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ERGONOMIC DESIGN AND EVALUATION USING A MULTIDISCIPLINARY APPROACH: APPLICATION TO HAND TOOLS

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by

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ABSTRACT

This thesis developed a multidisciplinary design approach for integrating ergonomics and engineering design technology (QFD). A modified HoQ (House of Quality) matrix adapted from QFD was proposed and utilized to systematically identify the critical ergonomic design area corresponding to functional user requirements as well as affective needs of user. A case study of screwdriver design was conducted to demonstrate the applicability of the proposed design methodology. As a result, 26 user satisfaction attributes were identified and classified into 3 user satisfaction dimensions (performance, physical interaction, affective image/impression) based on survey data using a total of 57 participants. With respect to level of experience, participants were divided into two groups. The result of comparison of two groups revealed that there was a clear distinction between two groups in terms of user needs or expectation. Regarding the relative importance of user needs or expectation, inexperienced users focused on the affective image/impression-related user needs while experienced users relatively focused on functionality-related user needs rather than affective image/impression. However, ranks of the user needs were significantly correlated between two groups. Interestingly, design priority of experienced users was distinctly divided while that of inexperienced users scattered across 25 product design attributes. Among the 25 product design attributes, physical handle characteristics were identified as critical ergonomic design areas. This thesis also developed a comprehensive ergonomic evaluation methodology comprising objective measurements and subjective measures associated to user satisfaction. A case study of screwdriver evaluation was conducted in order to prioritize five different screwdriver designs using two experimentations (maximum torque task and constant torque task) and a product-interactive questionnaire. The result, based on data using a total of 15 participants, indicated that the priority of screwdrivers varied over objective measurements and subjective evaluation. An integrated design priority measure, which incorporated 4 objective measures into subjective evaluation criteria corresponding to 26 user satisfaction attributes, was proposed and successfully accessed the priority of five different screwdriver designs from a holistic perspective. Finally, it is expected that the proposed ergonomic design and evaluation methodology could be applied to other hand tools.

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Chapter 1

INTRODUCTION

1.1 PROBLEM STATEMENT

Generally, hand tools are regarded to be as old as the human race. According to uncovered evidence, prehistoric humans already used hand tools as far back as about 10,000 years ago (Fraser, 1980). With addition of the handle, these hand tools have aided humans with range of motion, physical strength, and effectiveness of their functionality of upper extremities. As the needs of human beings have increased, new hand tools accordingly have been improved or invented with help of the technology development. In spite of development of mechanization and automation, surprisingly many such tools have changed very little. Specifically, non-powered tools, with minor change in terms of external design and materials, are still being used in our daily lives and industrial tasks. For example, despite advanced technologies, even 90% of the workers in the United States still use non-powered hand tools at work (Yun, 1994).

In nature, the uses of hand tools are commonly repetitive and require workers to exert high forces with high repetition within short cycle time. These kinds of hand tool induced work stressors on the upper extremities such as elbow, wrist, palm, and fingers are inevitable. They consequently give rise to a variety of problems such as cumulative trauma disorders (CTDs), reducing productivity, disabling individuals, and increasing medical costs for industry (Aghazadeh and Mital, 1987; Cederqvit and Lindberg, 1993; Freivalds, 1996). According to previous surveys, hand tools were involved in 9% of compensable work-related injuries. The upper extremities were the body parts injured in greater than half the cases (Mital, 1991). In reality, upper extremities were injured more often than any other part of body. It was also reported that overexertion injuries were specifically associated with the use of ratchets, wrenches and screwdrivers among various type of non-powered hand tools (Aghazadeh and Mital, 1987).

Over the past three decades, the proper design, evaluation, selection, and use of hand tools have been a major ergonomic concern. Basic ergonomic design principles and recommendations involved in tool design, ergonomic evaluation process for tools, and the attributes desirable for specific hand tools have been extensively developed by numerous ergonomists (Pheasant and O'Neil, 1975; Greenburg and Chaffin, 1977; Jonsson et al., 1977; Tichauer and Gage, 1977; Fraser, 1980; Eastman Kodak, 1983; Huston et al., 1984; Mital and Channaveeraiah, 1988; Johnson and Childress, 1988; Putz-Anderson, 1988; Mital, 1991; Chaffin et al., 1999). While the role of ergonomists in the course of product design is to mainly focus on the functionality and usability of product, ergonomics as a scientific discipline has brought remarkable benefits to users of products in terms of safety, comfort, productivity, and easy-of-use (Wickens et al., 1998).

However, there is a fundamental question about whether the ergonomically designed product really appeals to the potential customer or users (Liu, 2003). Obviously, the ergonomically designed product has made a great contribution to its market share. However, the majority of recent success in the market has resulted from not only product functionality or usability but also users' satisfaction or pleasure during their use of product (Simon and Benedyk, 2000). In order to compete and succeed in the market place, manufacturers will have to move from the physical quality to what customers really need as well as the subjective quality of their products (Nagamachi, 1997; Jordan, 1999; Liu, 2003). At the same time, it is emphasized that ergonomists must take a wider view of user-centered design and look both at functionality and at pleasurability (Green and Jordan, 2002). In this regard, somewhat newer approaches have been proposed to identify specific product attributes that respond to user's subjective feelings, and to incorporate subjective aspects of user into the automobiles, construction machinery, and consumer electronic products design (Nagamachi, 1995; Jindo and Hirasgo, 1997; Matsubara and Nagamachi, 1997; Nakada, 1997; Han et al., 2000; Lee et al., 2001; Green and Jordan, 2002; Han and Hong, 2003; Han and Kim, 2003; Han et al., 2004; Khalid and Helander, 2004; Petiot and Yannou, 2004; Yun et al., 2004; Lai et al., 2005). However, regarding the design and evaluation of hand tools, the majority of studies in the literature have focused on the functional aspect of hand tools rather than subjective aspects of the users. For example, existing techniques for design and evaluation of hand tools are still far from this newly evolved perspective. Moreover, there has been little effort to expand this perspective toward the area of hand tools design and evaluation in recent years. In fact, this approach is by no means easy since it inevitably includes complex and interdisciplinary endeavors (Kadefors et al., 1993; Simon and Benedyk, 2000).

Recently, a few studies on the ergonomic design of hand tools have been introduced from different design perspectives such as Quality Function Deployment (QFD) (Haapalainen et al., 2000; Marsot, 2005). According to the engineering design perspective, it is believed that methods for identifying user needs or expectation and prioritizing the importance of user needs are already available such as Axiomatic Design (Suh, 1990) and House of Quality (HoQ) (Houser and Clausing, 1988). However, these methodologies have some potential weaknesses in that the design decision can be biased by subjective judgment since they mainly rely on users' expectation and engineering design knowledge (Han et al., 2004). Even though user needs or expectation have been identified, prioritized, and incorporated into a product design, this does not mean that the designed product would completely satisfy user needs or expectation (Marsot, 2005). These weaknesses may be partly explained by the following two reasons. First, affective or emotional user needs to a product are relatively difficult to identify since they might be beyond the user's current knowledge or expectations (Kano et al., 1984; ReVelle et al., 1997). However, the affective or emotional user needs are as important as the functional user requirements. Next, user needs extremely vary between individuals due to their inherent characteristics such as level of experience (Khalid and Helander, 2004). Nonetheless, previous studies on the design of hand tools using QFD methodology just followed the exactly same technique (e.g., HoQ chart) provided by the engineering design discipline. However, they lacked explicit methodological evidence that affective or emotional user needs related to a product have been systematically identified and incorporated into the ergonomic design of the hand tools.

Therefore, in order to alleviate the weakness of previous studies, it is still required in the area of ergonomic design of hand tools to explore: (1) how to elicit users' functional needs as well as their affective needs related to user satisfaction in using a hand tool, (2) which attributes of a hand tool are closely linked to user's subjective opinions of a hand tool, (3) how much these attributes contribute to user's overall satisfaction in using a hand tool, and (4) how effectively to integrate ergonomics into the design methodology. In this regard, this study has been motivated by lack of literature exploring systematic methodology of identifying affective user needs or requirements and incorporating ergonomics knowledge into the product design process.

In general, ergonomic evaluation of a hand tool is a multifaceted task in that it comprises not only functional properties of a hand tool but also task variables as well as individual differences (Kadefors et al., 1993). Until now, most of previous studies, which have examined hand tool designs, have primarily focused on the functionality such as torque productions as a function of the handle characteristics based on biomechanical principles (Chaffin et al., 1999). In majority of literature, objective measures have been a primary technique utilized to evaluate hand tools. Such objective measures include torque/force production, muscular activity (EMG), grip force distribution and grip force, and wrist posture. Accordingly, the majority of existing ergonomic evaluation techniques generally may fall short of assessing users' subjective responses to a hand tool (Kadefors et al., 1993). A few approaches considering user's subjective aspects in using hand tools have been introduced in the design and evaluation of hand tools (Fellows and Freivalds, 1991; Hall, 1997; Chang et al., 1999; Kong and Freivalds, 2003; Kuijt-Evers et al., 2004). However, most of previous studies have considered only limited number of measures, not comprehensive evaluation criteria including user's subjective feelings or preference to a hand tool. Therefore, this study also has been motivated by lack of literature investigating not only effects of functional aspects of a hand tool on torque production capability and biomechanical and physiological stress but also effects of design attributes of the hand tool on user's subjective aspects from a holistic perspective.

1.2 STUDY OBJECTIVES AND HYPOTHESES

The purposes of this study are twofold. First, this study aims to develop a multidisciplinary design methodology incorporating ergonomics knowledge into an established engineering design technology (e.g., QFD) in order to respond to a variety of users' needs for enhancing their overall user satisfaction in using a hand tool.

As part of this methodological purpose, it is hypothesized that comprehensive user needs can be systematically identified by utilizing ergonomics knowledge instead of existing customer survey techniques. In order to verify the research hypothesis and accomplish the study objectives, following efforts are performed.

- Elicit comprehensive user needs/expectation related to user satisfaction by extensive ergonomics literature survey
- Identify user needs/expectation related to user satisfaction and prioritize them by questionnaire and statistical analysis
- Assess the design priority of product attributes of a hand tool by correlating weighted user needs with product design attributes of a hand tool
- Finally, identify the critical ergonomic design area of a hand tool with regard to user satisfaction

In addition, it is also hypothesized that user needs vary between individuals with respect to their level of experience in using a hand tool. Thus, this study also aims to investigate the difference of user needs and resulting critical ergonomic design area of a hand tool in terms of level of experience.

Second, another goal of this study is to develop a comprehensive ergonomic evaluation technique comprising both objective measurements and subjective evaluation from a holistic perspective. Consequently, this study also aims to systematically identify the best design of a hand tool among various design alternatives with respect to minimum exertion requirement and maximum user satisfaction. As part of this methodological purpose, it is hypothesized that the best design alternative of a hand tool can be reasonably derived by evaluating not only functionality of the hand tool with objective measures but also users' preference in terms of user satisfaction with subjective measures. Specifically, in order to develop a comprehensive ergonomic evaluation technique, following efforts are conducted in this study:

- Evaluate quantitatively the effects of design attributes of a hand tool on ergonomic effectiveness in terms of biomechanical, physiological, and psychophysical aspects of user using two experimentations
- Assess qualitatively the impacts of design attributes of a hand tool on users' subjective preference or expectation in terms of user satisfaction using a product-interactive questionnaire
- Develop an integrated design priority measure by incorporating objective performance measures with subjective evaluation measures so as to identify the overall priority of design alternatives of a hand tool

Finally, these proposed methodologies for ergonomic design and evaluation of hand tools are demonstrated using a case study of screwdriver design and evaluation, respectively.

