurate measurement techniques. Also add more standard measurements of restriction such as grip strength.
- Remove the within group part of the test and have the participants perform the test only in the suit. This will make for a more accurate analysis, especially during the statement interpretation and aggregation phases.
- Use the CN space in conjunction with prior work on the modules of the product pairs to validate that the KINdReD collection methodology actually places common functions in the proposed common module space.

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CHAPTER FOUR: GENERAL CONCLUSION

Extendable Results

Of the three hypotheses covered by this thesis, one has been proven to be correct through three different examinations, one is currently false, with easy changes suggested to reverse this, and one provides initial evidence that it is true, but is waiting for a later phase of the project to be addressed fully.

The current iteration of the disability simulation suit is working too well, providing greater physical restrictions than desired for the KINdReD research. However, flaws in the sample data used for the validation procedure must be addressed before the suit is rejected outright. Much information has been gathered which suggests that the suit is successful in stimulating the desired perceptual effects in participants. This perceptual matching between people with disabilities and people in the suit is especially important to KINdReD research and the gathering of useful customer needs.

It is likely that the methodology and mechanisms used in this research are valid, given a few minor tweaks suggested to remove some uncertainty in the analysis that may affect the results. Overall, the suit shows significant indications of validity, and the customer needs collected through the methods employed in this research are matching adequately. More work is required to finalize and extend the findings.

Additional Information

As part of the conclusion of this research, there are several discussions to be presented that did not have a logical place in the publications. Either because they speak to internal study design changes, or they are based on tentative information and require more formal examination and connection to the larger research at a later date.

- Weaknesses in the aggregation method.

When the knowledge graphs were randomized and the uniqueness and the statements determined to the second time the total number of unique needs was slightly different than the first time. This illustrates a flexibility in the analysis methodology that should not be there. However, when the original list contains 207 unique statements, a difference of 9 is only a 4.34% change. Also, each product pair category is changed by less than 15%, with an average change of only 5.13%. This small change can be attributed to the original measure being done with the researchers having no experience with the procedure. Since the rework was done later in the research, they had practice and could see what was similar more easily. This indicates that future work which uses this knowledge tracking procedure should pay careful attention to it and its practice bias issues.

- Weaknesses in the data collection procedure.

Since the people with no disabilities did phase one before phase two, almost all the comments in phase two were comparative. They would say things like, "this is more difficult in the suit" or "it feels the same as before". These types of comments are not easily translatable into CNs given that the statement does not contain the proper context to extract true meaning.

Also, the total number of useful comments from phase 2 was surprisingly low. This meant it was necessary to include phase 1 statements in the analysis, which was not the original study design.

The fact that G2 data with no suit is included in the CN space may be skewing our results. However, since the shape of the cluster is very similar for both groups it may also be having no effect. On average, only 45% of the statements that went into the aggregation coming from the phase 1 videos. This is a rough estimate based on interim documentation, which does not include the last two participants and the ice trays.

- Proposed resolutions to the collection weaknesses to address the applicability to the larger KINdReD research.

When research continues it should be done with a separate group of people wearing the suit. This will eliminate the need to use paired t-tests, which is good since the variances are so unequal.

It will also eliminate the confounding effect of phase 1. If the participants in Group 2 only perform phase 2, the test in the suit, they would have to articulate all their needs at once and will not be hindered by the desire to compare. This would ensure that our lists do not contain needs that are not applicable to the suit situation. It will provide less opportunity to collect extra data such as preference changes and useful comments about the suit, but the actual research question will be able to be addressed more confidently and more straightforward.

- Discussion of Participants' Stated Product Preference.

The fact that people with disabilities did not like the inclusive products better illustrates the fact that current inclusive design efforts do not always succeed. Speculation as to why this occurs is not warranted at this time, but it is an interesting thing to note that the group preferences were not as expected. The people in the suit far preferred the inclusive products, which might indicate that these products only help when the disability is extreme, as it has been shown to be with the suit.

As part of the interview, the participants were asked to say which product out of each pair they preferred. This was not done as part of the initial testing design so data regarding this is less consistent. It was a question that was discovered to be useful during testing to force participants to comment specifically. People without experience in protocol analysis found it difficult to articulate, and having to make a choice caused them to start thinking more clearly in the ways that were desired.

One issue that is easily identified is the can opener button. It was designed to hold the device closed so that users do not need to apply force to keep it closed while turning. However, it did not work adequately, and created difficulty for the G1 people since they lacked the dexterity to actually push the button to release the device. People in G2 latched onto the idea as novel or helpful and they were able to push it, but they did say it was harder in the suit.

It is recommended that the videos be reexamined to make sure that these numbers are correct before the findings are used widely. Since this question was not part of the initial interview design not everyone stated a preference and tracking of these statements is incomplete, the category marked "no pref.", meaning no preference, hence contains both statement of explicit, “both are bad” or “they are equal” variety and some interviews where the Q was not asked but they made such statements anyway on some of the products but not others. The next round of participant testing done, either at Oregon State University or Texas A&M University, include this activity from the start as it is interesting and useful in getting good information out of those people that do not grasp the protocol analysis idea well.

Table 4.1: Product preference raw numbers.

Preferences	**Group 1**	**Group 2 in suit**
Exclusive Can Opener	5	2
Inclusive Can Opener	2	7
No CO pref.	4	2
Exclusive Jar Opener	3	5
Inclusive Jar Opener	7	5
No JO pref.	1	1
Exclusive Garlic Press	5	1
Inclusive Garlic Press	2	9
No GP pref.	3	1
Exclusive Ice Tray	4	3
Inclusive Ice Tray	3	0
No IT pref.	2	2

Table 4.2: Product preference percentages.

preference for inclusive product in pair	**G1**	**G2**
CO	18%	64%
JO	64%	45%
GP	18%	82%
IT	33%	0%
preference for exclusive product in pair	**G1**	**G2**
CO	45%	18%
JO	27%	45%
GP	45%	9%
IT	44%	60%

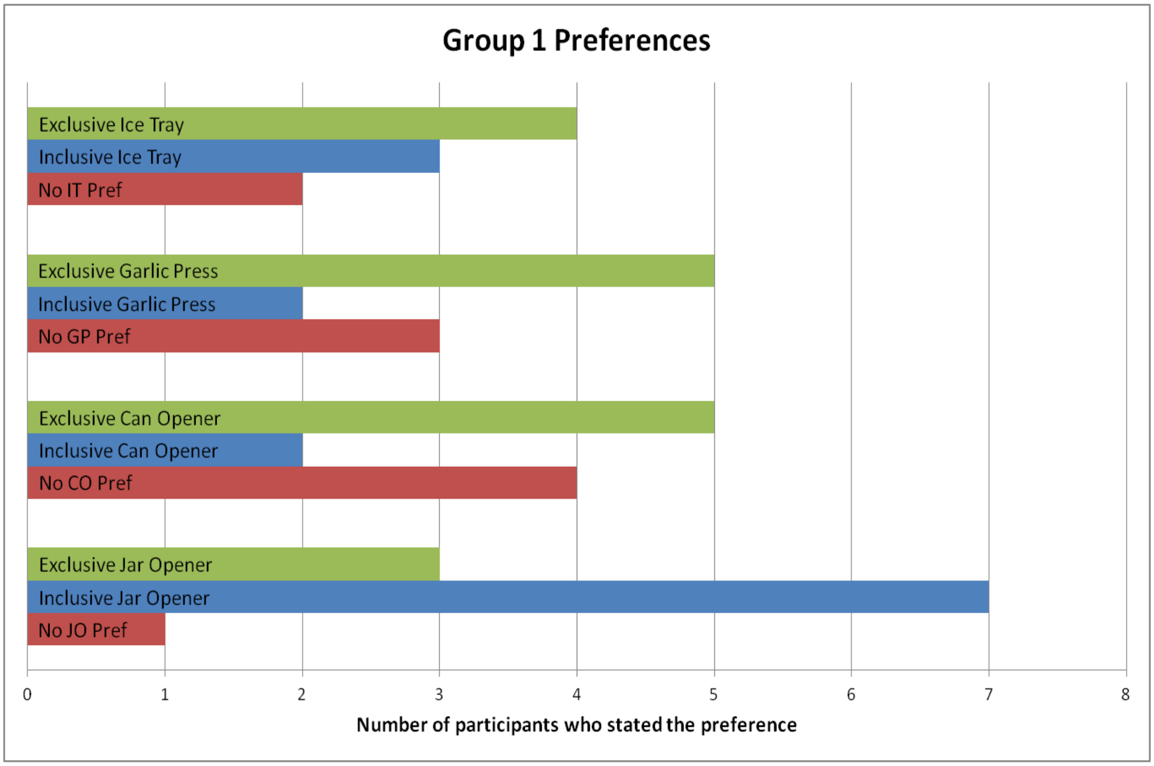


Figure 4.1: Product preferences of people with disabilities.

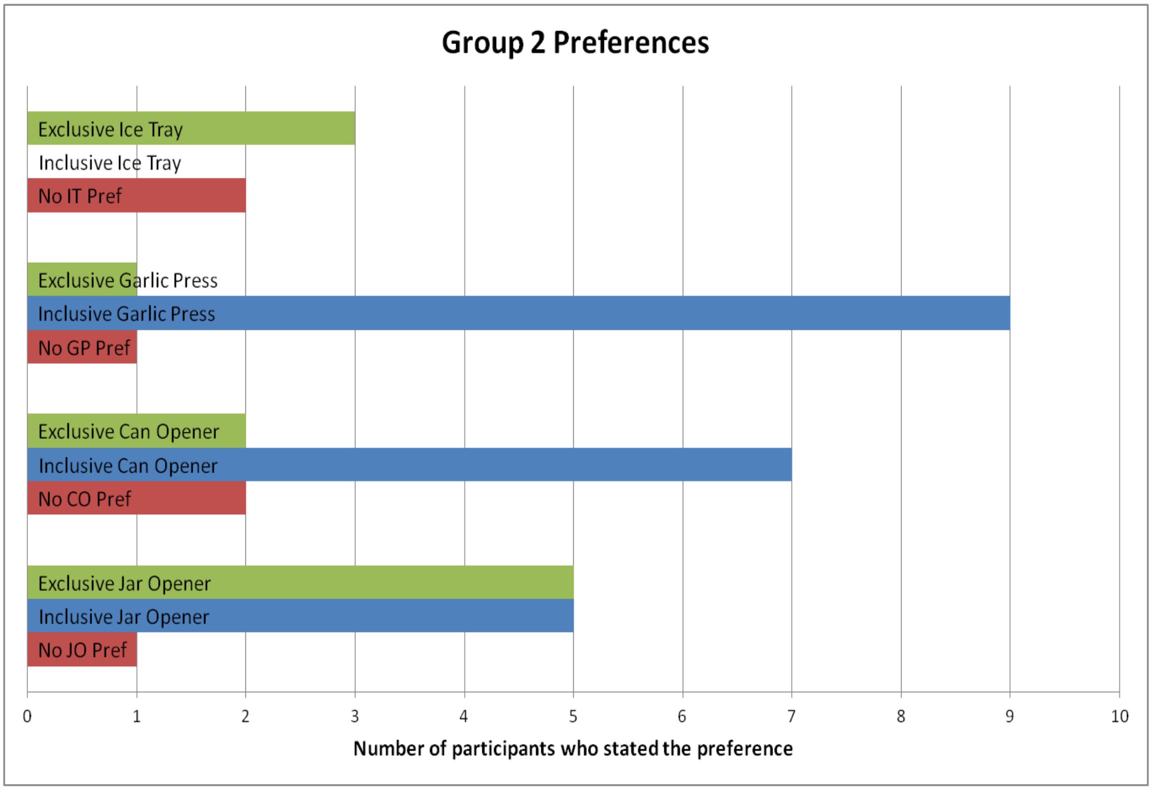


Figure 4.2: Product preferences of people without disabilities.

APPENDICES

APPENDIX A: Interview Script

Good morning/afternoon/evening.
Thanks for coming, we really appreciate it.

The first thing we need you to do is read and sign the consent form. As you read it if you have any questions or need something clarified just ask me.
(Answer Q's and make sure the doc is signed correctly.)

Ok, before we start on that I would like to get your permission to perform an optional part of the test. This is an easy way we found to get specific quantified metrics of how much the suit restricts. The peg test is used by occupational therapists as a measure of dexterity.
(Explain and administer peg test.)

Now move over to that seat and pretend to work so I can frame the camera properly.
Ok, first are you familiar with all these items and how they work? Which do you have experience with? When we get to the ice cube tray I will go into the other room to get a fresh full one out of the freezer.
(If not familiar give description from below.)
Garlic Press: You put the piece of garlic in the container and close the handles to cause the mechanism to crush the garlic out the holes.
Jar Opener: You fit the device onto the lid and then twist to remove...
Can Opener: You set the device against the can with the blade on the lid, then close the handles to cut into the can, then continue to hold it closed and turn the handle to move the device around the can.

So what we are essentially doing is a protocol analysis. This means we would like to hear what you are doing, why you are doing it that way, what you are thinking about the process, what parts of the activities you find difficult or easy, what you like or don't like about the product. Really anything, we need you to say it so we can capture all the information. Does that make sense?
(Even if they say yes give the example.)
Example: I want to turn on the TV so I search for the remote, I locate it, walk over and pick it up, it fits in my hand nicely and is not too heavy. I find the right button and press it. It is easy to see and to press. I locate the sensor, point the remote and watch for a response. Etc.