1.3 SIGNIFICANCE OF THE STUDY

In general, identification of customer needs is the first and the most important step in the development of any product (Suh, 1990; Hauser and Clausing, 1988). In addition, reliable and comprehensive user needs is crucial for developing usable products as well as fundamental to market success (Khalid and Helander, 2003). However, existing techniques for the identification of user needs in QFD methodology have inherent methodological limitations or drawbacks as followings (Akao, 1990; Griffin and Hauser, 1992; ReVelle et al., 1997; Govers, 2001): First, user needs are difficult to recognize since they are very general and vague as well as user needs are not always comprehensible. Second, existing customer survey may be appropriate for identifying only one-dimensional (performance-related) user needs. However, it is not sufficient to collect only customer's explicit requirement. Third, comprehensive customer surveys may result in excessive cost while small group of customers may not guarantee meeting customer needs thoroughly. Forth, must-be user needs can be missing when using existing customer survey since they are often too basic to mention while absence of must-be needs definitely results in customer dissatisfaction. Finally, attractive user needs are extremely difficult to identify since they usually may be beyond the customer’s current knowledge or expectations while discovering attractive user needs and translating them into product design attributes can definitely enhance user satisfaction.

Once the proposed methodology of identification of user needs is successfully demonstrated and validated, expected benefits are promising. First, the proposed technique can reduce the excessive cost for comprehensive customer survey. Second, it can increase the chance of capturing high-level (attractive) user needs which may not be identified by existing customer survey. Third, once the second benefit is realized, attractive user needs and potential demand on a product can be transformed into design details so as to enhance overall user satisfaction.

In general, a multidisciplinary approach must be supported by providing an appropriate and systematic way of integrating methods or models from different disciplines (Haapalainen et al., 2000). According to the extensive ergonomics literature survey (described in Chapter 2), there have been very few multidisciplinary studies on the ergonomic design and evaluation of hand tools (Haapalainen et al., 2000; Marsot, 2005). In addition, previous multidisciplinary studies simply followed the same approach provided by other disciplines. Therefore, it can be asserted that the proposed ergonomic design methodology of this study is novel and significant using a multidisciplinary approach in that this thesis intends to develop an integrated design methodology incorporating ergonomics into quality technology.

Clearly, ergonomics is an important part of a broad range of product developments. It is expected that product design engineers are well aware of the need for ergonomic design. However, they tend to make decisions on the basis of their intuitive judgments or expert subjective opinions even though they have dealt with ergonomic design principles continuously in their practice (Noblet, 1993; Han et al., 2004). In addition, they often do not have enough time or ergonomic expertise for a specific purpose. Even though there is abundant expertise on ergonomics, such information is too general and even scattered. As a result, in practice there are still difficulties in utilizing ergonomics knowledge effectively for a specific product or part design. Therefore, research is needed to develop a comprehensive ergonomic design methodology explaining how ergonomics expertise could be incorporated and transferred into a specific hand tool design systematically. Consequently, it is expected that this thesis might present a normative example that can help product design engineers as well as tool manufacturers. It is also expected that the proposed methodology in this study will be applicable to a variety of hand tools. Moreover, the findings of this study will be expected to serve as a basis for the ergonomic design and evaluation criteria to be used in new design or revision of hand tools. Eventually, once aforementioned expectations are realized, this thesis might contribute to the better communication between ergonomists and product design engineers as well as between tool manufacturers and their customers.

1.4 ORGANIZATION OF DISSERTATION

This dissertation is organized into seven chapters as follows:

- Chapter 1 provided a detailed introduction, which conveyed the problem statements and justified study objectives and significance of this study.
- Chapter 2 reviewed relevant research background motivating this study, and summarized previous research findings as a basis of this dissertation.
- Chapter 3 developed a multidisciplinary approach for ergonomic design of hand tools by integrating ergonomics knowledge and quality function deployment methodology.
- Chapter 4 demonstrated the multidisciplinary approach for ergonomic design of hand tools using a case study of screwdriver
- Chapter 5 presented a comprehensive ergonomic evaluation technique applied to hand tools.
- Chapter 6 presented the result of the case study of screwdriver evaluation to demonstrate the proposed ergonomic evaluation technique.
- Chapter 7 discussed research findings in this study, contribution of this thesis, future research, and addressed concluding remarks.

Chapter 2

LITERATURE REVIEW

2.1 RESEARCH BACKGROUNDS

2.1.1 Ergonomic Perspective: Beyond Usability

Adapting the idea from a hierarchy of human needs developed by Abraham Maslow (1970), Jordan (1999) initially applied it to ergonomics domain and proposed a hierarchy of user needs in order to establish a constructive basis that can help to broaden and extend the scope of ergonomics beyond usability on the product design process. After combing a similar hierarchy regarding product requirements for user needs, a hierarchy of user needs, when interacting with products, was proposed as shown in Figure 2.1 (Bonapace, 2002).

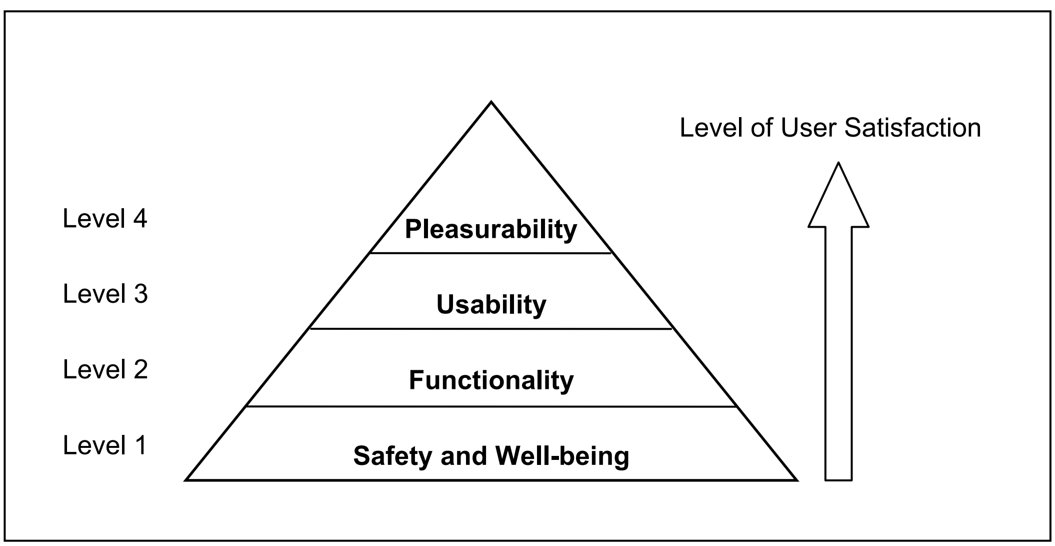


Figure 2.1. Hierarchy of user needs when interacting with products
(Adapted from: Bonapace, 2002)

Over the last decades, functionality of a product has long been the most important factor in designing a product. If a product does not have the right function required to perform the intended tasks, a product cannot be usable. Consequently, it is the common belief that lack of functionality may result in losing competitiveness in the marketplace (Rudy, 1997; Anna, 2000). In order to adequately response to user needs at this level, it is absolutely required to understand the product design attributes as well as other factors affecting product functionality with regard to what an attribute of a product will be used for, and the context and environment in which it will be used (Jordan, 1999).

However, once appropriate functionality is satisfied, the user has tendency to need something more beyond the functionality (Jordan, 1999). In this sense, product usability can be one of them and recently considered more important than the functionality in the product design (Rubin, 1994; den Buurman, 1997; Eklund, 1997; Rudy, 1997; Anna, 2000; Han and Hong, 2003). In this regard, Jordan (1999) asserted that "*functionality is a pre-requisite of usability, but it does not guarantee usability.*" In order to capture the usability, a product must be designed by adapting some or all of the ergonomic design principles related to a given product (Jordan, 1999). With respect to this level, a number of researchers have argued that subjective satisfaction of users should be included in the concept of usability in the consumer product domain (Nielsen, 1996; den Buurman, 1997; Han et al., 2000). Wichansky (2000) also claimed that product usability is a function of both the user's performance and the user's subjective satisfaction.

Recently, users' subjective aspects such as satisfaction, pleasure, and feelings towards a product are greatly emphasized in the level of pleasurability. Though some researchers still argue that pleasurability, from a view of user satisfaction, might be treated an expanded concept of product usability (Nielsen, 1996; den Buurman, 1997; Han et al, 2000; Han and Hong, 2003), pleasurability can be regarded as a somewhat new concept beyond the traditional concept of usability (Jordan, 1999; Green and Jordan, 2002). In addition, product pleasurability has been accepted as a new challenge in the area of ergonomics (Green and Jordan, 2002). Since the 1990s, a number of researchers have tried to capture this concept in a practical manner, and to incorporate it into the product development process. Examples include emotional usability (Logan 1994), Kansei engineering (Nagamachi 1995), Sensorial Quality Assessment (Bandini-Buti et al., 1997), pleasure of use (Jordan, 1997), four pleasure framework (Macdonald, 1998), and a new concept of product usability (Han et al., 2000).

Recently, a series of questionnaire studies have been carried out in order to investigate which attributes relate to pleasure or displeasure and how users describe the feature that corresponds to their subjective feelings in use of products such as pepper grinders, nut crackers, and bottle openers (Hauge-Nilsen and Flyte, 2002). Their results showed that the product attributes or features, which were identified to be closely associated with pleasurability, were aesthetics, effectiveness, grip, easy of use, and easy control of the product. The features identified to be closely related to displeasure were uncomfortable grip, unacceptable force, ineffectiveness, and safety issues. Their findings clearly indicated that functionality-based product design did not guarantee a pleasurable product. In other words, functionally well-designed product may not guarantee users' satisfaction or pleasure.

Therefore, it might be noticeable that a common finding among those studies is that user's subjective aspects such as taste, preference, and satisfaction were classified in detail, and then incorporated into a specific product design. In other words, users' subjective aspects were thoroughly investigated and systematically considered in the product design process.

2.1.2 Quality Perspective

Besides aforementioned ergonomic endeavors, a number of different techniques and approaches have been proposed for investigating the relationship between product design attributes and user needs to a given product in order to enhance overall user satisfaction. In the area of quality technology, Quality Function Deployment (QFD) is a well-known and an established methodology that has been systematically adapting its methods to product development and production process (Hauser and Clausing, 1988; Akao, 1990). Basically, QFD aims at translating customer or user needs into the product characteristics by systematically reflecting "voice of customer" throughout each stage of the product development process (Hauser and Clausing, 1988).

QFD method can be compared to "participatory ergonomics" where the users are involved in developing and implementing the engineering design technology (Imada and Noro, 1991). In addition, the user-oriented or user-centered product development method in ergonomics also may look like the QFD method in the procedure of translating user demands into technical and measurable terms. Moreover, a high quality product developed by the QFD method may be regarded as an ergonomic product in that user needs have been systematically translated into a product (Bergquist and Abeysekera, 1996).

In this regard, it might be advantageous to adapt the main concept of QFD into the area of ergonomics. There is a well-defined conceptual model of quality in QFD. The Kano model (Kano et al., 1984) originally defined three types of customer requirements or needs related to quality: ***must-be***, ***one-dimensional***, and ***attractive*** requirement using a two-dimensional space with two axes. The vertical axis relates the extent that the customer is satisfied while the horizontal axis indicates the extent to which a particular requirement is actually deployed. Since the introduction of Kano model, this approach and related concepts have been well accepted in the area of quality technology (ReVelle et al., 1997; Govers, 2001). The three types of customer requirements or needs influence customer satisfaction in different ways when met as follows (Figure 2.2):

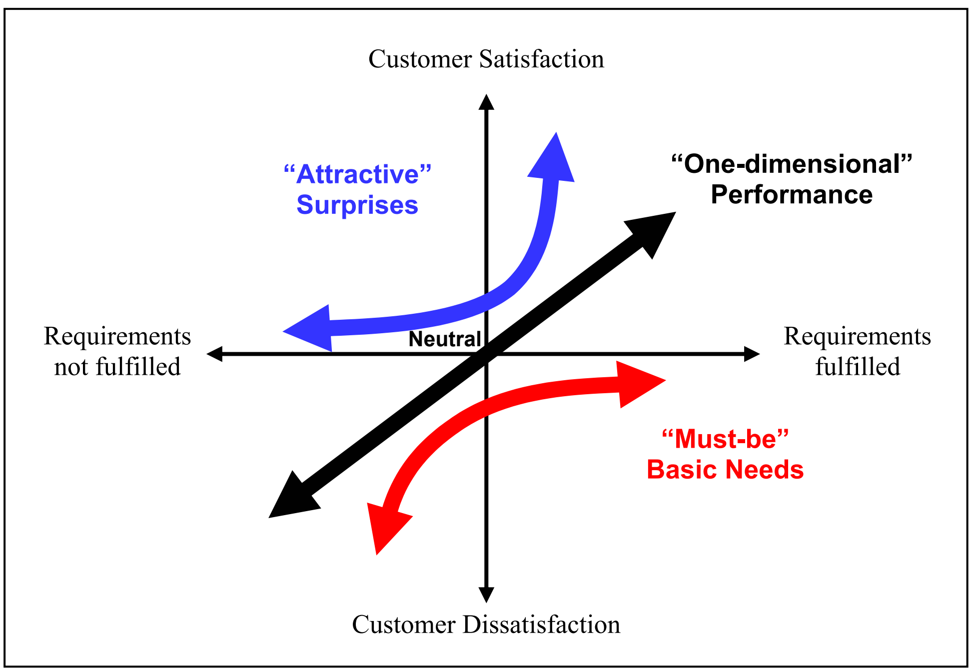


Figure 2.2. Three types of customer needs from the Kano model (Adapted from: Kano et al., 1984; ReVelle et al., 1997)

- ***Must-be requirements*** (also called basic requirements) are often so basic that the customer may not mention them. Once these requirements are satisfied, they are often unnoticed by most customers. However, the absence of must-be needs definitely results in customer dissatisfaction. Therefore, must-be requirements must be fulfilled.
- ***One-dimensional requirements*** (also called performance requirements) are typically identified by just asking customers what they want. It is definitely the easiest of the three requirements to discover information related to requirements. There are several approaches to establish and accumulate information about one-dimensional requirements. Examples include survey, interview, and questionnaire.
- ***Attractive requirements*** (also called unknown requirements) are extremely difficult to identify since they might be beyond the customer's current knowledge or expectations. The absence of attractive requirements may not affect customer satisfaction since customers usually have no idea about them. Therefore, it is obvious that product design engineers or ergonomists are fully responsible for discovering attractive requirements and translating them to product design attributes or characteristics for enhancing overall customer satisfaction.

Lastly, it should be emphasized that the Kano model is dynamic over time in that attractive needs yesterday can be one-dimensional needs today, and then must-be needs tomorrow (ReVelle et al., 1997).

2.2 QUALITY FUNCTION DEPLOYMENT (QFD)

2.2.1 Introduction

Over the last decades, a number of methodologies have been developed to make the product design development more efficient and more effective. In the area of engineering design technology, QFD has been systematically adapting its methodology to product development (Hauser and Clausing, 1988; Akao, 1990). The most attractive feature of QFD is the focus on "***voice of customer***" which is the driving force of QFD methodology (Govers, 2001). Consequently, the product development process is driven by the "voice of customer" rather than technology or a product designer's creativity (Armacost et al., 1994). Moreover, QFD is a methodology for translating voice of customer throughout each stage of the product development and production process (Hauser and Clausing, 1988; Kim, 1997; Shin and Kim, 2000; Govers, 2001). In this sense, QFD is generally accepted as a systematic methodology for the product planning, engineering, and manufacturing stages (Hauser and Clausing, 1988; Akao, 1990; Kim, 1997; Shin and Kim, 2000).

QFD was originally developed in 1972 at Mitsubishi's Kobe shipyards. Later, Toyota began to apply QFD to auto-bodywork with impressive results (Akao, 1990). Xerox and Ford initiated the use of QFD in mid-1980s and over 100 companies were reported to be using QFD in the United States (Griffin and Hauser, 1992). Nowadays, QFD is used successfully across a broad range of industries around the world (Chan and Wu, 2002).

It should be emphasized that QFD is concerned mostly with the process of improving an existing product by translating customer requirements or expectations into the product, though QFD may be used as a means for developing new products. QFD focuses on identifying the “right” customer as well as their demands for a given product, and aims at translating them into product characteristics. In addition, QFD emphasizes the properties required of the products in use. The next step is to translate the customer demands into technical and measurable terms in the following product development process. In this regard, QFD is most effectively applied to any known existing product and well established market segment (Akao, 1990; Chan and Wu, 2002).

2.2.2 Methodology of QFD

A brief summary of the QFD methodology is addressed in this section. The basic process of QFD is to translate the “voice of customer” (customer needs) into product design attributes or engineering characteristics, and subsequently into part or component characteristics, the process operations, and production requirements associated with the manufacturing process.

The QFD methodology consists of four basic stages of QFD process. Based on the findings of product planning stage (Phase I), the QFD process continues with the following three similar matrices as shown in Figure 2.3 (Shin and Kim, 2000).

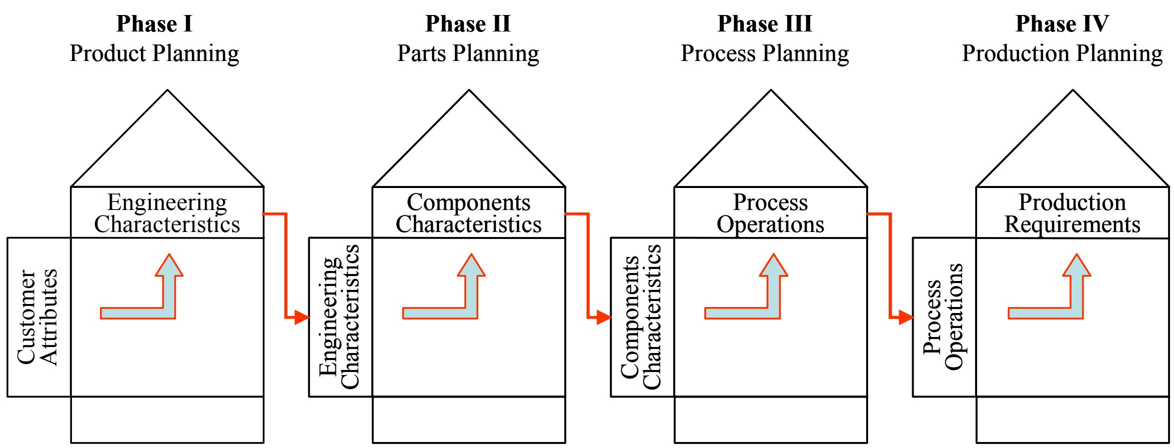


Figure 2.3. Four stages of the QFD process: translations of customer requirements (Adapted from Shin and Kim, 2000)

Customer's attributes (CAs) and their relationships with design or engineering characteristics (ECs) are the driving forces of QFD methodology (Govers, 2001). In the QFD analysis, a matrix format, named "House of Quality (HoQ)" is utilized as the principal tool (Hauser and Clausing, 1988). Though the structure of HoQ can vary with respect to the objective, stage, and scope of the application, a HoQ typically contains information on CAs and their importance ratings, ECs and their correlations, relationships between CAs and ECs, competitive benchmarking data about CAs and ECs (Shin and Kim, 2000). Though HoQ charts can have different components, a typical format of HoQ chart for the product planning phase is described in Figure 2.4.

A standard set of HoQ chart includes customer attributes (CAs) and their relative importance, design or engineering characteristics (ECs), relationship matrix between CAs and ECs, correlations among ECs, importance ratings of CAs, benchmarking data on CAs and ECs, and target levels of ECs. In general, building the HoQ includes the following basic steps (Vairaktarakis, 1999; Shin and Kim, 2000):

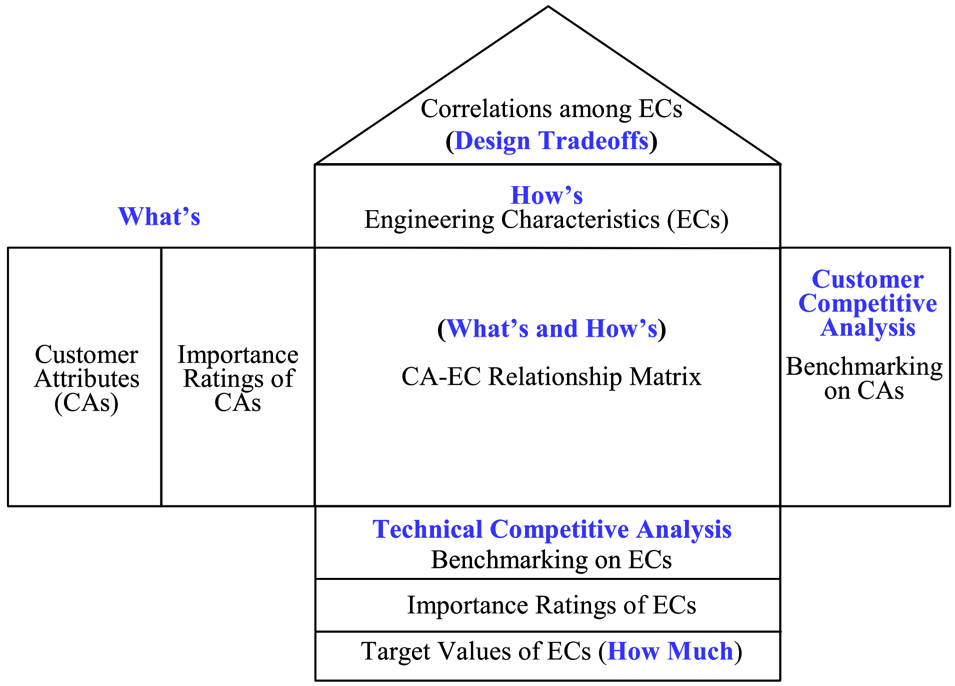


Figure 2.4. Framework of House of Quality Chart
(Adapted from: Vairaktarakis, 1999; Shin and Kim, 2000)

- **Identify customer attributes (CAs):** the voice of customer is named as customer attributes that relate to customer requirements for a given product. Information about customer attributes can be obtained from various sources such as surveys, focus groups, interviews, questionnaire, etc. (Bossert, 1991). Usually, customer requirements are difficult to recognize since they are very general and vague. Moreover, it is not sufficient to simply respond to the customer's voices since they are not always comprehensible (Govers, 2001).
- **Importance ratings of CAs:** ratings of absolute or relative importance for each customer attributes can be obtained from various methods. Typically scale rating methods (1-5 or 1-10) are used for relative importance ratings of CAs (Kim, 1997). A number of alternatives associated with rating methods

have been used in QFD analysis. Examples include MADM (Multi Attribute Decision Making) (Keeney and Raiffa, 1976), AHP (Saaty, 1990), and Linguistic data based on Fuzzy set theory (Shen et al., 2001).