“I am turning on the camera now.”
Introduction: Date, time, participant number, part of group X, phase 1.
First, we have to check that you understand the test so in your own words please give me a brief description of what we will be doing today.
(Wait, and clarify is wrong)

OK, you may start using the products from either side of the line, remember to talk.
(Perform phase one)

Ok, now I'd like you to tell me which product from each set you prefer and why.

Camera Off / Put on suit
(perform peg test again)

Camera On
(Perform Phase Two)
(Get product preferences again)

Now that you have experienced it some, we would like to get your general thoughts on the suit. How well does it restrict you? What works well and what doesn't? How do you feel in it? Etc.

Follow-up Questions: After this experiment do you think you have a better understanding of the issues faced by people with disabilities? What personal experience do you have with people with disabilities.

Camera Off
Remove suit/ask which email to use for survey/give flier so they can recruit/clean up

---

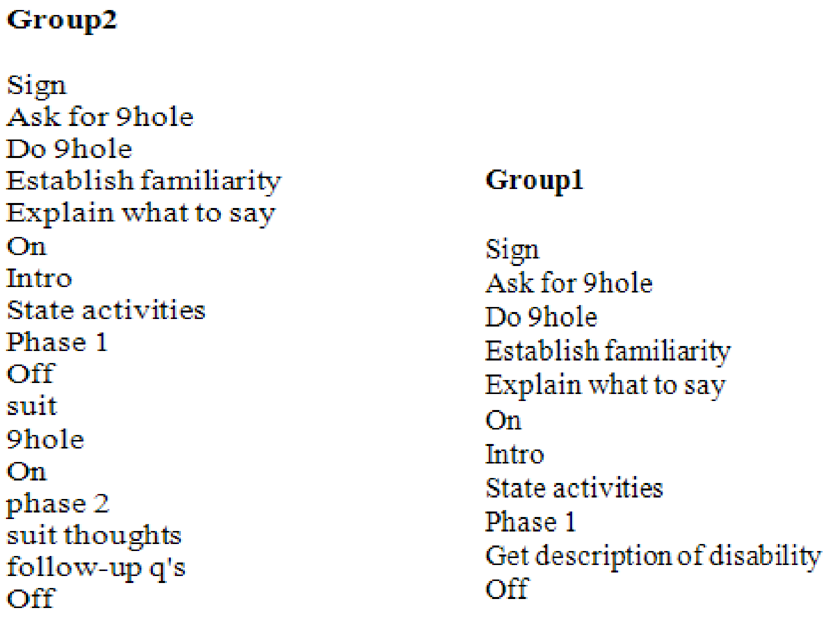
IF Group 1: after phase 1 and preference statements…

All right, now is the part where you describe exactly what your disability is. What parts of you are effected in what ways and how severely.
(record explanation)

Ok, that's all we need from you, thanks so much for coming in to help.

Offer to show them the suit/ ask which email to use /give flier so they can recruit/clean up

Notes to remember order



Group2

Sign
Ask for 9hole
Do 9hole
Establish familiarity
Explain what to say
On
Intro
State activities
Phase 1
Off
suit
9hole
On
phase 2
suit thoughts
follow-up q's
Off

Group1

Sign
Ask for 9hole
Do 9hole
Establish familiarity
Explain what to say
On
Intro
State activities
Phase 1
Get description of disability
Off

APPENDIX B: Tables of Customer Needs (statements and data)

			G2 Jar Openers				
Weight Avg	**Frequency**	**ID Tag**	**CN Statement :** Product should…	**MIN**	**MAX**	**stdev**	
4.1	9	J-2-1	be easy to understand / intuitive	3	5	0.7378	
4.1	2	J-2-2	have a non-slip surface	3	5	0.8755	
4.2	1	J-2-3	require only a little dexterity / coordination	3	5	0.7888	
3.5	6	J-2-4	indicate direction of turn	1	5	1.3540	
3.9	1	J-2-5	amplify the applied torque	3	5	0.7378	
3.9	1	J-2-6	work in multiple positions	2	5	1.3703	
4.3	5	J-2-7	require only low forces to operate	3	5	0.8232	
4.4	3	J-2-8	be easy to twist	3	5	0.6992	
4.2	2	J-2-9	be easy to grip	3	5	0.6324	
3.7	1	J-2-10	be easy to assemble	2	5	1.0593	
4.2	1	J-2-11	work easily with either hand	2	5	1.0327	
4.3	3	J-2-12	operate with as few steps as possible	3	5	0.8232	
4.2	1	J-2-13	not have moving parts that can break and fail	2	5	1.1352	
3.8	1	J-2-14	handle should fit nicely in the hand	3	5	0.6324	
4.5	4	J-2-15	be easy to attach to lid	4	5	0.5270	x
4.3	1	J-2-16	unscrew smoothly so as not to spill	3	5	0.8232	
3.9	6	J-2-17	have clear directions	3	5	0.7378	
4.4	11	J-2-18	grip lid securely	4	5	0.5163	x
3.5	2	J-2-19	be easy to push	**0**	5	1.5092	
3.2	3	J-2-20	provide feedback that it is secure	**0**	**4**	1.2292	
3.6	3	J-2-21	feel secure	2	5	0.8432	
4.6	1	J-2-22	work on multiple can sizes	3	5	0.6992	
3.6	3	J-2-23	provide a method for gripping the jar as well as the lid	**0**	5	1.5776	
3.9	1	J-2-24	stay level with little effort	3	5	0.8755	
4.2	1	J-2-25	take off the seal with little force	3	5	0.7888	
3.2	1	J-2-26	appear approachable	1	5	1.3165	
3.5	1	J-2-27	knob should be capable of breaking the seal	**0**	5	1.9002	
3.2	1	J-2-28	be lightweight	2	5	0.9189	

			G2 Can Openers				
Weight Avg	**Frequency**	**ID Tag**	**CN Statement :** Product should…	**MIN**	**MAX**	**stdev**	
4.1	3	C-2-1	operation should be clear / obvious	3	5	0.9944	
4.3	2	C-2-2	stay in place	3	5	0.9486	
4.1	1	C-2-3	provide assistance opening the device	2	5	1.1005	
1.9	2	C-2-4	be attractive	**0**	5	1.4491	
3.5	2	C-2-5	have a rubber gripping surface	2	5	1.0801	
4.3	1	C-2-6	be easy to remove from can	4	5	0.4830	x
3	1	C-2-7	be made of a material that feels nice to hold	2	**4**	0.4714	
4.4	11	C-2-8	be easy to turn / twist	3	5	0.6992	
4	1	C-2-9	hands should fit easily around knob	3	5	0.6666	
4.4	5	C-2-10	be easy to squeeze	3	5	0.6992	
4.1	1	C-2-11	remain sharp for a long time	3	5	0.7378	
3.6	1	C-2-12	help remove the top after cutting	3	5	0.6992	
4.4	5	C-2-13	pierce the can with little effort	3	5	0.6992	
4.4	1	C-2-14	not dig into the hand	3	5	0.6992	
4.1	2	C-2-15	be easy to maneuver	3	5	0.7378	
3.5	2	C-2-16	provide feedback that it is secure	**0**	5	1.3540	
3.2	1	C-2-17	have consistent motion	1	**4**	1.0327	
2.8	1	C-2-18	be familiar	1	5	1.3165	
2.5	2	C-2-19	have easy to press buttons	**0**	5	1.9002	
3.9	1	C-2-20	be simple	3	5	0.9944	
4.3	6	C-2-21	operate with low force / strength	3	5	0.8232	
3	1	C-2-22	have thick handles	2	5	0.8164	
4.3	1	C-2-23	operation should be easy to learn	3	5	0.6749	
4.4	2	C-2-24	be usable with either hand	3	5	0.8432	
3	1	C-2-25	have nice feeling knob and handles	2	**4**	0.4714	
4.2	1	C-2-26	have sharp blade	3	5	0.6324	
4.7	2	C-2-27	be easy to attach to can	4	5	0.4830	x
4.7	1	C-2-28	cut continuously without skipping spots	4	5	0.4830	x
2.1	1	C-2-29	have small handles	**0**	**3**	0.9944	
4.2	1	C-2-30	have a way to stay steady / aligned on can	3	5	0.7888	
3.7	1	C-2-31	have explanatory symbols	3	5	0.8232	
3.4	1	C-2-32	be small enough to fit well in hand	3	5	0.6992	
2.6	1	C-2-33	be easy to store	1	**4**	0.8432	
4.1	3	C-2-34	be easy to grip	3	5	0.8755	
4.1	4	C-2-35	remain closed easily	2	5	1.1005	
4	1	C-2-36	requires as few steps as possible to use	3	5	0.8164	
1.6	1	C-2-37	be curved	**0**	**3**	1.1737	

			G2 Garlic Presses				
Weight Avg	**Frequency**	**ID Tag**	**CN Statement :** Product should…	**MIN**	**MAX**	**stdev**	
4.4	14	G-2-1	require only small force to squeeze closed	3	5	0.6992	
4.1	2	G-2-2	be easy to grip/grasp	2	5	0.9944	
2.6	5	G-2-3	have large handles	2	**3**	0.5163	
3.2	2	G-2-4	have a large gripping surface	2	5	0.9189	
3.9	1	G-2-5	provide force regardless of hand span or mechanism position	2	5	0.9944	
4.3	1	G-2-6	sized appropriately for all hands	3	5	0.8232	
4.5	6	G-2-7	accommodate any size garlic clove in compartment / holder	3	5	0.7071	
4.1	1	G-2-8	be easy to pick up	2	5	1.1005	
3.7	1	G-2-9	have a non-slip surface	3	5	0.8232	
4.1	2	G-2-10	be simple	3	5	0.8755	
4.2	1	G-2-11	allow one-handed usage	2	5	1.0327	
4.3	1	G-2-12	transfer energy efficiently	3	5	0.6749	
2.9	1	G-2-13	look simple	1	5	1.3703	
3.1	1	G-2-14	have a nice grip	2	5	0.9944	
4.5	3	G-2-15	be easy to insert/load garlic into place	3	5	0.8498	
3.6	1	G-2-16	feel durable	1	5	1.1737	
3.8	2	G-2-17	accommodate small hand spans	3	5	0.7888	
4.3	1	G-2-18	require only low dexterity	3	5	0.8232	
2.7	1	G-2-19	be compact	1	5	1.1595	
3.5	1	G-2-20	provide a mechanical advantage	**0**	5	1.4337	
4.6	8	G-2-21	parts should align automatically without manual adjustment	4	5	0.5163	x
3.9	3	G-2-22	operation should be obvious / intuitive	3	5	0.7378	
1.9	1	G-2-23	be aesthetically pleasing	1	**4**	1.1005	
4.1	5	G-2-24	be easy to maneuver / manipulate	3	5	0.9944	
4.2	3	G-2-25	be easy to clean	3	5	0.7888	
4.2	3	G-2-26	be efficient (material vs. effort)	3	5	0.9189	
3.5	1	G-2-27	be large enough to allow use of both hands	1	5	1.1785	
2.9	1	G-2-28	be lightweight	2	5	0.9944	
3.9	2	G-2-29	have rounded edges so as not to dig into the hand	3	5	0.9944	
3.9	3	G-2-30	fit in the hand comfortably / well	3	5	0.8755	

			G2 Ice Cube Trays				
Weight Avg	**Frequency**	**ID Tag**	**CN Statement :** Product should…	**MIN**	**MAX**	**stdev**	
3.625	2	I-2-1	have a way to remove a single cube	1	5	1.4079	
3	2	I-2-2	be familiar	2	5	1.0690	
2.375	1	I-2-3	be interesting/novel in design	1	5	1.3025	
3.5	2	I-2-4	be made of flexible material	2	5	0.9258	
4.375	4	I-2-5	require low finger strength	3	5	0.7440	
4	1	I-2-6	simplify the task	2	5	1.0690	
3.875	1	I-2-7	function no matter the size of the cube	2	5	1.1260	
4.125	1	I-2-8	be easy to grip	2	5	0.9910	
4.125	2	I-2-9	operation should be obvious	3	5	0.9910	
3.75	1	I-2-10	function with a variety of motions	3	5	0.8864	
4.25	1	I-2-11	release cubes with 100% effectiveness	3	5	0.8864	
4.5	1	I-2-12	operation should not be awkward or cumbersome	3	5	0.7559	
4	1	I-2-13	prevent the ice from spilling out	3	5	0.9258	
4	2	I-2-14	require the same amount of effort for each cube	3	5	0.9258	
4.375	1	I-2-15	keep the cube under the user's control	4	5	0.5175	x
4	2	I-2-16	lid should be easy to remove	2	5	1.0690	