- **Identify design or engineering characteristics (ECs):** the information about ECs also can be obtained by the same methods utilized in the first step. However, ECs should be measurable so as to fulfill the customer requirements. Inherently, ECs differ from product to product. Even a simple product may have a large number of ECs. It definitely results in a large size HoQ chart. As the size of a HoQ increases, complexity increases very fast so as to require a huge amount of time, effort, and cost for the QFD analysis (Shin and Kim, 2000).
- **Relate the customer attributes (CAs) to design or engineering characteristics (ECs):** relationship analysis between CAs and ECs usually can be conducted by the rating scales (1-3-5 or 1-3-9) or using strength symbols (weak, medium, and strong). It should be emphasized that the weighting scales have a strong and direct impact on the QFD analysis. However, none of weighting scales provides an explicit justification for the choice of a weighting scale (Shin and Kim, 2000). A number of alternatives assessing the relationships between CAs and ECs have been suggested for the QFD analysis. Examples include Multivariate Statistical Methods, Design of Experiments (Ross 1988), Simulation (Lorenzen et al. 1993), and Linguistic Data based on Fuzzy Set Theory (Shen et al. 2001). During the analysis in this

step, there might be various methodological difficulties such as inconsistency and complexity due to a large size of HoQ (Shin and Kim 2000).

- **Build correlation matrix among design or engineering characteristics:** the correlation matrix among ECs is built in the roof of a HoQ. Correlation analysis aims to identify interaction (positive or negative) between ECs and their design tradeoffs. Inconsistency of correlation might also result from mistakes in assessing correlation and unclear definition of ECs (Shin et al., 1999).
- **Compute absolute/relative importance ratings of engineering characteristics:** In this step, absolute or relative importance ratings of engineering characteristics are conducted using the knowledge of product designers and engineers.
- **Conduct customer and technical competitive analysis:** competitive benchmarking data on the CAs for a given product and competitor's products should include the customer's assessment instead of professional knowledge from the product designer or engineer. However, technical competitive benchmarking assessments on the ECs usually utilize professional knowledge.

Besides above mentioned components in the QFD analysis, various purpose-built components with respect to objective and scope of the application can be included in a HoQ (Hauser and Clausing, 1988; Akao, 1990; ReVelle et al., 1997).

2.3 ERGONOMIC DESIGN PROCESS

In the area of ergonomics design methodology, "High Touch" design process is one of such efforts which incorporate the user's viewpoint into the product design process for ergonomically customized products. From the methodological viewpoint, High Touch is operationally defined as ***"transformation of the consumer's implicit needs and potential demand on a product into design details"*** (Lee et al., 1997). High Touch design process is characterized by systematic application of ergonomic design considerations into product design using a hierarchical structure of design variables, a relationship matrix among design variables, and systematic evaluation of potential product functions. Using this design process, about 50 products were developed and a large portion of them came to the market successfully (Lee at al., 2001). Figure 2.5 illustrates the High Touch design process (Lee at al., 2001).

A promising benefit of High Touch design process is that it uses the hierarchical structure of various sets of variables such as user characteristics (also called human variables) and design attributes of a product (also called product variables). Specifically, various aspects of user characteristics as well as product variables required to perform tasks are formulated into the hierarchical structures, respectively. From these two hierarchies, a relationship matrix between human variables and product variables is formed and analyzed. Given a target product, the matrix analysis can help ergonomists and product design engineers find potential shortcomings in the product, and to provide necessary adjustment and improvement of the product by using ergonomic design principles in great details.

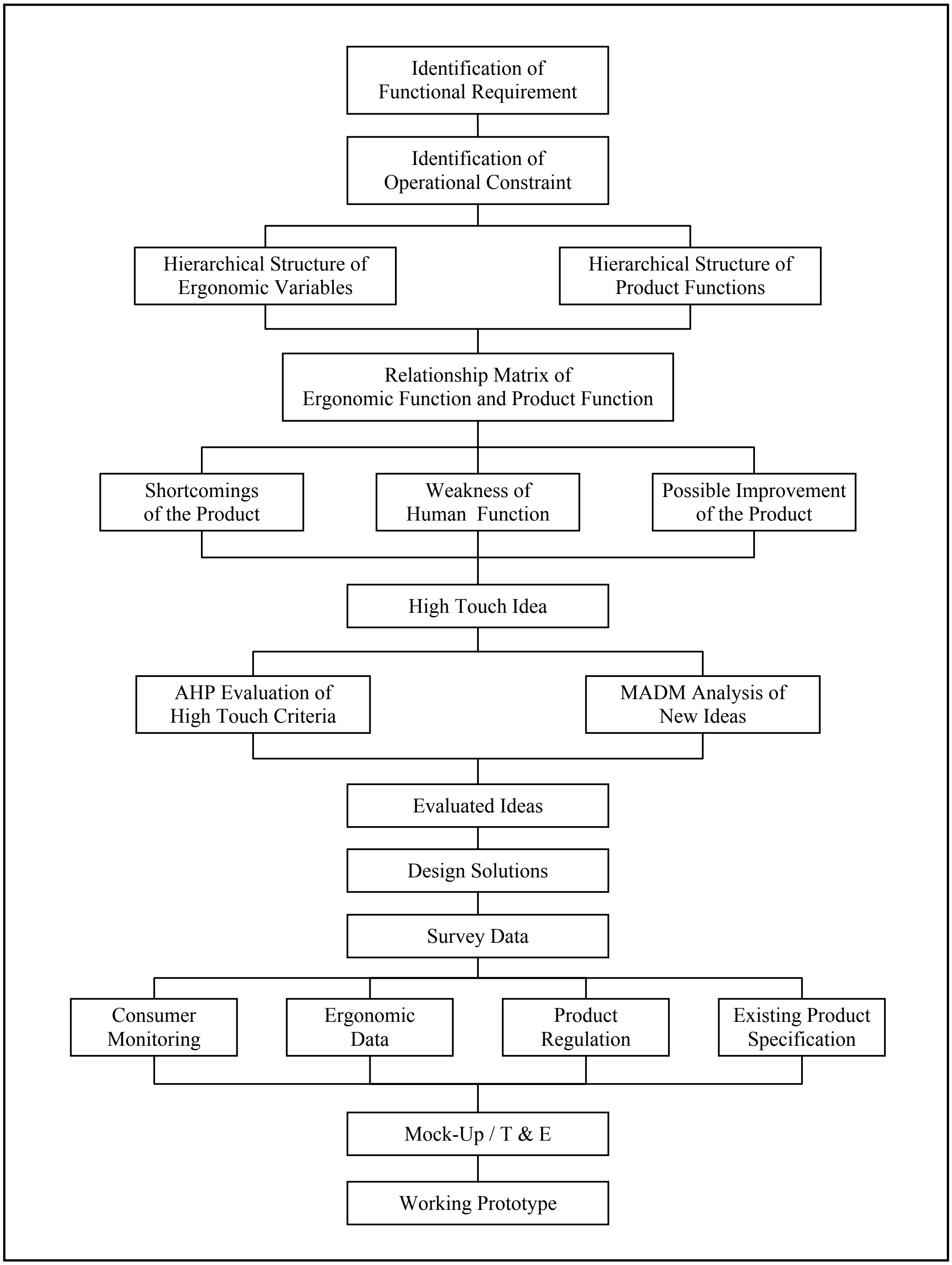


Figure 2.5. High Touch design process (Source: Lee et al., 2001)

In addition, the analytical tool such as Analytic Hierarchy Process (AHP: Saaty, 1990) is applied to produce a relative importance or priority of design attributes considered in the design and evaluation stage. AHP has been successfully used to prioritize a set of requirements and to select many alternatives meeting those requirements. This method employs pairwise comparisons on hierarchically organized elements to produce a very accurate set of priorities (Saaty, 1990; Armacost et al., 1994).

However, High Touch design process has been mainly applied to consumer electronic products. Though the concept of High Touch design process might be beneficial to any kind of product development, no attempt has been made to systematically translate ergonomic design principles to hand tools design. Ergonomic design of a hand-held remote controller is a similar example to show the possibility for incorporating the concept of High Touch design into the design of hand tools in that function of a human hand was extensively investigated and ergonomic grip was greatly emphasized (Lee at al., 1997). Accordingly, this example can be one motivation of this thesis aiming to investigate which product attributes are closely linked to user's characteristics and how ergonomic design principles are systematically applied to the design of hand tools such as a screwdriver. Specifically, this study aims at exploring a novel methodology for ergonomic design of hand tools with the idea of hierarchical analysis. In addition, a relationship matrix analysis between user characteristics and product functions is adapted in order to investigate potential design attributes of a given product. Finally, weighted scoring method is employed to produce the relative importance or priority of ergonomic design attributes to be considered in great details for the ergonomic design of a hand tool.

2.4 ERGONOMIC DESIGN OF HAND TOOLS

Ergonomic design of hand tools may be essential for the enhancement of user's comfort, safety, health, and well-being since well-designed hand tools can reduce the risk of occupational injuries (Kadefors et al., 1993; Lewis and Narayan, 1993; Sperling et al., 1993; Freivalds, 1996). In order to ergonomically design hand tools, it is required to consider hand tool's functional properties, quality and reliability as well as user's subjective expectations and apprehensions (Sperling et al., 1993). For the ergonomic design and evaluation of hand tools, relevant methods include initial field studies, measurements of performance (productivity and precision, applied force/torque output), monitoring of wrist deviation angle, assessing pain and discomfort, and muscular activities (EMG) (Kadefors et al., 1993).

In the area of ergonomic design and evaluation of hand tools, traditional approaches have mainly focused on the functionality of hand tools. However, recently product usability or pleasurability has become one of the major issues since users are demanding more comfortable and more efficient hand tools. Accordingly, the ergonomic design of hand tools can be appreciated from different perspectives. For example, subjective opinions on a product can be requested from the customer, or various checklists can be used. However, this may not be enough since the concept of product usability is very complicated and interdisciplinary (Niemelä et al., 2000; Han et al., 2000). Therefore, this section reviews previous research findings in the literature as a basis of ergonomic design of hand tools.

2.4.1 Ergonomic Design Principles of Hand Tools

A number of ergonomic guidelines for hand tool design, evaluation, and selection have been introduced based on published literature (Pheasant and O'Neil, 1975; Greenburg and Chaffin, 1977; Jonsson et al., 1977; Tichauer and Gage, 1977; Fraser, 1980; Eastman Kodak, 1983; Huston et al., 1984; Mital and Channaveeraiah, 1988; Johnson and Childress, 1988; Putz-Anderson, 1988; Mital, 1991; Chaffin et al., 1999).

For example, six fundamental basic requirements, which an efficient hand tool must fulfill, were proposed by Drillis (1963) as follows:

- It must perform effectively the function for which it is intended
- It must be properly proportioned to the anthropometric dimensions of the operator to maximize the efficiency of human movement
- It must be designed to suit the strength and work capacity of the operator. Thus allowances must be made for the individual difference such as gender, training level, and physical fitness of the user
- It should not cause undue fatigue and it should not demand awkward work postures
- It must provide sensory feedback in the form of pressure, some shock, texture, temperature to the user
- The capital and maintenance cost should be reasonable

2.4.2 Design Characteristics of Hand Tools

Handle Diameter

Numerous previous studies have long considered the effect of handle diameter on the force exertion in use of hand tools. Even though there are some conflicting results, obviously handle diameter is an important factor that can significantly influence force exertion, torque performance, finger force distribution, joint configuration, stress on the upper extremities, and subjective user's preferences to a hand tool in performing manual work.

For the optimum handle diameter for the power grip, Rubarth (1928) recommended 45 mm based on their empirical judgments of stair rails. Hall and Bernett (1956) suggested 32mm based on minimum EMG activity while 51 mm gave the greatest feeling of safety and 48 mm was the overall preference. However, Ayoub and Lo Presti (1971) reported 38 mm is the most efficient and the least fatiguing in terms of grip force-EMG activity ratio. Khalil (1973) found that 32 mm was the best with respect to lowest forearm EMG activity in a static loading task. Rigby (1973) reported that 38 mm is the best for heavy loads and full encirclement of the hand. Pheasant and O'Neill (1975) found that grip strength decreases beyond 50 mm in screwdriving task. Drury (1980) reported that the optimum grip was between 31 and 38 mm in diameter in both subjective ratings and grip strength reductions. Cochran and Riley (1982) tested various task such as push, pull and thrust. Their results showed maximum force capabilities in handle sizes of 28.6 ~ 35.0 mm and 35.0 ~ 41.0 mm for female and male, respectively.

For precision and manipulation tasks, Cocharan and Riley (1983) suggested that the smallest handles of 22 mm were found to be the best. Replogle (1983) found that

50mm is the best for maximum torque. Eastman Kodak (1983) reported that 40 mm is the best for power grip and 12 mm is for precision grip. Yakou et al. (1997) also found that the optimal grasping diameter depends strongly on the length of the hand. Their result showed that optimum grasping diameters for the males were 30 ~ 40 mm which are about 10% larger than those for the females. Hall (1997) reported that the subjects strongly preferred cylinders with 30-40 mm diameter. A noticeable shortcoming of these previous studies is that they did not consider the effect of handle size relative to the size of the user's hand. In nature, hand size can vary significantly across population (Eastman Kodak, 1983). In this regard, customization of handle size to user's hand size has been emphasized by some researchers (Grant et al., 1992; Yakou et al., 1997; Kong, 2001; Kong and Lowe, 2003). Grant et al. (1992) suggested that a handle 10 mm smaller than the user's inside grip diameter is optimal. Kong and Lowe (2003) recommended that 64% normalized hand size (NHS) ratio in maximum gripping task. They also suggested 87% NHS for comfort and 78% NHS for torque task, respectively.

In summary, the lesson based on the various research findings might be that optimum handle diameter can vary with respect to hand size and task characteristics. Table 2.1 summarized the previous handle diameter studies.

Table 2.1. Summary of handle diameter studies

Reference	Recommendation	Consideration
Rubarth (1928)	45 mm	Empirical judgments
Hall & Bennett (1956)	32 mm 48 mm 51 mm	Minimum EMG activity Overall preference Safety feeling
Ayoub & Lo Presti (1971)	21 mm 38 mm	Minimum EMG activity Efficiency and fatigue
Khalil (1973)	32 mm	Least EMG activity
Rigby (1973)	38 mm	Full encirclement of the hand
Pheasant & O'Neill (1975)	50 mm	Maximum torque
Drury (1980)	31 mm 38 mm	Subjective rating Grip strength
Cocharan and Riley (1982)	28.6 ~ 35.0 mm 35.0 ~ 41.0 mm	Female (maximum force) Male (maximum force)
Cocharan and Riley (1983)	22 mm	Precision and manipulation tasks
Eastman Kodak (1983)	12 mm 40 mm	Precision grip Power grip
Replogle (1983)	50 mm	Maximum torque
Grant et al. (1992)	X-10 mm	10mm smaller than the user's inside grip diameter (X)
Hall (1997)	30 ~ 40 mm	User preference in screwdriving
Yakou et al. (1997)	30 ~ 40 mm	Female 10% smaller
Kong and Lowe (2003)	64% NHS* 78% NHS* 87% NHS*	Maximum gripping task Maximum torque Comfort in torque task

Note: NHS (Normalized Hand Size)

Handle Length

There are relatively few studies on the length of handle compared to handle diameter. With respect to anthropometric dimension of human hand, 100 mm is a reasonable minimum to fit adults since hand breadth is 71mm for a 5th percentile female and 97mm for a 95th percentile male (Garrett, 1971). However, some researchers (Konz, 1990; Johnson, 1993) recommended that 125 mm may be more comfortable. For considering the effect of a glove, Eastman Kodak (1983) suggested at least 12.7 mm be added in the handle length while Konz (1990) recommended that 25.4 mm be added. For an external precision grip, a minimum of 100 mm was recommended since handle should be supported at the base of the thumb or the first finger. In addition, the length of handle should pass the palm but not hit the wrist in the use of an internal precision grip (Konz, 1990).

A previous study (Johnson, 1993) suggested that the handle length should be long enough not to compress the median or ulnar nerve at the distal palm or wrist. One interesting research finding reported by Magill and Konz (1986) was that the length of handle grip was experimentally proportional to the screwdriver torque. Based on the previous findings, it might be concluded that optimum handle length can vary across grip types and task characteristics. Table 2.2 summarized the previous handle length studies.

Table 2.2. Summary of handle length studies

Reference	Recommendation	Consideration
Garrett (1971)	100 mm	Hand breadth
Eastman Kodak (1983)	+12.7 mm	Glove effect
Konz (1990)	100 mm 125 mm +25.4 mm	External precision grip Comfort Glove effect
Johnson (1993)	125 mm	Comfort

<u>Handle Shape</u>

For a power grip task, the handle shape should maximize the contact area between the palm and the handle so as to distribute pressure. In nature, the handle with circular cross sectional shape was found to provide the greatest torque (Rubarth, 1928).

Khalil (1973) reported that there was little difference between an elliptical shape and a spherical shape based on EMG activity. According to Pheasant and O'Neill (1975), effect of handle shape on grip fatigue did not show any significant difference in manual lifting. For pulling and thrusting force, however, triangular cross section was best (Cochran and Riley, 1982) while triangular shape was worst for rolling type manipulation (Cochran and Riley, 1986). A rectangular shape with ratio of width to height from 1:1.25 to 1:1.5 was a good compromise (Cochran and Riley, 1986). Bullinger and Solf (1979) reported that hexagonal shape provided the highest torque in comparison to conventional shape since it best fits the contours of the palm and thumb in both power and precision grip. In this manner, Kong and Freivalds (2003) tested seven meat hook handles varying different shapes. They reported that double frustum shaped handles produced significantly larger maximum pulling force and showed the best force efficiency and lowest subjective discomfort.

For screwdriving tasks, the end of handle should be rounded in order to prevent undue pressure at the palm. Triangular shape handle generally produce more torque than cylindrical shape screwdrivers since the chances of slippage are reduced (Mital and Channaveeraiah, 1988). In addition, T-type handles showed 50% increase in torque compared to straight screwdriver handles (Pheasant and O'Neill, 1975).

A final note on shape is that finger grooves and identifications are generally undesirable since they can only fit to a particular hand size (Tichauer, 1973; Mital, 1991; Johnson, 1993). Finger rings are also undesirable due to the same reason (Meagher, 1987). However, slight and uniform surface indentations are acceptable as they may produce greater torque exertion capability (Tichauer and Gage, 1977). With regard to the above findings, one might conclude that optimal handle shape may be closely dependent on the type of task and motions involved. Table 2.3 summarized the previous handle shape studies.

Table 2.3. Summary of handle shape studies

Reference	Recommendation	Consideration
Rubarth (1928)	Circular	Power grip
Cochran and Riley (1982)	Triangular	Pulling and thrusting force
Cochran and Riley (1983)	Triangular (worst)	Rolling type manipulation
Cochran and Riley (1986)	Rectangular	No rolling on the table
Bullinger and Solf (1979)	Hexagonal	highest torque in power and precision grip
Mital and Channaveeraiah (1988)	Triangular	Screwdriving torque
Pheasant and O'Neill (1975)	T-type	50% increase in screwdriving torque
Tichauer (1973) Meagher (1987) Mital (1991) Johnson (1993)	Avoid finger grooves, ring, and identifications	Only fit to a particular hand size
Kong and Freivalds (2003)	Double frustum	Force efficiency and subjective discomfort in pulling task

Handle Surface Properties

Grip surface/texture/materials are another important factor of handle designs since they have a profound effect on the local pressure produced at the hand (Sperling et al., 1993). Perceived pain and discomfort caused by high local external pressure generally can reduce both the efficiency of the work and the user satisfaction with the tool (Fraser, 1980; Yun et al., 1992; Sperling et al., 1993). Non-slip surface such as adhesive tape and suede is not always good since it may abrade the hand skin and hinder hand positioning (Drury, 1980; Buchholz et al., 1988).

Fellow and Freivalds (1991) reported that a foam rubber grip resulted in better subjective measure of hand/forearm fatigue and hand tenderness than wood grip. Their finding indicated that a uniform force distribution may positively affect consumer satisfaction with hand tools. Chang et al. (1999) tested three different handle types (a conventional wood handle, solid fiberglass, hollow fiberglass handle) and reported that hollow fiberglass handle was more efficient than other handles in terms of physiological efficiency and subjective acceptability. However there is no comprehensive quantitative study on the effects of handle materials on both a user's performance capability and biomechanical stress on the human body

Chapter 3

ERGONOMIC DESIGN OF HAND TOOLS

3.1 INTRODUCTION

This study aims to develop a novel design methodology using a multidisciplinary approach. For this purpose, a multidisciplinary design methodology integrating ergonomics into QFD method was proposed in this chapter. Specifically, this exploratory approach is to investigate the possibilities and advantages of adapting the HoQ method for ergonomic design of hand tools, and to develop an integrated design technique for linking the design attributes of a hand tool to the users' subjective needs in terms of user satisfaction.