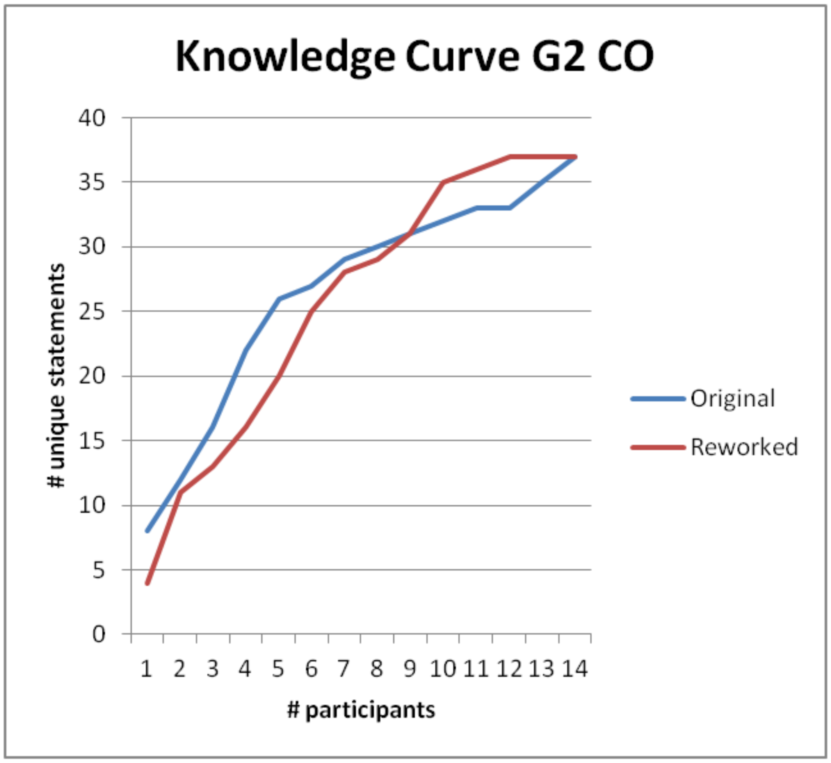
			G1 Ice Cube Trays				
Weight Avg	**Frequency**	**ID Tag**	**CN Statement :** Product should…	**MIN**	**MAX**	**stdev**	
4.13	1	I-1-1	require low finger mobility	3	5	0.8345	
3.38	1	I-1-2	have cushy grip surfaces	**0**	5	1.6850	
4.00	1	I-1-3	effectively utilize both hands	2	5	1.1952	
3.63	1	I-1-4	not need pressure applied to rigid areas	2	5	1.3025	
3.25	2	I-1-5	be easy to understand	1	5	1.5811	
3.13	1	I-1-6	have large handles	**0**	5	1.9594	
4.13	1	I-1-7	provide easy way to loosen cubes	2	5	0.9910	
4.50	3	I-1-8	provide easy way to remove cubes	4	5	0.5345	x
2.88	1	I-1-9	be familiar	1	5	1.2464	
3.88	1	I-1-10	be flexible	2	5	1.1260	
3.25	1	I-1-11	be usable with only one hand	1	5	1.3887	
4.00	1	I-1-12	be simple	3	5	0.7559	
4.00	2	I-1-13	require only low force to work	3	5	0.9258	

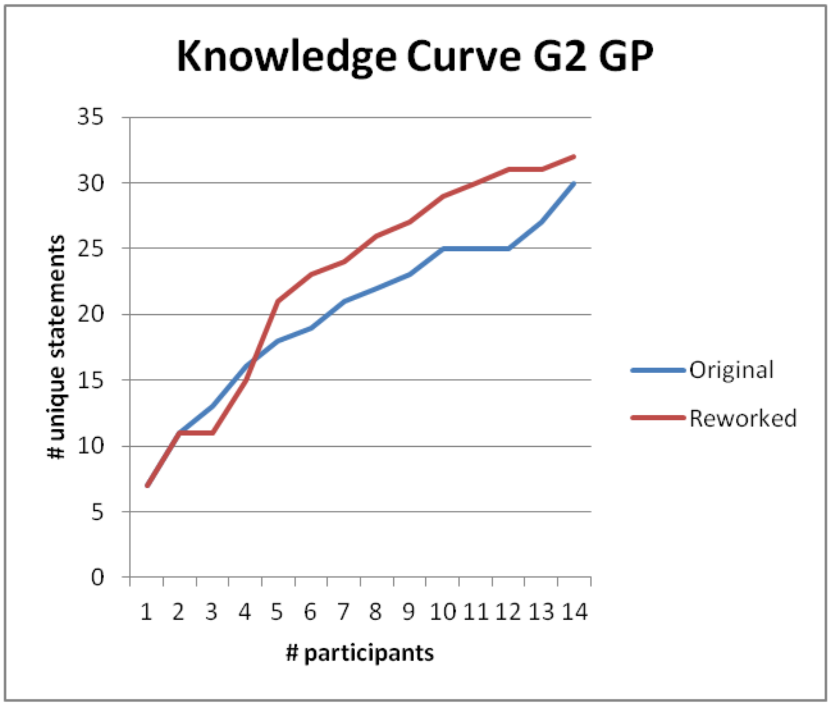
			G1 Jar Openers				
Weight Avg	**Frequency**	**ID Tag**	**CN Statement :** Product should…	**MIN**	**MAX**	**stdev**	
2.50	1	J-1-1	look simple	**0**	5	1.6036	
3.88	2	J-1-2	be usable by either hand	2	5	0.9910	
4.17	2	J-1-3	be to assemble	2	5	1.3292	
4.13	5	J-1-4	be easy to understand	2	5	1.2464	
2.75	1	J-1-5	have rubber coating on handle	1	5	1.3887	
3.50	1	J-1-6	require only one hand to work	1	5	1.5119	
3.88	2	J-1-7	provide a way to grip jar as well	2	5	1.1260	
3.88	3	J-1-8	require only small forces to use	2	5	1.1260	
4.00	1	J-1-9	have a feature to assist with breaking the seal	2	5	1.1952	
3.63	2	J-1-10	provide stability	2	5	1.0607	
4.00	1	J-1-11	not have exposed sharp edges	2	5	0.9258	
3.88	3	J-1-12	have an easy to turn knob	2	5	0.9910	
4.38	1	J-1-13	unscrew without knocking over the jar	4	5	0.5175	x
4.38	3	J-1-14	require low torque to twist off lid	4	5	0.5175	x
3.50	8	J-1-15	have clear directions indicate direction of turn	1	5	1.3093	
2.50	1	J-1-16	look safe	1	5	1.3093	
4.13	1	J-1-17	work on multiple jar sizes	2	5	1.1260	
3.88	2	J-1-18	have a nice grip	2	5	1.1260	
3.63	1	J-1-19	operate with as few steps as possible	3	5	0.9161	
3.13	2	J-1-20	have large gripping surfaces	2	5	0.9910	
4.00	6	J-1-21	grip lid securely	2	5	1.0690	
4.25	2	J-1-22	be easy to attach to lid	3	5	0.7071	

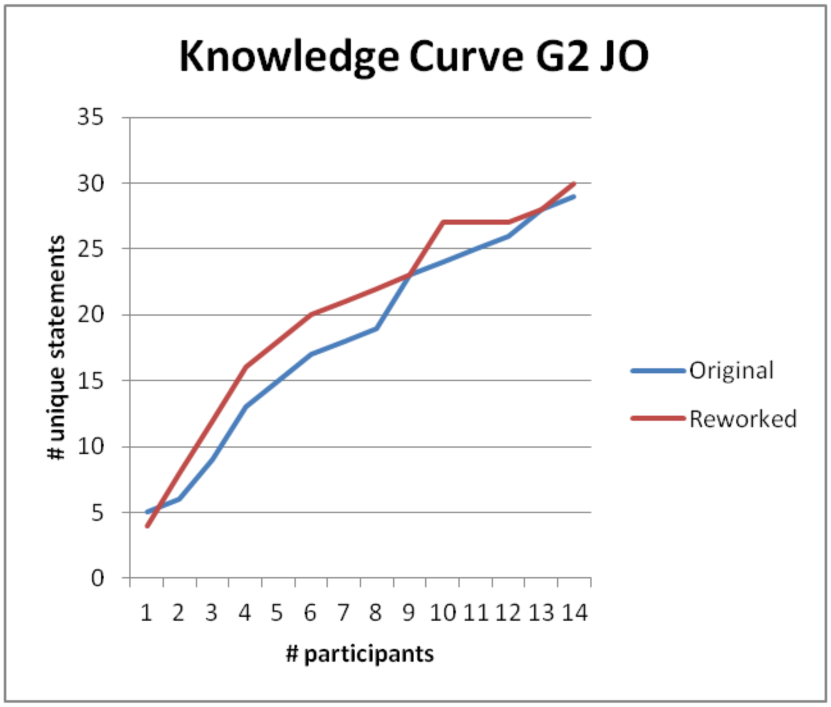
			G1 Can Openers				
Weight Avg	**Frequency**	**ID Tag**	**CN Statement :** Product should…	**MIN**	**MAX**	**stdev**	
4.00	1	C-1-1	be durable	2	5	1.0690	
3.88	2	C-1-2	be usable with either hand	2	5	1.1260	
3.00	1	C-1-3	have rubber coating	1	5	1.4142	
3.38	1	C-1-4	allow sufficient grip with one hand	2	5	1.1877	
3.75	2	C-1-5	not require hand to stay closed	2	5	1.2817	
4.25	2	C-1-6	have blunt / padded edges so as not to dig into user	3	5	0.8864	
3.38	1	C-1-7	have large handles	2	5	1.1877	
4.38	1	C-1-8	be efficient	3	5	0.7440	
3.25	1	C-1-9	have longer knob for more leverage	1	5	1.2817	
3.50	1	C-1-10	positions user's hands comfortably	2	5	0.9258	
3.88	1	C-1-11	operation should be simple	2	5	1.3562	
3.13	1	C-1-12	operate with a push action instead of a squeeze	2	5	0.9910	
3.00	1	C-1-13	shape should not be straight	1	5	1.5119	
3.13	1	C-1-14	function with pressure from multiple angles	2	5	0.8345	
4.25	5	C-1-15	be easy to turn	3	5	0.7071	
4.25	1	C-1-16	turn smoothly	3	5	0.7071	
4.25	1	C-1-17	provide the right leverage	3	5	0.7071	
4.25	1	C-1-18	remain in cutting position	3	5	0.7071	
4.00	3	C-1-19	have nice gripping surface	2	5	0.9258	
4.00	2	C-1-20	require only low force to hold closed	2	5	1.0690	
2.38	6	C-1-21	not have a separate release	1	5	1.3025	
2.63	2	C-1-22	be familiar	2	5	1.1877	
3.88	2	C-1-23	remain in position easily	3	5	0.8345	
3.50	2	C-1-24	be lightweight	2	5	1.0690	
4.25	3	C-1-25	require only minimal squeeze force to puncture can	3	5	0.7071	
3.50	1	C-1-26	have a non-slip grip surface	2	5	1.1952	
3.63	1	C-1-27	remain sharp as long as possible	1	5	1.3025	
4.00	2	C-1-28	be easy to understand	2	5	1.1952	
3.75	1	C-1-29	put user at the right height	2	5	1.4880	

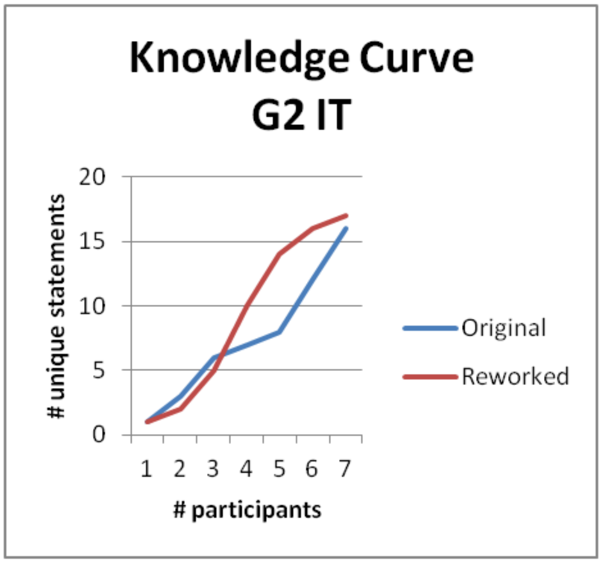
			G1 Garlic Presses				
Weight Avg	**Frequency**	**ID Tag**	**CN Statement :** Product should…	**MIN**	**MAX**	**stdev**	
3.13	1	G-1-1	have obvious holder	1	5	1.4577	
3.13	3	G-1-2	require only modest hand spans	2	5	1.1260	
2.50	1	G-1-3	not be sloped	1	5	1.1952	
3.75	1	G-1-4	provide stability	2	5	1.1650	
3.75	1	G-1-5	have a non-slip gripping surface	2	5	1.0351	
4.00	4	G-1-6	parts should align automatically without manual adjustment	2	5	1.0690	
4.13	1	G-1-7	be efficient	3	5	0.8345	
4.38	2	G-1-8	accommodate multiple sizes of garlic	4	5	0.5175	x
3.00	1	G-1-9	have curved handles	1	5	1.5119	
4.13	1	G-1-10	prevent user fingers from being caught / squished	2	5	1.1260	
3.88	1	G-1-11	be rounded so as not to cut into the hand	2	5	1.2464	
3.75	3	G-1-12	have obvious operation	2	5	1.2817	
4.38	2	G-1-13	have simple garlic insertion method	4	5	0.5175	x
4.38	8	G-1-14	require only low grip force / pressure to close	4	5	0.5175	x
3.38	1	G-1-15	have cushy grip surfaces	1	5	1.4079	
3.50	2	G-1-16	be lightweight	2	5	1.0690	
1.63	1	G-1-17	have a thin grip	**0**	**3**	0.9161	
3.00	1	G-1-18	be large enough to accommodate both hands	2	5	1.3093	
4.38	1	G-1-19	provide a good grip	3	5	0.7440	
2.63	1	G-1-20	have a familiar shape	1	5	1.1877	
4.50	2	G-1-21	be easy to clean	4	5	0.5345	x
4.38	1	G-1-22	allow application of uniform pressure	4	5	0.5175	x
3.50	1	G-1-23	only involve one hand	2	5	1.3093	
3.63	1	G-1-24	be conducive to applying pressure	2	5	1.0607	
2.63	1	G-1-25	have large handles	**0**	5	1.5980	
4.13	3	G-1-26	be easy to manipulate / maneuver	2	5	0.9910	
3.75	1	G-1-27	employ pressing rather than squeezing mechanism	2	5	1.1650	