According to published literature, QFD is regarded as an established, interdisciplinary, and systematic methodology which can be applied to a wide range of applications in the product development. Therefore, it might be advantageous to adapt QFD method for developing ergonomic hand tools to transfer "voice of customer" into product characteristics by systematically reflecting user needs at every level of the ergonomic product development process (Bergquist and Abeysekera, 1996; ReVelle, 1997). Until now, there are few studies using QFD method in the ergonomic product design area. Those studies in the literature have proved that QFD method is an effective approach to match the user's needs with product characteristics in several design applications such as safety shoes (Bergquist and Abeysekera, 1996), pruning shears (Haapalainen et al., 2000), small container (Guedez et al., 2001), and boning knife (Marsot, 2005). However, they lacked explicit methodological evidence that human abilities and limitations have been systematically considered. In addition, the above mentioned studies have simply followed the same QFD analysis technique without suggesting any systematic way of incorporating ergonomics knowledge into the product development.

In order to develop ergonomic products, besides user needs and requirements related to the product, human physiological and psychological abilities and limitations have to be seriously taken into consideration (Lee et al., 1997). By adapting the QFD method, the user needs can be matched with the product characteristics. However, human abilities and limitations should be considered with the help of ergonomics knowledge in the product development process. Consequently, this is a clear distinction between quality product and ergonomic product. To some extent, QFD may look similar to the High Touch design process in that both methodologies employ same analytical techniques with respect to hierarchical structure, relationship matrix analysis, and priority analysis. However, there is a clear distinction between QFD and High Touch design process in that High touch process employs hierarchically decomposed human variables developed by ergonomic experts in the form of user characteristics for the relationship matrix analysis, while QFD employs customer survey such as questionnaire or interview as a means of identifying the user needs or customer attributes.

This chapter focuses on the development of a multidisciplinary approach for integrating two established design methodologies from different disciplines. The procedure of the multidisciplinary approach is as follows:

- First, a conceptual model of human-hand tool system was developed in order to thoroughly investigate the embedded characteristics as well as important factors affecting the ergonomic design of a hand tool.
- Second, a technique that enables ergonomics knowledge such as human physiological and psychological abilities and limitations as well as ergonomic design principles to be embedded into the identification of potential ergonomic design area and design attributes of a hand tool was adapted from High Touch design process.
- Third, from the extensive ergonomics literature survey, a questionnaire for identifying user satisfaction attributes was developed to elicit critical users' functional and affective needs related to a hand tool.
- Fourth, by adapting QFD methodology, a modified HoQ chart was developed for integrating ergonomics into QFD to assess the design priority of ergonomic product design attributes of a hand tool related to user needs associated with user satisfaction in using the hand tool.
- Finally, a case study of screwdriver design was conducted to demonstrate the applicability of the proposed multidisciplinary design methodology.

3.2 HUMAN-HAND TOOL SYSTEM

In order to ergonomically design a product or system in the design process, it is necessary to systematically and thoroughly investigate the embedded characteristics as well as factors affecting the design attributes of ergonomic design of a product (Lee, 1995; Lee et al., 1997). In this respect, from the established ergonomic design principles, recommendation, checklist, and guidelines, a conceptual model for understanding various factors influencing the ergonomic design of human-hand tool system is proposed as shown in Figure 3.1. It is generally assumed that the ergonomic function of the human-hand tool system is a product of the following variables:

- Human variables (user characteristics)
- Product variables (design characteristics)
- Task variables (task requirements)
- Qualitative variables (user's qualitative needs)

For the application of ergonomic design of a hand tool, human variables (user characteristics), qualitative variables (user needs or expectation), and product variables (design characteristics) are thoroughly investigated based on the extensive ergonomics literature survey, engineering design knowledge from the tool manufacturers, and well-designed questionnaire to elicit user needs related to the hand tool.

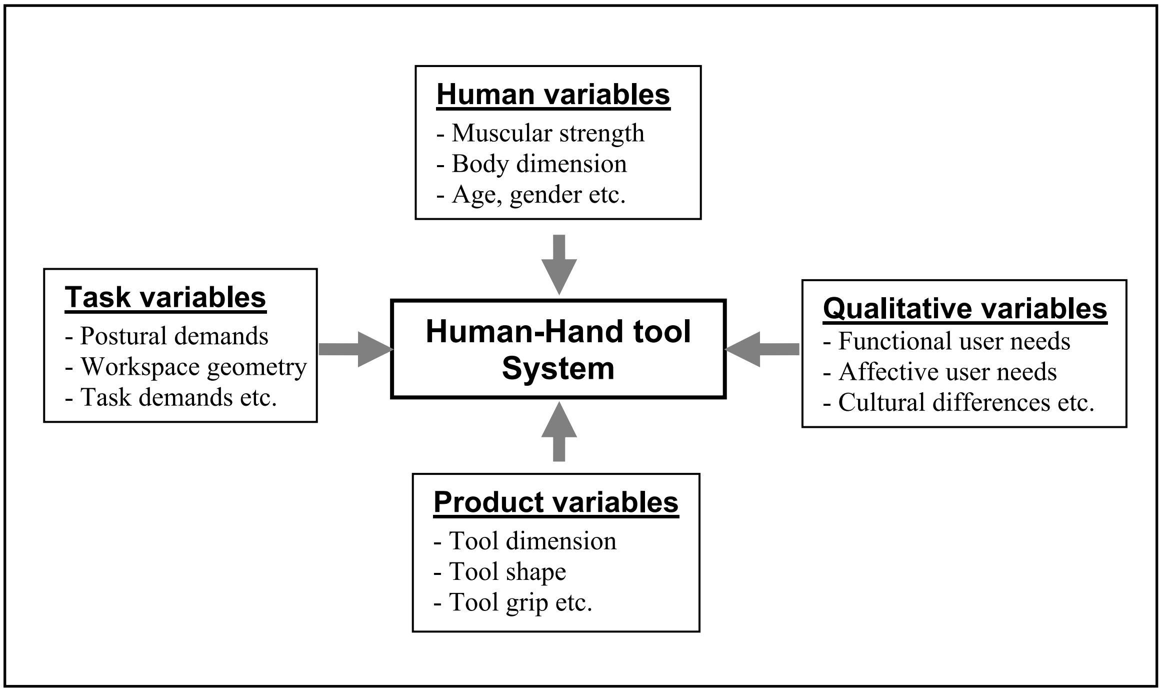


Figure 3.1. Factors affecting the ergonomic design of human-hand tool system

3.2.1 Human Variables

In general, human variables are multi-dimensional. For example, human muscular strength could be defined in various dimensions by task demands involved in a given product. This may imply that strength should be decomposed into more detailed sub variables with a hierarchical structure (Lee et al., 1997; Han and Hong, 2003). Obviously, the human variables are intrinsically different from person to person. In addition, a variety of user characteristics can be included in human variables such as age, gender, nationality, and level of experience (novice or expert).

3.2.2 Product Variables

Based on the engineering design knowledge and ergonomics design literature of hand tools, product variables such as functional properties of a hand tool can be thoroughly investigated and systematically represented as a hierarchical structure of various functional aspects of the hand tool. According to the published literature, examples include various functional properties of a hand tool such as tool dimension, handle shape, and handle surface characteristics. For the reliability of case study, professional engineering design knowledge from the tool manufacturers as well as ergonomic design knowledge from extensive literature survey were collected and utilized in this study.

3.2.3 Qualitative Variables

For the methodological purpose of this study, the user needs or requirements related to a given product can be defined as the qualitative variables. In nature, user needs or requirements depend directly upon product design attributes (Nagamachi, 1995; Han and Hong, 2003). For example, if a user wants an impression such as “comfort”, then it is necessary to investigate what product attributes make the user feel comfortable. In order to answer this question, the relationship between qualitative variables and product design attributes should be analyzed (Han and Hong, 2003).

In order to investigate the user needs to a hand tool, a questionnaire method has been mainly utilized according to the QFD approach. However, in this study, from the extensive ergonomics literature survey, a questionnaire for identifying user satisfaction attributes was formulated and utilized to elicit users’ functional and affective needs related to a hand tool. In addition, statistical analysis was employed to test the reliability of questionnaire so as to extract critical user satisfaction attributes associated with user satisfaction.

3.2.4 Task Variables

The consideration on task variables may include biomechanical and physiological load such as force/torque exertion required to perform a task, temporal demands such as duration and frequency, postural demand such as wrist/hand/arm posture including flexion, extension, pronation, supination, radial deviation, and ulnar deviation, and effect of workspace geometry. In this study, task variables were embedded into ergonomic design attributes derived from relationship analysis between human variables and product variables. In addition, task variables were considered by a proposed ergonomic evaluation experimentation technique (completely described in Chapter 5). Moreover, based on the established literature, task requirements were seriously considered with regard to ergonomic design principles, guidelines, checklists, and recommendations related to a specific design attribute of a hand tool.

3.3 FRAMEWORK OF A MULTIDISCIPLINARY APPROACH

A multidisciplinary approach for ergonomic design process is proposed as shown in Figure 3.2. The detailed information about each step is described as follows.

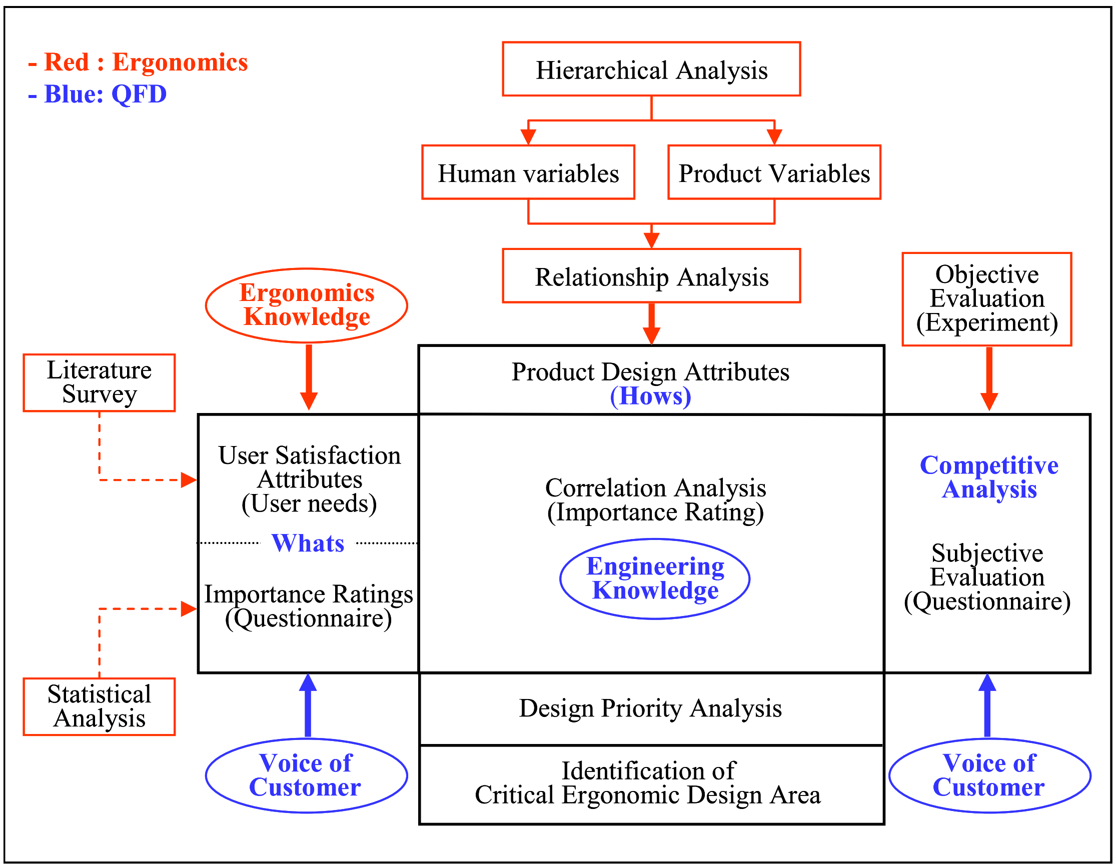


Figure 3.2. A conceptual model for ergonomic design of hand tools: integrating ergonomics into a modified HoQ chart of QFD

3.3.1 Hierarchical Analysis

Various aspects of human variables and its functional limits can be formulated into the hierarchical structure. Similarly, a number of design attributes of a hand tool are also expressed as a hierarchical structure of various sets of product variables (Lee et al., 1997; Lee et al., 2001). In this thesis, product variables (screwdriver) and human variables were identified and represented with hierarchical structures in Chapter 4. For the practical applicability of a case study, hierarchical structures of both variables were formulated based on the extensive literature survey.

3.3.2 Identification of Product Design Attributes

A technique of relationship matrix analysis was adapted from High touch design process proposed by Lee et al. (1997). Given a product, the relationship matrix analysis can provide ergonomists and product designers with shortcomings, weaknesses, and necessary implementations of the product (Lee et al., 1997). Based on the hierarchical structures of human variables and product variables, a relationship matrix (human variables vs. product variables) is formulated. In the relationship matrix, human variables are assigned to its rows and product variables to its columns, respectively. A focus group consisting of ergonomists and product design engineers is employed in this step and the relationship matrix is utilized to thoroughly investigate potential ergonomic design attributes to be seriously considered in the next steps. Specifically, check/no-check evaluation method is employed based on whether any ergonomic problem or potential improvement possibility exists in a particular cell in the relationship matrix.

3.3.3 Identification of User Satisfaction Attributes

According to the engineering design literature, identification of user needs is probably the most important step in the product design process (Suh, 1990; Hauser and Clausing, 1988). However, there might be still lack of knowledge about how to elicit, assess, and utilize user needs for a specific design purpose (Khalid and Helander, 2004). In addition, when one is considering user needs thoroughly, literature emphasizes some drawbacks of QFD method as follows. Therefore, in order to adapt QFD method for ergonomics design area, the following methodological concerns in the QFD analysis should be resolved or at least alleviated.

- Customer attributes are very difficult to recognize because the voices of the customer are not always clear and comprehensible (ReVelle et al., 1997). In addition, users cannot always know what they really want (Kano et al., 1984; ReVelle et al., 1997). Moreover, user needs might be different with respect to their level of experience (novice or expert) as well as their inherent characteristics such as age and gender (Khalid and Helander, 2004).
- It is not sufficient to simply respond to the customer's explicit "performance" (one-dimensional) needs. Hence, it is absolutely necessary to identify not only "must-be" (basic) needs but also "attractive" needs (Govers, 2001). In general, the affective user needs are equally important when they are compared with the functional needs (Khalid and Helander, 2004).
- In order to identify customer attributes thoroughly, existing QFD methods are mostly based on customer surveys. However, comprehensive customer surveys may result in excessive cost while choosing customer attributes from

small group of customers may not guarantee meeting customer expectations thoroughly (Griffin and Hauser, 1992).

For a potential solution to mitigate the above mentioned drawbacks of QFD, literature suggests that ergonomics knowledge makes it possible to reveal information of the potential user needs or requirements (Nagamachi, 1995; Lee et al., 1997; Han and Hong, 2003). Therefore, the integration of ergonomics knowledge and QFD method might be a useful approach for ergonomically designing high quality products (Bergquist and Abeysekera, 1996). Hence, this study concentrates on identifying comprehensive user needs, closely associated with user satisfaction, that facilitate the integrated design methodology.

According to the published literature, user satisfaction is multi-dimensional and it should be defined and classified into several distinct dimensions (Han et al., 2000; Han et al., 2004). For the basis of this approach, a conceptual model of user satisfaction dimensions in using hand tools was adapted from the published literature (Han et al., 2000; Han et al., 2004; Kuijt-Evers et al., 2004). The conceptual model is presented in Figure 3.3 and its functional definition is as follows.

- ***Performance***: measured quantitatively by performing tasks using a hand tool
- ***Physical interaction***: physical properties of a hand tool or its impact from physical interaction between user and a hand tool
- ***Affective image/impression***: user's subjective aspects, evaluative feelings or impression related to the appearance of a hand tool

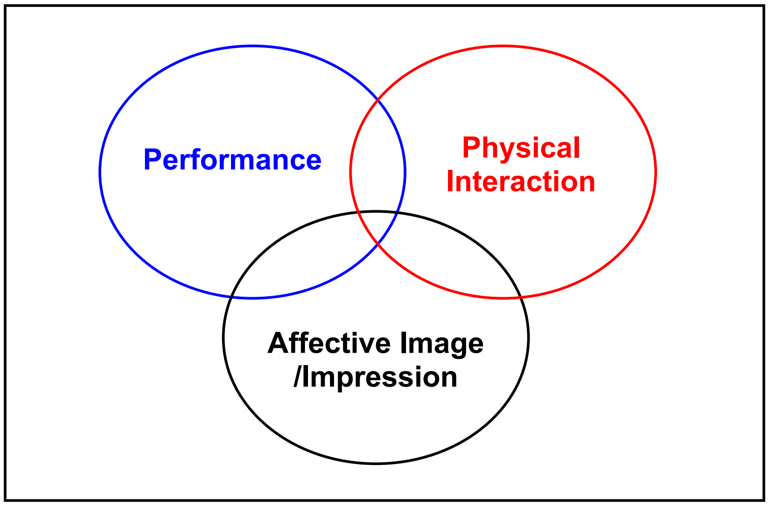


Figure 3.3. A conceptual model for user satisfaction dimensions in using hand tools (Adapted from: Han et al., 2000; Kuijt-Evers et al., 2004)

In this thesis, a stepwise approach was utilized to identify user satisfaction attributes for providing meaningful list of user needs, describing their relationship with regard to user satisfaction, and predicting the degree of their impacts on overall user satisfaction so as to identify critical user needs in terms of user satisfaction as shown in Figure 3.4 and detailed explanation is as follows:

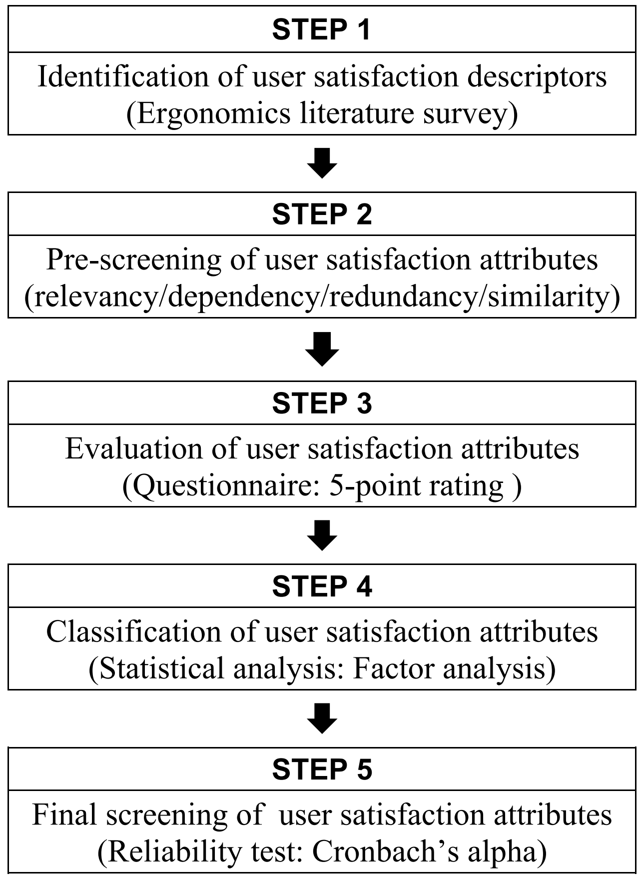


Figure 3.4. A framework for identifying user satisfaction attributes

<u>STEP 1: Identification of User Satisfaction Descriptors</u>

Step 1 aims to collect all possible list of attributes that could underlie user satisfaction in using hand tools. From the extensive survey of ergonomics literature including ergonomic design recommendations/checklists/guidelines for hand tools, an initial list of user satisfaction attributes is collected to elicit comprehensive user needs including users' functional and affective needs associated with user satisfaction in using hand tools.

STEP 2: Pre-screening of User Satisfaction Attributes

Step 2 aims to gain meaningful list of user needs with respect to user satisfaction. With regard to the initial list of user satisfaction descriptors, pre-screening including grouping/eliminating/combining procedure is performed by ergonomists based on such criteria as relevancy, dependency, redundancy, and similarity. Pre-screened user satisfaction attributes are functionally defined, and then translated into user-friendly terms for the formulation of questionnaire in the next step.

STEP 3: Evaluation of User Satisfaction Attributes

Step 3 aims to gain reliable data about user needs with respect to user satisfaction, questionnaire survey is employed to collect various user needs or expectations embedded in user satisfaction attributes related to user satisfaction. Questionnaire consists of full set of pre-screened list of user satisfaction attributes. Each of questions consists of a user satisfaction attribute and its functional definition. 5-point liner numeric rating scale is utilized to measure the relative importance of each user satisfaction attribute. In addition, open-ended question associated with each user satisfaction attribute is employed to capture the unrestricted voice of user.

STEP 4: Classification of User Satisfaction Attributes

From the result of questionnaire survey, user satisfaction attributes are analyzed and classified into meaningful categories related to user satisfaction dimensions. Statistical analysis such as Principal Component Analysis (PCA) with varimax rotation is utilized for classifying user satisfaction attributes.

STEP 5: Final Screening of User Satisfaction Attributes

In order to gain more reliable data about user needs with respect to user satisfaction, the internal consistency reliability of user satisfaction attributes is tested with Cronbach's coefficient alpha statistic (James, 1995). The resulting final list of user satisfaction attributes is utilized as an input of a modified HoQ chart in the next steps. Based on these results, it is expected to identify more reliable and comprehensive user needs to be utilized in the following stages of the proposed design method.

3.3.4 Correlation Analysis

Using a modified correlation matrix (Table 3.1) adapted from HoQ method, correlation analysis between user satisfaction attributes and product design attributes is performed. The final list of user satisfaction attributes (denoted by USA_i) is written in the rows of the correlation matrix with corresponding importance scores (denoted by U_i). Product design attributes are listed in the columns of the correlation matrix (denoted by PDA_j). Ergonomists and Engineers are employed in this evaluation stage and their professional knowledge is utilized to evaluate how much each of product design attributes impacts on the related user satisfaction attributes using strength symbol or rating scale which has the same interval (5-point) as used in importance rating on user satisfaction attributes (Table 3.2). However, intermediate values (2 & 4) are utilized to describe the compromise situations between ergonomists and engineers. The resulting rating score of the impact of the j^{th} product design attributes (PDA_j) on the i^{th} user satisfaction attributes (USA_i) is written in a matrix cell denoted by P_{ij}.