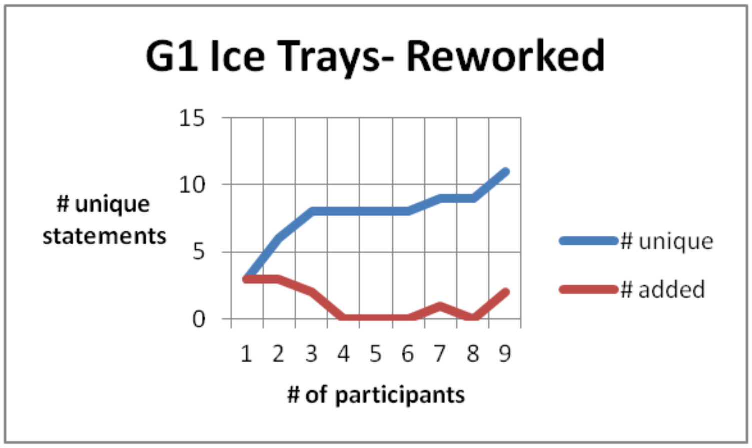
APPENDIX C: Knowledge Tracking Graphs

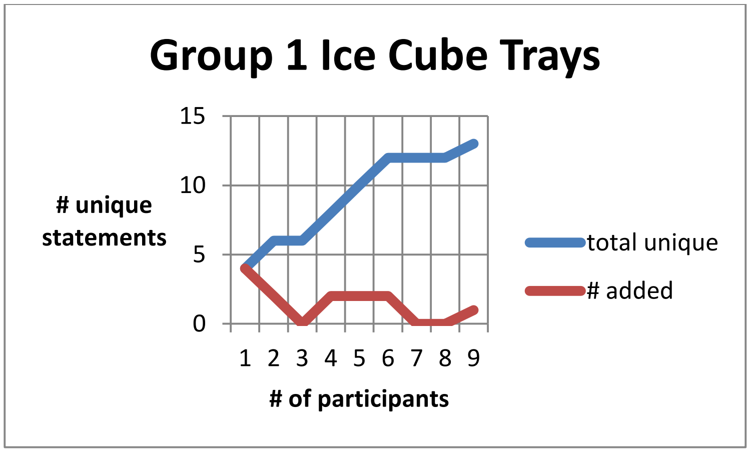


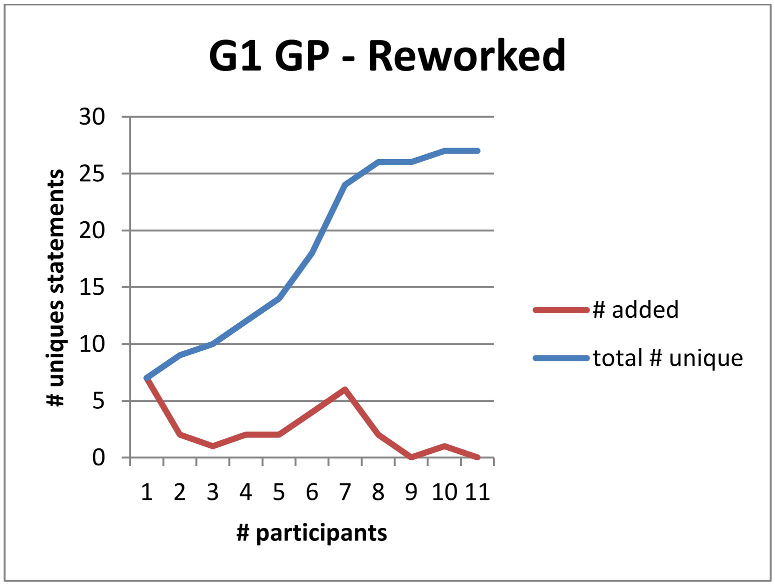


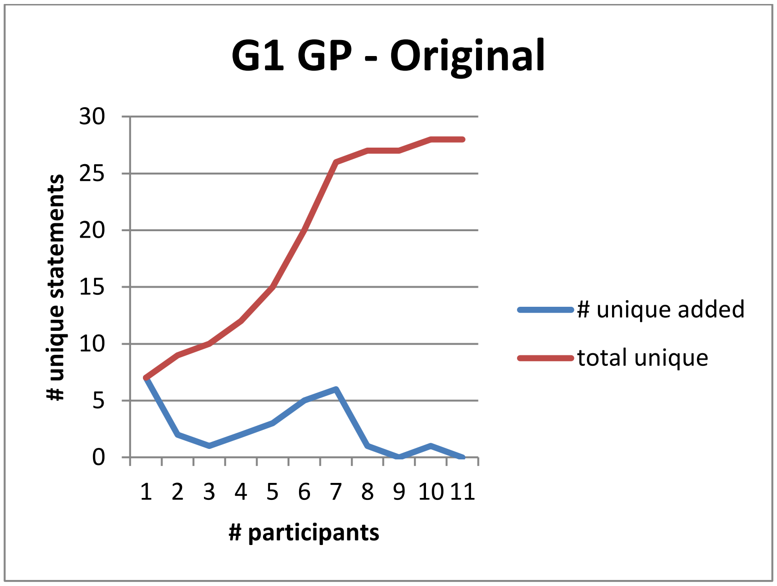

Knowledge Curve G2 JO
35
30
25
20
15
10
5
0
unique statements
1 2 3 4 5 6 7 8 9 10 11 12 13 14
participants
Original
Reworked

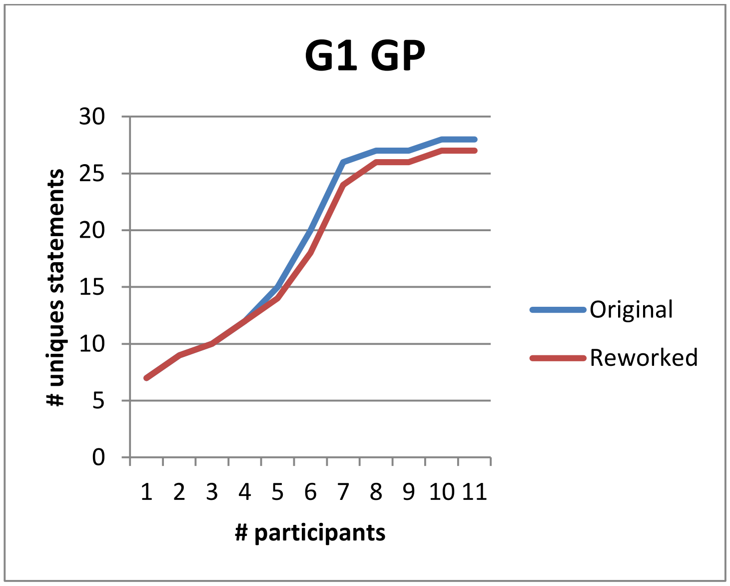

Knowledge Curve G2 IT
20
15
10
5
0
unique statements
1 2 3 4 5 6 7
participants
Original
Reworked

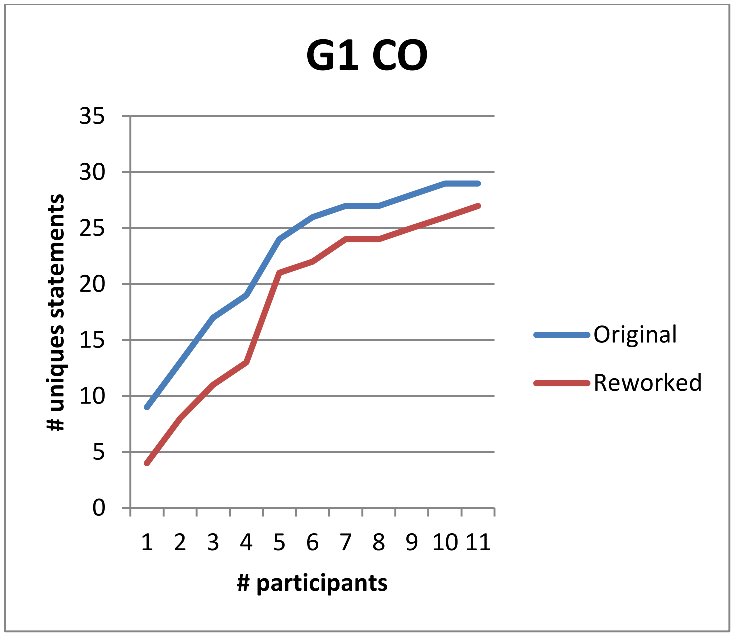

G1 Ice Trays- Reworked
15
10
5
0
unique statements
1 2 3 4 5 6 7 8 9
# of participants
unique
added

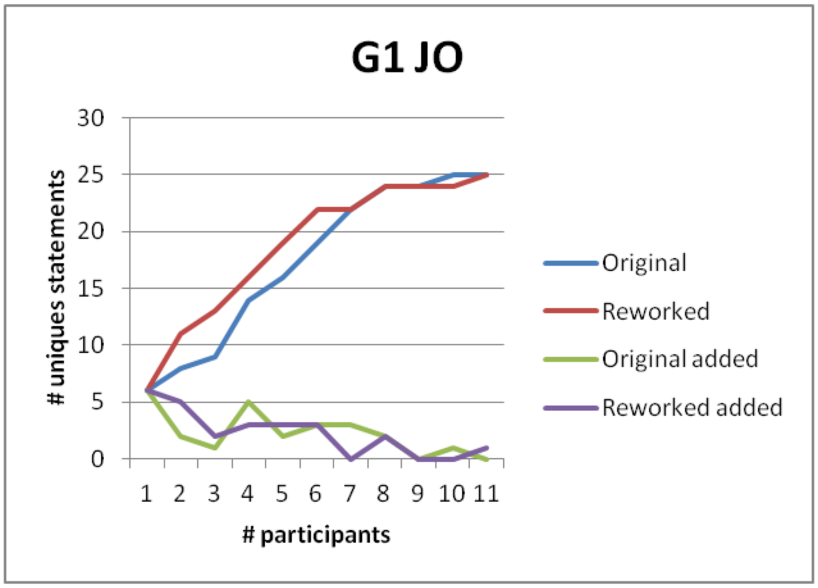

Group 1 Ice Cube Trays
15
10
5
0
unique statements
1 2 3 4 5 6 7 8 9
# of participants
total unique
added

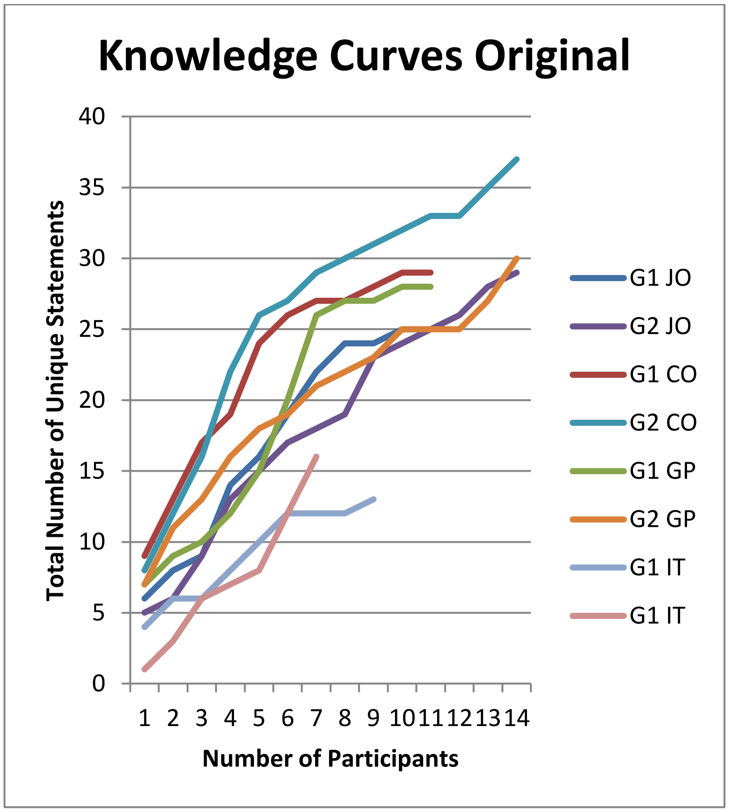

G1 GP - Reworked
30
25
20
15
10
5
0
uniques statements
1 2 3 4 5 6 7 8 9 10 11
participants
added
total # unique


G1 GP - Original
30
25
20
15
10
5
0
unique statements
1
2
3
4
5
6
7
8
9
10
11
participants
unique added
total unique


G1 GP
30
25
20
15
10
5
0
uniques statements
1
2
3
4
5
6
7
8
9
10
11
participants
Original
Reworked


G1 CO
uniques statements
0
5
10
15
20
25
30
35
1 2 3 4 5 6 7 8 9 10 11
participants
Original
Reworked


G1 JO
uniques statements
0
5
10
15
20
25
30
1 2 3 4 5 6 7 8 9 10 11
participants
Original
Reworked
Original added
Reworked added


Knowledge Curves Original
Total Number of Unique Statements
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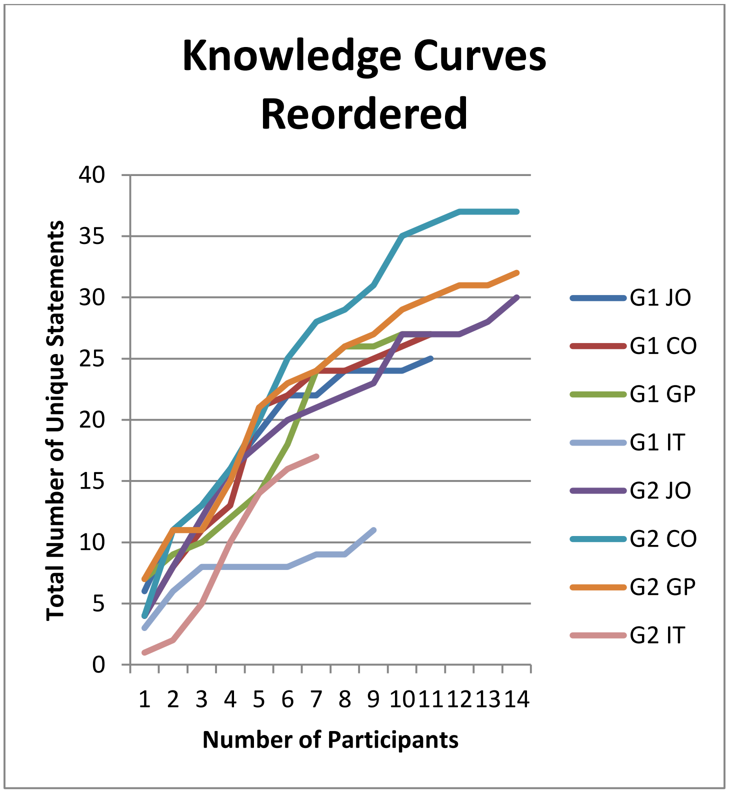
35
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Number of Participants
G1 JO
G2 JO
G1 CO
G2 CO
G1 GP
G2 GP
G1 IT
G1 IT


Knowledge Curves Reordered
Total Number of Unique Statements
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35
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Number of Participants
G1 JO
G1 CO
G1 GP
G1 IT
G2 JO
G2 CO
G2 GP
G2 IT

APPENDIX D: Similarity Calculation Exercises

1: Ice Tray CN Matching.

G2	**Ice Cube Trays**			**G1**	**Ice Cube Trays**		
	Product should…				Product should…		
CN Tag	**CN Statement**	**similarity measure**	**match tag**	**CN Tag**	**CN Statement**	**similarity measure**	**match tag**
I-2-1	have a way to remove a single cube	n		I-1-1	require low finger mobility	n	
I-2-2	be familiar	s	a	I-1-2	have cushy grip surfaces	n	
I-2-3	be interesting/novel in design	n		I-1-3	effectively utilize both hands	n	
I-2-4	be made of flexible material	s	b	I-1-4	not need pressure applied to rigid areas	n	
I-2-5	require low finger strength	s	c	I-1-5	be easy to understand	s	d
I-2-6	simplify the task	n		I-1-6	have large handles	n	
I-2-7	function no matter the size of the cube	n		I-1-7	provide easy way to loosen cubes	n	
I-2-8	be easy to grip	n		I-1-8	provide easy way to remove cubes	n	
I-2-9	operation should be obvious	s	d	I-1-9	be familiar	s	a
I-2-10	function with a variety of motions	n		I-1-10	be flexible	s	b
I-2-11	release cubes with 100% effectiveness	n		I-1-11	be usable with only one hand	n	
I-2-12	operation should not be awkward or cumbersome	n		I-1-12	be simple	n	
I-2-13	prevent the ice from spilling out	n		I-1-13	require only low force to work	s	c
I-2-14	require the same amount of effort for each cube	n					
I-2-15	keep the cube under the user's control	n			s = similar n = not similar		
I-2-16	lid should be easy to remove	n					
				G1	4 similar 9 not		
G2	4 similar 12 not			**30.7%**	**projection = 4/(9+4) = 0.307692**		

2: Garlic Press CN Matching.

G2	**Garlic Presses**			**G1**	**Garlic Presses**		
	Product should…				Product should…		
CN Tag	**CN Statement**	**similarity measure**	**match tag**	**CN Tag**	**CN Statement**	**similarity measure**	**match tag**
G-2-1	require only small force to squeeze closed	s	a	G-1-1	have obvious holder	n	
G-2-2	be easy to grip/grasp	s	f	G-1-2	require only modest hand spans	s	h
G-2-3	have large handles	s	b	G-1-3	not be sloped	n	
G-2-4	have a large gripping surface	n		G-1-4	provide stability	n	
G-2-5	provide force regardless of hand span or mechanism position	s	q	G-1-5	have a non-slip gripping surface	s	d
G-2-6	sized appropriately for all hands	n		G-1-6	parts should align automatically without manual adjustment	s	i
G-2-7	accommodate any size garlic clove in compartment / holder	s	c	G-1-7	be efficient	s	m
G-2-8	be easy to pick up	n		G-1-8	accommodate multiple sizes of garlic	s	c
G-2-9	have a non-slip surface	s	d	G-1-9	have curved handles	n	
G-2-10	be simple	n		G-1-10	prevent user fingers from being caught / squished	n	
G-2-11	allow one-handed usage	s	e	G-1-11	be rounded so as not to cut into the hand	s	p
G-2-12	transfer energy efficiently	n		G-1-12	have obvious operation	s	j
G-2-13	look simple	n		G-1-13	have simple garlic insertion method	s	g
G-2-14	have a nice grip	n		G-1-14	require only low grip force / pressure to close	s	a
G-2-15	be easy to insert/load garlic into	s	g	G-1-15	have cushy grip surfaces	n	

	place						
G-2-16	feel durable	n		G-1-16	be lightweight	s	o
G-2-17	accommodate small hand spans	s	h	G-1-17	have a thin grip	n	
G-2-18	require only low dexterity	n		G-1-18	be large enough to accommodate both hands	s	n
G-2-19	be compact	n		G-1-19	provide a good grip	s	f
G-2-20	provide a mechanical advantage	n		G-1-20	have a familiar shape	n	
G-2-21	parts should align automatically without manual adjustment	s	i	G-1-21	be easy to clean	s	l
G-2-22	operation should be obvious / intuitive	s	j	G-1-22	allow application of uniform pressure	s	q
G-2-23	be aesthetically pleasing	n		G-1-23	only involve one hand	s	e
G-2-24	be easy to maneuver / manipulate	s	k	G-1-24	be conducive to applying pressure	n	
G-2-25	be easy to clean	s	l	G-1-25	have large handles	s	b
G-2-26	be efficient (material vs. effort)	s	m	G-1-26	be easy to manipulate / maneuver	s	k
G-2-27	be large enough to allow use of both hands	s	n	G-1-27	employ pressing rather than squeezing mechanism	n	
G-2-28	be lightweight	s	o				
G-2-29	have rounded edges so as not to dig into the hand	s	p				
G-2-30	fit in the hand comfortably / well	n			s = similar n = not similar		
G2	17 similar 12 not			G1	17 similar 10 not		
				62.9%	**projection = 17/(17+10) = 0.62963**		

3: Can Opener CN Matching.

G2	**Can Openers**			**G1**	**Can Openers**		
	Product should…				Product should…		
CN Tag	**CN Statement**	**similarity measure**	**match tag**	**CN Tag**	**CN Statement**	**similarity measure**	**match tag**
C-2-1	operation should be clear / obvious	s	a	C-1-1	be durable	n	
C-2-2	stay in place	s	b	C-1-2	be usable with either hand	s	n
C-2-3	provide assistance opening the device	n		C-1-3	have rubber coating	s	c
C-2-4	be attractive	n		C-1-4	allow sufficient grip with one hand	n	
C-2-5	have a rubber gripping surface	s	c	C-1-5	not require hand to stay closed	n	
C-2-6	be easy to remove from can	n		C-1-6	have blunt / padded edges so as not to dig into user	s	h
C-2-7	be made of a material that feels nice to hold	s	s	C-1-7	have large handles	s	m
C-2-8	be easy to turn / twist	s	d	C-1-8	be efficient	n	
C-2-9	hands should fit easily around knob	n		C-1-9	have longer knob for more leverage	n	
C-2-10	be easy to squeeze	s	e	C-1-10	positions user's hands comfortably	n	
C-2-11	remain sharp for a long time	s	f	C-1-11	operation should be simple	s	k
C-2-12	help remove the top after cutting	n		C-1-12	operate with a push action instead of a squeeze	n	
C-2-13	pierce the can with little effort	s	g	C-1-13	shape should not be straight	s	r
C-2-14	not dig into the hand	s	h	C-1-14	function with pressure from multiple angles	n	
C-2-15	be easy to maneuver	n		C-1-15	be easy to turn	s	d
C-2-16	provide feedback that it is secure	n		C-1-16	turn smoothly	s	i
C-2-17	have consistent motion	s	i	C-1-17	provide the right leverage	n	
C-2-18	be familiar	s	j	C-1-18	remain in cutting position	s	o
C-2-19	have easy to press	n		C-1-19	have nice gripping	s	p s

	buttons				surface		
C-2-20	be simple	s	k	C-1-20	require only low force to hold closed	s	q l
C-2-21	operate with low force / strength	s	l	C-1-21	not have a separate release	n	
C-2-22	have thick handles	s	m	C-1-22	be familiar	s	j
C-2-23	operation should be easy to learn	n		C-1-23	remain in position easily	s	b
C-2-24	be usable with either hand	s	n	C-1-24	be lightweight	n	
C-2-25	have nice feeling knob and handles	n		C-1-25	require only minimal squeeze force to puncture can	s	e g l
C-2-26	have sharp blade	n		C-1-26	have a non-slip grip surface	n	
C-2-27	be easy to attach to can	n		C-1-27	remain sharp as long as possible	s	f
C-2-28	cut continuously without skipping spots	s	o	C-1-28	be easy to understand	s	a
C-2-29	have small handles	n		C-1-29	put user at the right height	n	
C-2-30	have a way to stay steady / aligned on can	n					
C-2-31	have explanatory symbols	n					
C-2-32	be small enough to fit well in hand	n					
C-2-33	be easy to store	n					
C-2-34	be easy to grip	s	p				
C-2-35	remain closed easily	s	q				
C-2-36	requires as few steps as possible to use	n			s = similar n = not similar		
C-2-37	be curved	s	r				
G2	19 similar 18 not			G1	16 similar 13 not		
				60.3%	**projection = 16/(16+13) = 0.551724** **projection = 17.5/(16+13) =0.603448** **projection = 19/ (16+13) = 0.655172**		

4: Jar Opener CN Matching.

G2	**Jar Openers**			**G1**	**Jar Openers**		
	Product should…				Product should…		
CN Tag	**CN Statement**	**similarity measure**	**match tag**	**CN Tag**	**CN Statement**	**similarity measure**	**match tag**
J-2-1	be easy to understand / intuitive	s	a	J-1-1	look simple	s	q
J-2-2	have a non-slip surface	n		J-1-2	be usable by either hand	s	g
J-2-3	require only a little dexterity / coordination	n		J-1-3	be easy to assemble	s	f
J-2-4	indicate direction of turn	s	b	J-1-4	be easy to understand	s	a
J-2-5	amplify the applied torque	n		J-1-5	have rubber coating on handle	n	
J-2-6	work in multiple positions	n		J-1-6	require only one hand to work	n	
J-2-7	require only low forces to operate	s	c	J-1-7	provide a way to grip jar as well	s	o
J-2-8	be easy to twist	s	d	J-1-8	require only small forces to use	s	c
J-2-9	be easy to grip	s	e	J-1-9	have a feature to assist with breaking the seal	s	r
J-2-10	be easy to assemble	s	f	J-1-10	provide stability	s	p
J-2-11	work easily with either hand	s	g	J-1-11	not have exposed sharp edges	n	
J-2-12	operate with as few steps as possible	s	h	J-1-12	have an easy to turn knob	s	d
J-2-13	not have moving parts that can break and fail	n		J-1-13	unscrew without knocking over the jar	s	j
J-2-14	handle should fit nicely in the hand	n		J-1-14	require low torque to twist off lid	s	m
J-2-15	be easy to attach to lid	s	i	J-1-15	have clear directions indicate direction of turn	s	b k
J-2-16	unscrew smoothly so as not to spill	s	j	J-1-16	look safe	s	q
J-2-17	have clear directions	s	k	J-1-17	work on multiple jar sizes	s	n
J-2-18	grip lid securely	s	l	J-1-18	have a nice grip	s	e
J-2-19	be easy to push	s	m	J-1-19	operate with as few	s	h

					steps as possible		
J-2-20	provide feedback that it is secure	n		J-1-20	have large gripping surfaces	n	
J-2-21	feel secure	n		J-1-21	grip lid securely	s	l
J-2-22	work on multiple can sizes	s	n	J-1-22	be easy to attach to lid	s	i
J-2-23	provide a method for gripping the jar as well as the lid	s	o				
J-2-24	stay level with little effort	s	p				
J-2-25	take off the seal with little force	n					
J-2-26	appear approachable	s	q				
J-2-27	knob should be capable of breaking the seal	s	r		s = similar n = not similar		
J-2-28	be lightweight	n					
G2	18 similar 10 not			G1	18 similar 4 not		
					projection = 18/(18+4) = 0.8181818		**81.8%**

Appendix E: Frequency Difference Calculations.

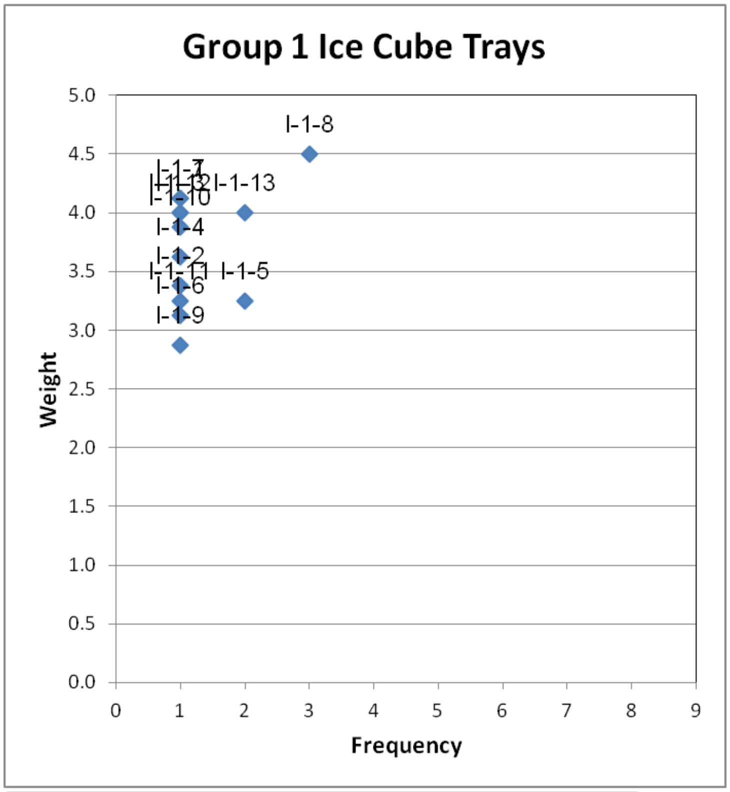
Jar Openers - CNs in common						
Statement	**F G2 #**	**F G1 #**	**F G2 %**	**F G1 %**	**diff**	**significant**
be easy to understand / intuitive	9	5	64.3%	45.5%	18.8%	
indicate direction of turn	6	8	42.9%	72.7%	29.9%	x
require only low forces to operate	5	3	35.7%	27.3%	8.4%	
be easy to twist	3	3	21.4%	27.3%	5.8%	
be easy to grip	2	2	14.3%	18.2%	3.9%	
be easy to assemble	1	2	7.1%	18.2%	11.0%	
work easily with either hand	1	2	7.1%	18.2%	11.0%	
operate with as few steps as possible	3	1	21.4%	9.1%	12.3%	
be easy to attach to lid	4	2	28.6%	18.2%	10.4%	
unscrew smoothly so as not to spill	1	1	7.1%	9.1%	1.9%	
have clear directions	6	8	42.9%	72.7%	29.9%	x
grip lid securely	11	6	78.6%	54.5%	24.0%	x
require low torque to twist off lid	2	3	14.3%	27.3%	13.0%	
						% significant
						0.23077

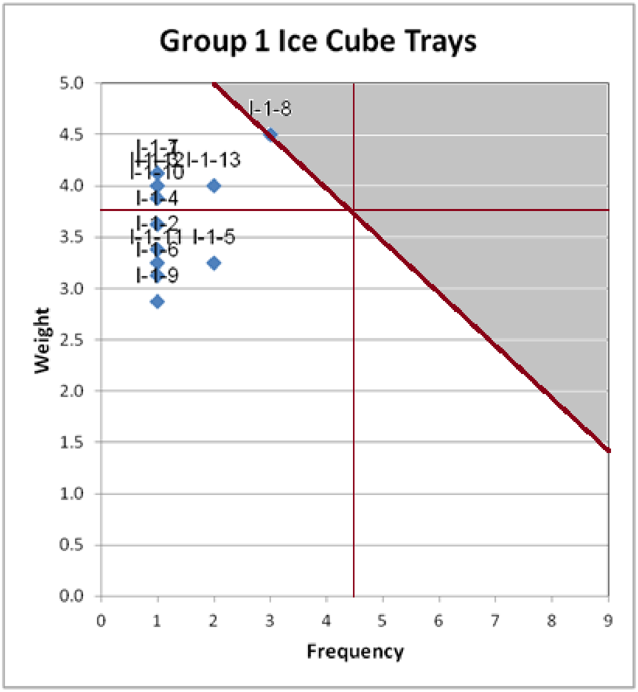
Ice Trays - CNs in common						
Statement	**F G2 #**	**F G1 #**	**F G2 %**	**F G1 %**	**diff**	**significant**
be familiar	2	1	22.22%	14.29%	7.94%	
be made of flexible material	2	1	22.22%	14.29%	7.94%	
require low finger strength	4	2	44.44%	28.57%	15.87%	
operation should be obvious	2	2	22.22%	28.57%	-6.35%	
			0 % large difference in Frequency			

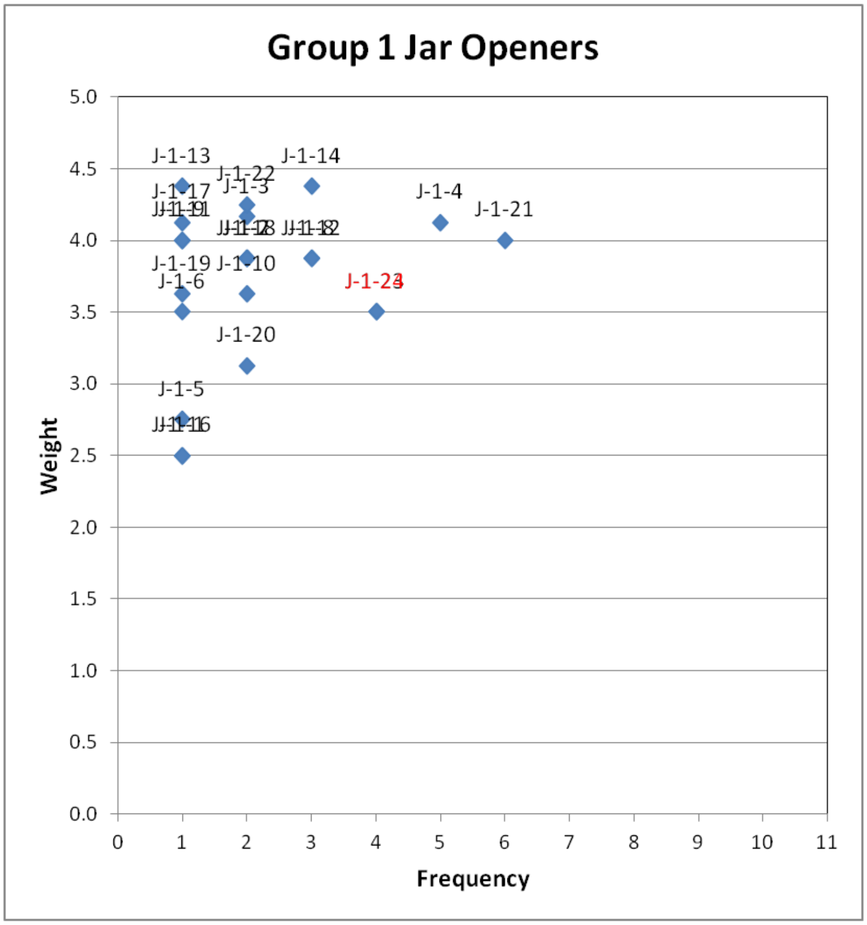
Can Openers - CNs in common						
Statement	**F G2 #**	**F G1 #**	**F G2 %**	**F G1 %**	**diff**	**significant**
operation should be clear / obvious	3	2	21.43%	18.18%	3.25%	
stay in place	2	2	14.29%	18.18%	3.90%	
cut continuously without skipping spots	1	1	7.14%	9.09%	1.95%	
be curved	1	1	7.14%	9.09%	1.95%	
have a rubber gripping surface	2	1	14.29%	9.09%	5.19%	
be made of a material that feels nice to hold	1	3	7.14%	27.27%	20.13%	x
be easy to turn / twist	11	5	78.57%	45.45%	33.12%	x
pierce the can with little effort	5	3	35.71%	27.27%	8.44%	
not dig into the hand	1	2	7.14%	18.18%	11.04%	
be easy to squeeze	5	3	35.71%	27.27%	8.44%	
remain sharp for a long time	1	1	7.14%	9.09%	1.95%	
have consistent motion	1	1	7.14%	9.09%	1.95%	
be familiar	1	2	7.14%	18.18%	11.04%	
be simple	1	1	7.14%	9.09%	1.95%	
operate with low force / strength	6	2	42.86%	18.18%	24.68%	x
have thick handles	1	1	7.14%	9.09%	1.95%	
be usable with either hand	2	2	14.29%	18.18%	3.90%	
be easy to grip	3	3	21.43%	27.27%	5.84%	
remain closed easily	4	2	28.57%	18.18%	10.39%	
						% significant
						0.15789

Garlic Presses - CNs in common						
Statement	**F G2 #**	**F G1 #**	**F G2 %**	**F G1 %**	**diff**	**significant**
require only small force to squeeze closed	14	8	100.0%	72.7%	27.3%	x
be easy to grip/grasp	2	1	14.3%	9.1%	5.2%	
have large handles	5	1	35.7%	9.1%	26.6%	x
provide force regardless of hand span or mechanism position	1	1	7.1%	9.1%	1.9%	
accommodate any size garlic clove in compartment / holder	6	2	42.9%	18.2%	24.7%	x
have a non-slip surface	1	1	7.1%	9.1%	1.9%	
allow one-handed usage	1	1	7.1%	9.1%	1.9%	
be easy to insert/load garlic into place	3	2	21.4%	18.2%	3.2%	
accommodate small hand spans	2	3	14.3%	27.3%	13.0%	
parts should align automatically without manual adjustment	8	4	57.1%	36.4%	20.8%	x
operation should be obvious / intuitive	3	3	21.4%	27.3%	5.8%	
be easy to maneuver / manipulate	5	3	35.7%	27.3%	8.4%	
be easy to clean	3	2	21.4%	18.2%	3.2%	
be efficient (material vs. effort)	3	1	21.4%	9.1%	12.3%	
be large enough to allow use of both hands	1	1	7.1%	9.1%	1.9%	
be lightweight	1	2	7.1%	18.2%	11.0%	
have rounded edges so as not to dig into the hand	2	1	14.3%	9.1%	5.2%	
						% significant
						0.23529

APPENDIX F: Customer Need Space Graphs, marked and unmarked. Top, plain CN space graph. Bottom, graph marked with cut-off lines and module regions.



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0
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4
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7
8
9
10
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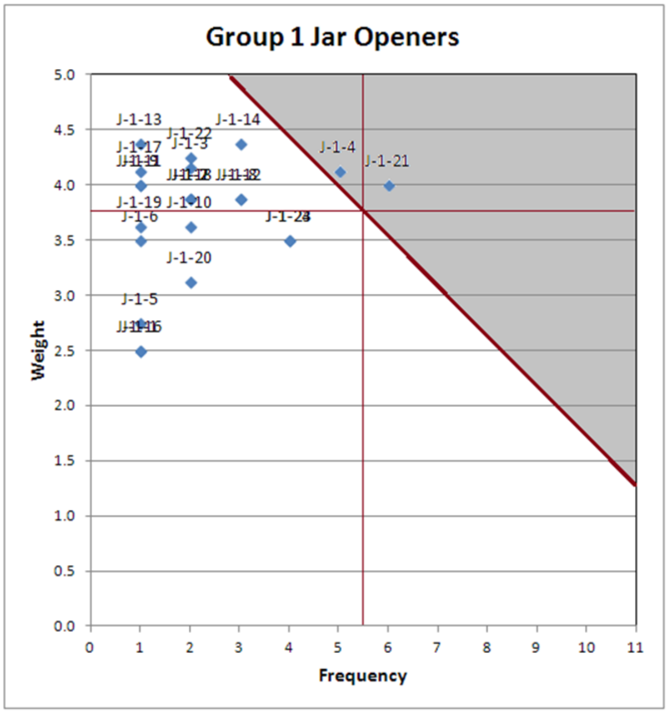
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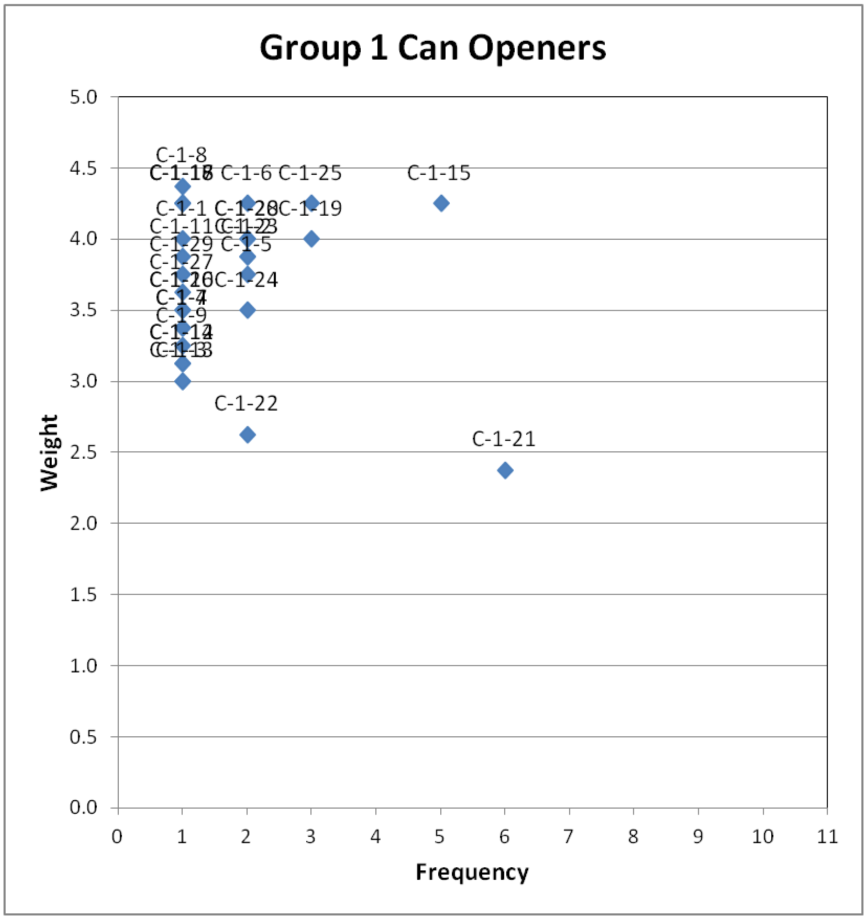
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7
8
9
10
11
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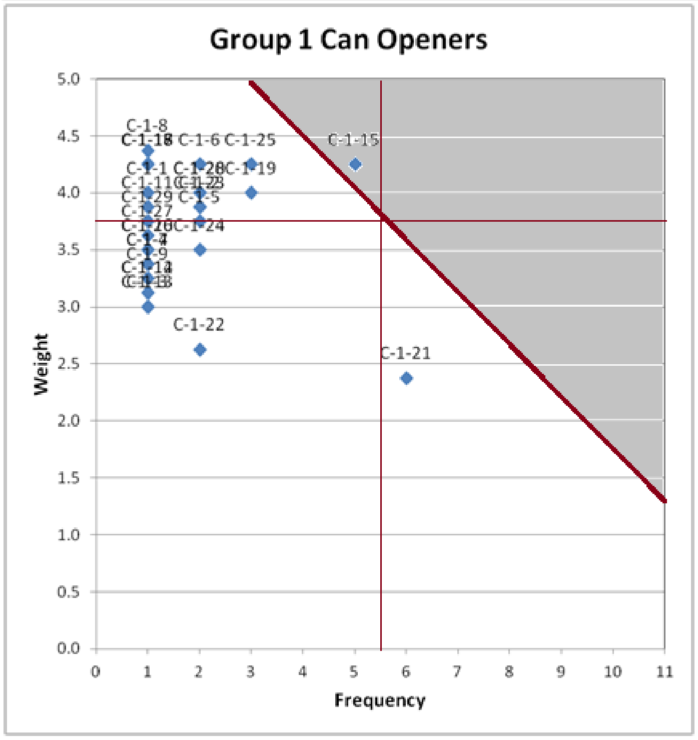
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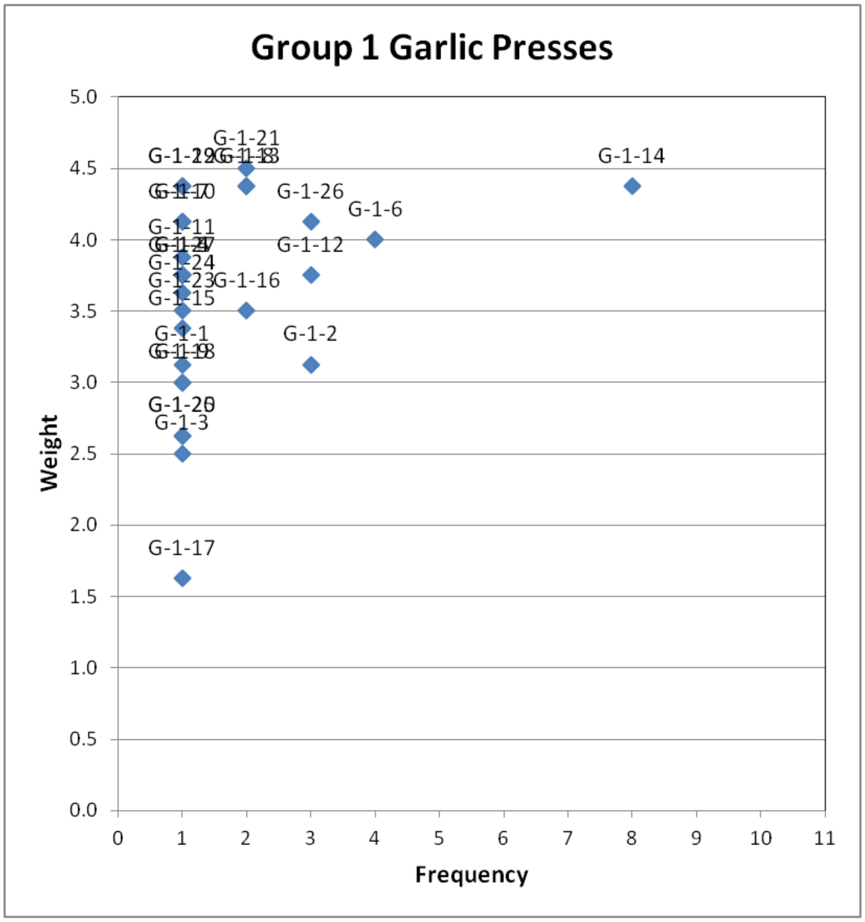
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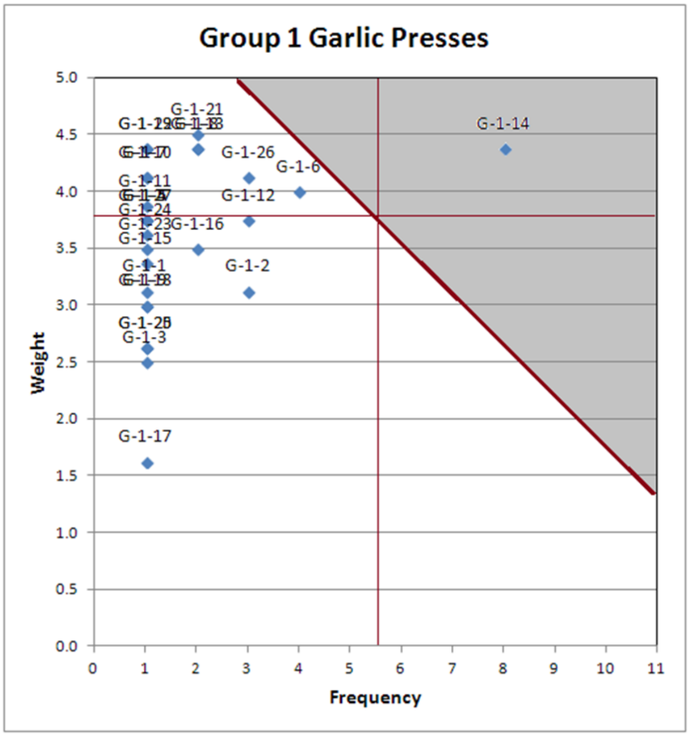
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6
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8
9
10
11
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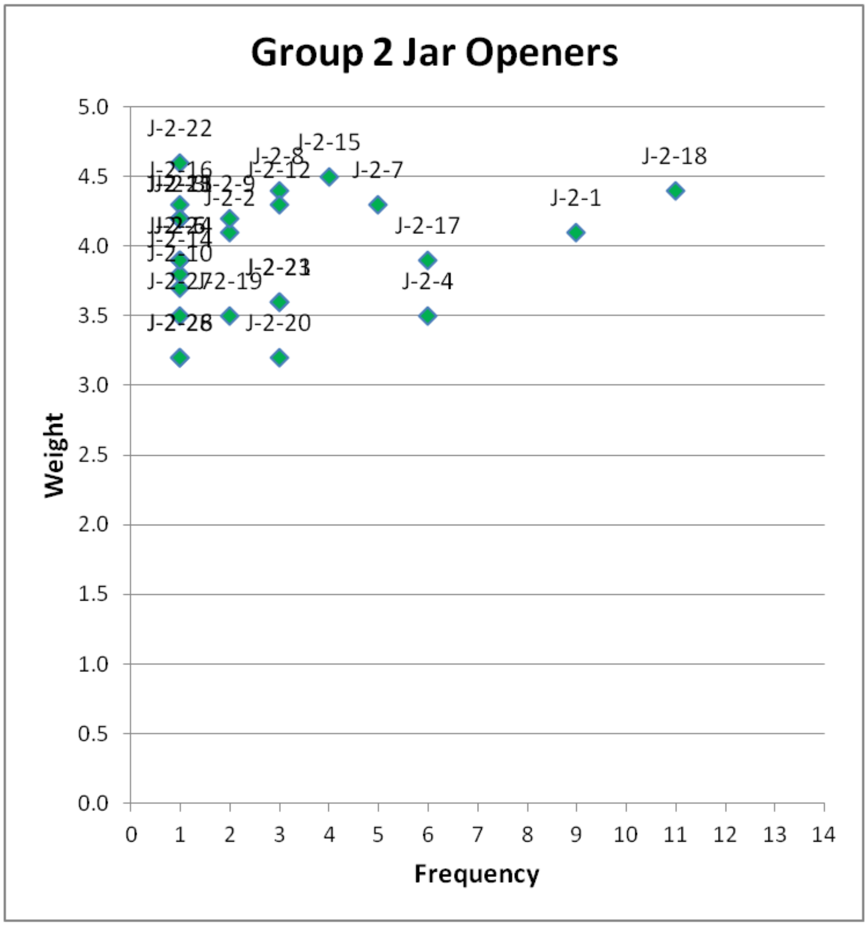
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0
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9
10
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12
13
14
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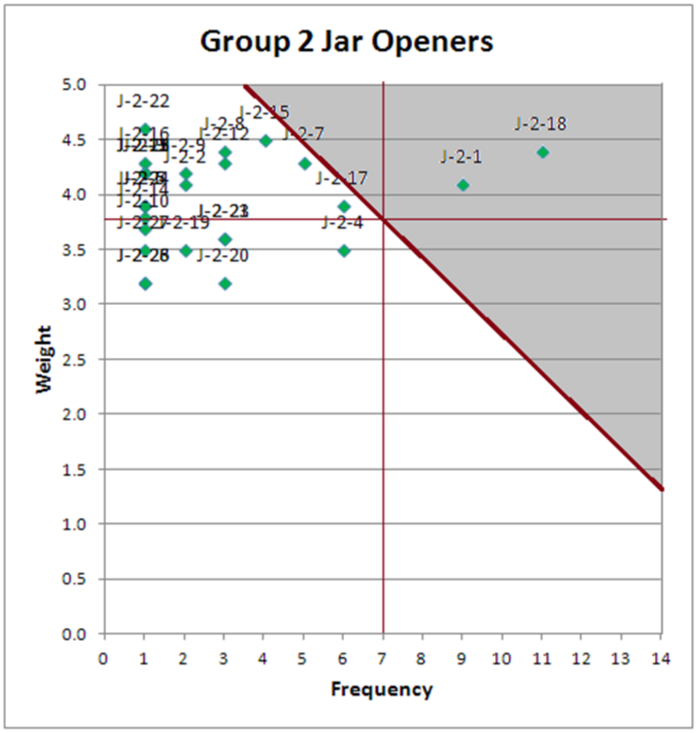
J-2-10
J-2-23
J-2-4
J-2-19
J-2-20
J-2-28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Weight
Frequency
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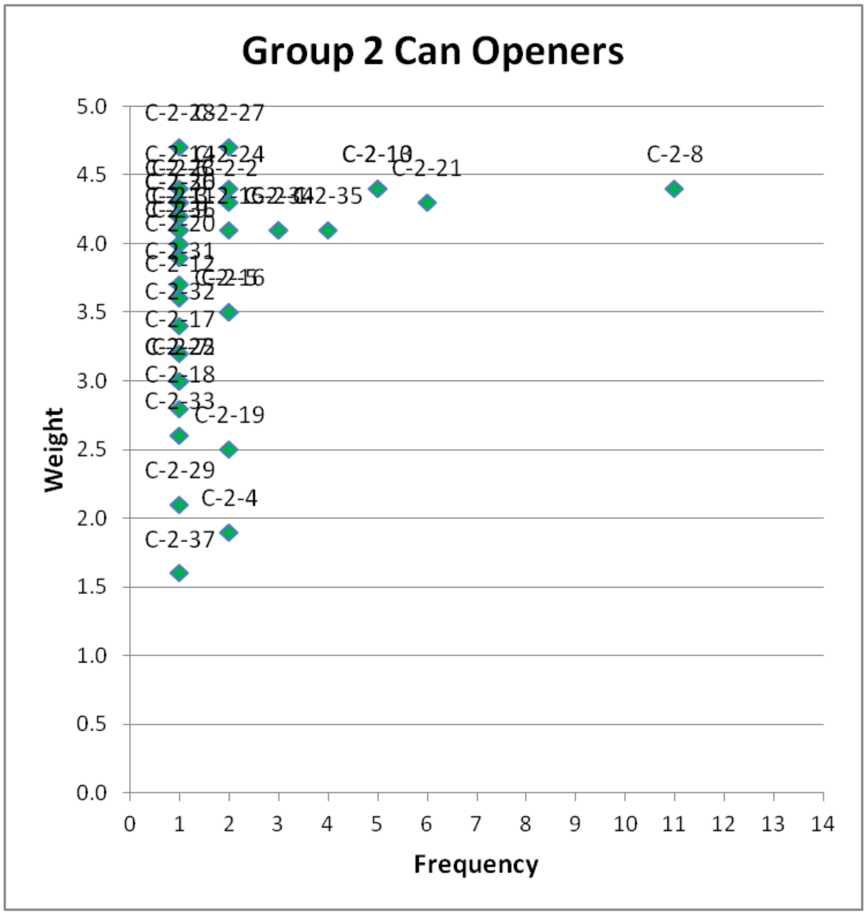
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
J-2-22
J-2-16
J-2-8
J-2-15
J-2-12
J-2-7
J-2-9
J-2-2
J-2-18
J-2-1
J-2-17
J-2-14
J-2-10
J-2-23
J-2-4
J-2-19
J-2-20
J-2-28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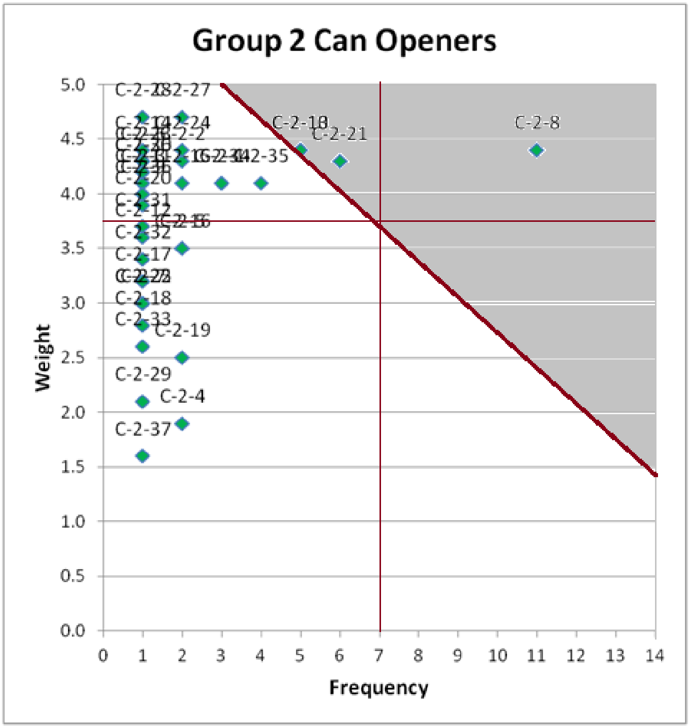
Weight
Frequency
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
C-2-27
C-2-24
C-2-2
C-2-35
C-2-21
C-2-8
C-2-20
C-2-31
C-2-12
C-2-32
C-2-17
C-2-18
C-2-33
C-2-19
C-2-29
C-2-4
C-2-37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Weight
Frequency
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4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
C-2-27
C-2-24
C-2-2
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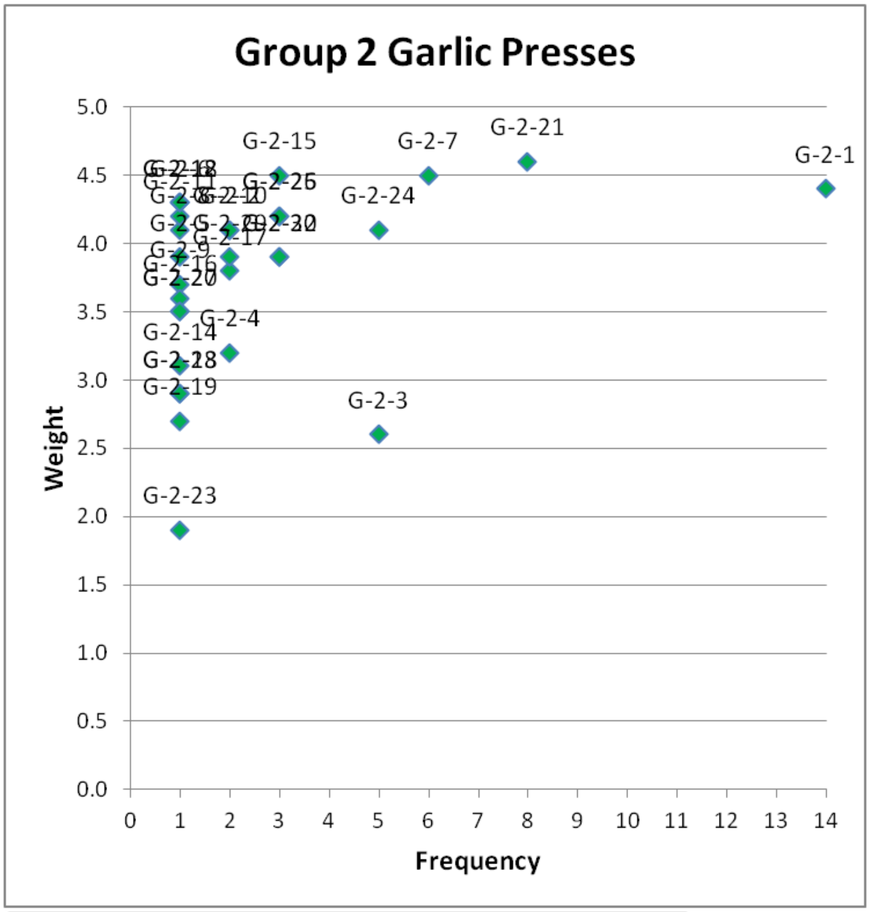
C-2-19
C-2-29
C-2-4
C-2-37


Group 2 Garlic Presses
Weight
Frequency
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3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
G-2-15
G-2-7
G-2-21
G-2-1
G-2-26
G-2-24
G-2-17
G-2-9
G-2-20
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G-2-14
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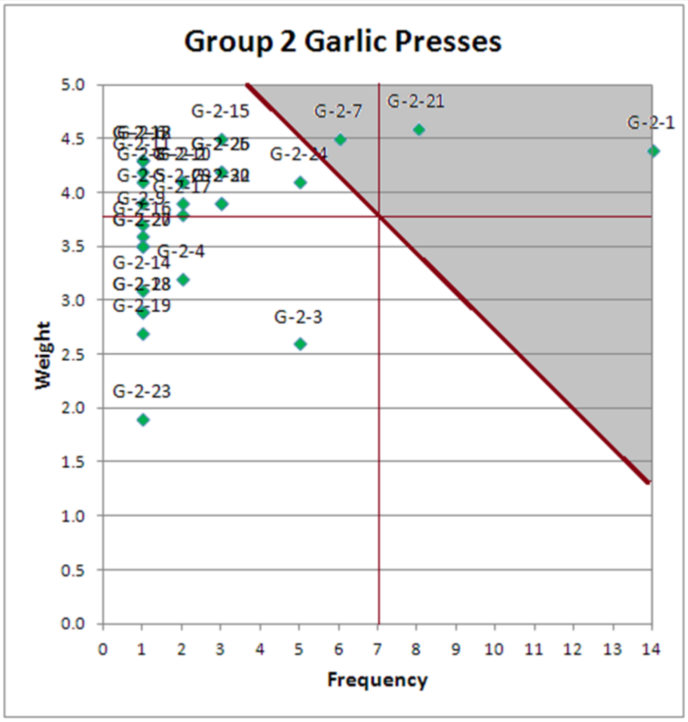
G-2-3
G-2-23


Group 2 Garlic Presses
Weight
Frequency
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4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
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8
9
10
11
12
13
14
G-2-15
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G-2-21
G-2-1
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G-2-24
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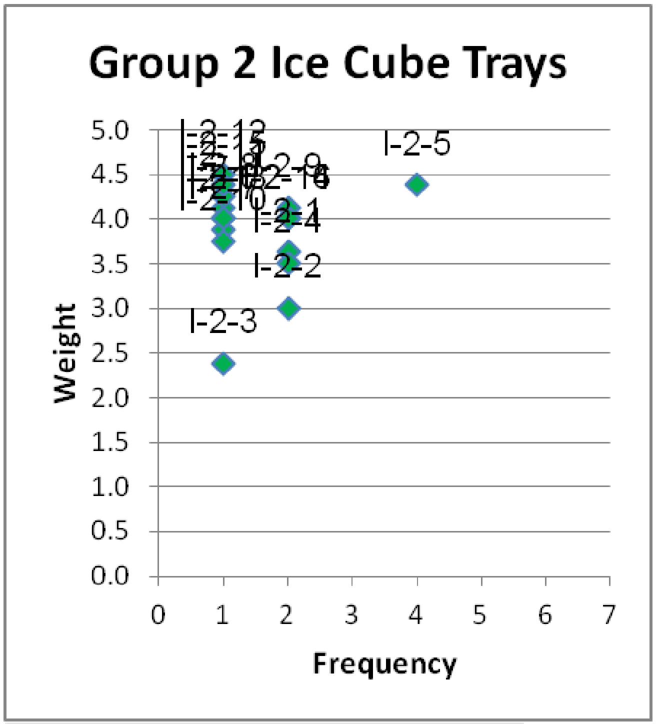
Group 2 Ice Cube Trays
Weight
Frequency
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3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
I-2-12
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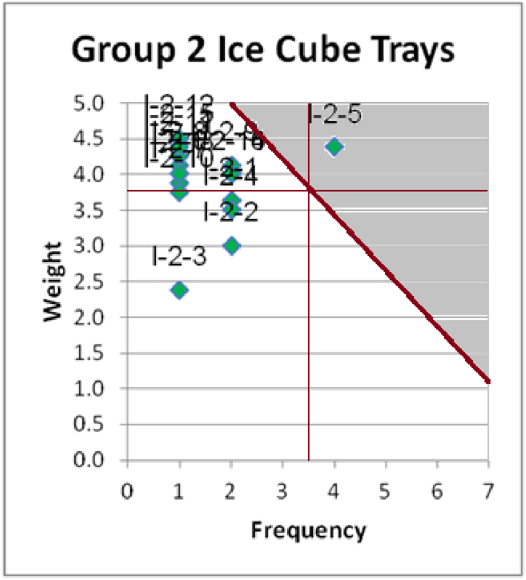
I-2-16
I-2-10
I-2-5
I-2-1
I-2-4
I-2-2
I-2-3


Group 2 Ice Cube Trays
Weight
Frequency
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4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
I-2-12
I-2-9
I-2-16
I-2-10
I-2-5
I-2-1
I-2-4
I-2-2
I-2-3

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VITA

Jessica Armstrong grew up in Boise, Idaho with her mother Jolene and two sisters, Sarah and Rachel. She was interested in science and space travel from a young age. She came to Oregon State University for the Engineering Physics program, since she could not decide between these two exciting disciplines. The undergraduate engineering design classes won her over and she returned to OSU for a Masters in Mechanical Engineering Design. In the first term of graduate school she was introduced to the field of human factors and was excited to be able get a minor in Human Systems Engineering as well. Her goal in life is to work for the private space industry and improve humanity's ability to explore the universe. She is married to a wonderful Entomologist/Cutco field sales manager named Matthew Olsen. They met in 2006, when he held the door open so she could carry a 5 foot steel honeycomb up the steps of their dorm after rescuing it from the cleanout of the basement of her work, the OSU Theater Department. Together they run the business Caged River Jewelry, making jewelry out of Trichoptera cases which they collect/raise themselves and process for durability according to a secret process. Their babies are a black cat named Bella, and a bunch of fish.