Table 3.1. A modified HoQ matrix for design priority analysis

User Satisfaction Attributes		Product Design Attributes			
		PDA_1	PDA_2	PDA_3	PDA_j
USA_1	U_1	P_{12}			P_{1j}
USA_2	U_2		P_{22}		
USA_3	U_3			P_{33}	
USA_i	U_i	P_{i1}			P_{ij}
Overall score		S_1	S_2	S_3	S_j

Table 3.2. Rating scale for correlation analysis

Scale	Description
Blank	No correlation
1	Weakly correlated
3	Correlated
5	Strongly correlated

3.3.5 Design Priority Analysis

Finally, overall importance score of each product design attribute associated with user satisfaction is calculated by the following equation.

$$S_j = \sum_i U_i P_{ij}$$

Where, S_j : overall importance score of the j^{th} product design attribute
U_i : importance score of i^{th} user satisfaction attribute
P_{ij} : score of the impact of the j^{th} design attributes on the i^{th} user needs

Design priorities or weights of product design attributes are represented by the overall importance score of each product design attribute and an overall design priority may indicate which product design attributes support the focus of the ergonomic design of a product as well as user satisfaction. Finally, in order to demonstrate the applicability of the proposed design methodology, a case study was conducted on the ergonomic design of screwdriver in the Chapter 4.

Chapter 4

CASE STUDY: ERGONOMIC DESIGN OF SCREWDRIVER

4.1 INTRODUCTION

A case study of screwdriver was conducted to demonstrate the applicability of the proposed design methodology. Figure 4.1 shows the procedure of the case study for ergonomic design of screwdriver using a multidisciplinary approach.

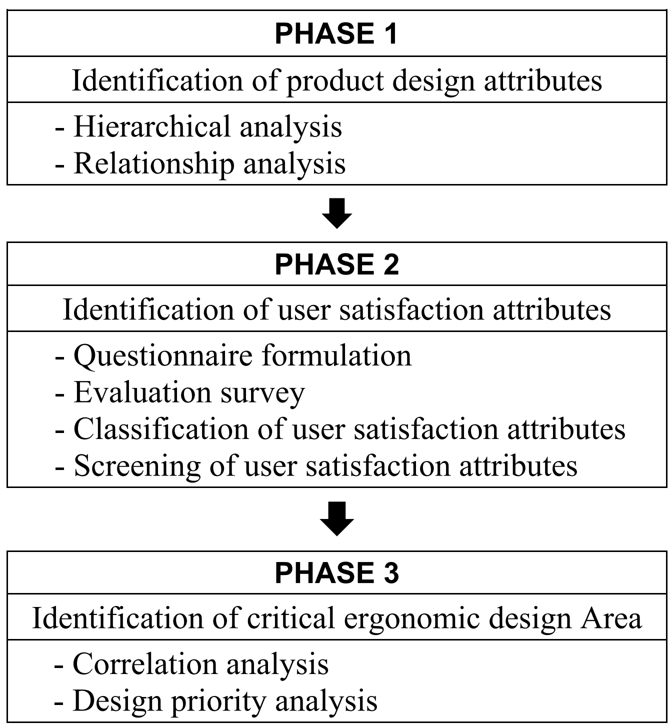


Figure 4.1. Procedure of case study for ergonomic design of screwdriver

4.2 IDENTIFICATION OF PRODUCT DESIGN ATTRIBUTES

In accordance with a multidisciplinary approach of the proposed design methodology ergonomic design process proposed in section 3.3, the detailed information about each step is described as follows.

4.2.1 Hierarchical Analysis

According to the literature, various aspects of human variables and its functional limits can be formulated into the hierarchical structure. In addition, a number of design attributes of a product also can be expressed as a hierarchical structure of various sets of product variables (Lee et al., 1997; Lee et al., 2001). In this respect, product variables of screwdriver and human variables were identified and represented with hierarchical structures as shown in Table 4.1 and 4.2. For the practical applicability of a case study, hierarchical structures of both variables were formulated based on the extensive ergonomics literature survey. Specifically, hierarchical structure of human variables was adapted from the established High touch design process (Lee et al., 1997). Regarding the product information about screwdriver, engineering knowledge and design information were collected from tool manufacturers, and then analyzed by ergonomists.

Table 4.1. Hierarchical structure of human variables (Adapted from: Lee et al., 1997)

	Level 1	Level 2	Level 3
Human variables	Sensing	Visual sensing	- Visual acuity - Color perception - Depth perception - Visual angle - Visual field etc.
		Auditory sensing	- Audibility - Audible intensity - Frequency sensing - Sound location etc.
		Tactile sensing	- Pressure perception - Friction perception - Temperature perception - Vibration perception etc.
		Kinesthetic sensing	- Body segment position perception - Gravity, acceleration, rotation perception etc.
		Other sensing	- Olfactory sensing - Gustatory sensing etc.
	Information processing	Channel processing	- Channel capacity - Processing time - Compatibility - Channel switching etc.
		Decision making	- Estimation - Interpretation - Reasoning etc.
		Memory	- Short-term memory - Long-term memory - Working memory etc.
		Attention	- Selective attention - Focused attention - Divided attention etc.
	Motor function	Work capacity	- Strength (static, dynamic) - Endurance - Range of motion - Muscle fatigue etc.
		Motor coordination	- Controllability - Body balance - dexterity etc.
		Reaction	- Simple reaction - Choice reaction - Reflex etc.
	Individual characteristics	Anthropometric characteristics	- Body segment dimensions (length, width, breadth, height etc.) - Weight etc.
		Demographic characteristics	- Age, Gender - Occupation, Education - Nationality, Experience - Hand laterality etc.

Table 4.2. Hierarchical structure of product variables (screwdriver)

	Level 1	Level 2	Level 3
Product Variables	Handle	Size	- Diameter - Length - Circumference
		Shape	- Cross-sectional shape - End shape - Guard - Sharp edge/corner
		Surface	- Texture - Material - Finger grooves/rings - Friction
		Grip	- Grip type - Handle orientation - One/two-handed grip
		Weight	- Mass - Center of gravity
	Shaft	Size	- length - diameter
		Physical characteristics	- Flexibility - Magnetize - Material etc
	Bit	Bit type	- Philips - Slotted screws - Socket cap - Pozidriv/Supadriv - TORX etc.
		Functionality	- Reversible bits - Universal holder - Depth stop etc.

4.2.2 Relationship Analysis

The relationship matrix analysis adapted from High touch design process (Lee et al., 1997) was employed in this section. Based on the hierarchical structures of human variables and product variables (developed in the section 4.2.1), a relationship matrix (human variables vs. product variables) was formulated. In the relationship matrix, human variables were assigned to its rows and product variables to its columns, respectively. A focus group consisting of two ergonomists and a product design engineer was employed in this step. With their personal communication, check/no-check evaluation method was employed to thoroughly identify potential product design attributes. As a result, 25 product design attributes were identified to be seriously considered in the following steps. An example of initial relationship matrix analysis (screwdriver handle) was illustrated in Table 4.3. The final result of relationship matrix analysis was formulated with a hierarchical structure as shown in Table 4.4.

Table 4.3. A sample of relationship matrix analysis (screwdriver handle)

Human variables (Ergonomic functions for screwdriving)	Product variables (Screwdriver handle)														
	Size			Shape				Surface			Grip			Weight	
	Diameter	Length	Circum-ference	Cross-section	End shape	Guard	Angle	Texture	Material	Groove	Type	Orien-tation.	Laterality	Mass	COG
Individual Characteristics															
Anthropometry															
Finger size	○	○	○	○	○	○	○			○					
Hand length	○	○	○	○	○		○			○					
Hand breadth	○	○	○	○	○	○	○			○					
Forearm reach															
Demographic char.															
Age								○						○	○
Gender	○	○	○	○	○	○								○	○
Hand laterality						○	○			○		○	○		
Experience								○	○	○	○	○		○	○
Cultural difference				○	○			○	○		○		○		
Sensing															
Visual sensing							○	○							
Visibility							○	○							
Color perception									○						
Tactile sensing															
Pressure perception	○	○	○	○	○	○	○	○	○	○	○				
Friction perception	○	○	○	○	○	○		○	○	○	○				
Motor function															
Work capacity															
Muscle strength	○	○	○	○	○	○	○	○	○	○	○	○		○	○
Endurance				○	○	○	○	○	○	○	○	○		○	○
Range of motion		○					○				○	○	○		
Motion coordination															
Kinesthetic feedback						○		○	○	○					
Controllability	○	○	○	○	○	○	○			○	○	○		○	○
Dexterity	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

Note: Potential ergonomic product design area (○)

Table 4.4. Hierarchical structure of product design attributes (screwdriver)

Level 1	Level 2	Level 3 (Product Design Attributes)
Handle	Physical dimension	Handle diameter
		Handle length
		Handle weight
	Shape	Cross-sectional shape of handle
		Longitudinal shape of handle
		Front shape of handle (thumb area)
		End shape of handle
	Surface property	Handle texture
		Handle material/finish
		Handle groove
		Handle color
Shaft	Dimension	Shaft length
		Shaft diameter
	Physical property	Shaft material/finish
		Shaft color
Bit/Tip	Dimension	Bit type
		Bit size
	Physical property	Bit material/finish
		Bit color
Supplementary function		Rotation holder
		Bit storage (cap compartment)
		Bit changer (interchangeable bits)
		Magnetic bit (tip)
		Barcode/Tag/Label
		Hole

4.3 IDENTIFICATION OF USER SATISFACTION ATTRIBUTES

4.3.1 Questionnaire Formulation

From the extensive review of ergonomics literature such as design guidelines, recommendations, and checklists of hand tools, a total of 60 user satisfaction descriptors related to user satisfaction in using hand tools were initially collected (Table 4.5). Next, pre-screening procedure including eliminating, combining, and translating 60 descriptors to user satisfaction attributes was performed by ergonomists. As a result, a total of 30 user satisfaction attributes were defined and translated using user-friendly terms for the questionnaire survey as shown in Table 4.6.

Table 4.5. User satisfaction descriptors in using hand tools

User Satisfaction Descriptors	User Satisfaction Descriptors
1. Easy to use/understand usage 2. Easy to carry/store/pick up & put down 3. Easy to recognize 4. Easy to maintain/clean/repair 5. All-weather proof/ provide climatic comfort 6. Be hygienic 7. Force exerted from hand/tool 8. Be safe 9. Task performance (torque/force) 10. Provide the required force/torque output 11. Provide the required precision 12. Effectiveness: perform the right function to be intended 13. Efficiency: maximize the efficiency of human movement 14. Fit the work task 15. Fit the working object and workspace 16. Avoid damage to the working object 17. High productivity 18. Durability (duration of product or part life) 19. Weight of tool: as light as the function requires 20. Easy to take along 21. Good handle hardness 22. Provide multi-function 23. Provide an adequate grip and a possibility for grip variation 24. Fit right and left hand or two hand operation 25. Fit the hand size and work capacity (strength) of the user group 26. Provide feedback of completed work 27. Allow for individual difference such as gender, age, training level 28. Provide grip comfort 29. No irritation of tissue	30. No pain 31. Good fit in anthropometric dimension of user group 32. No peak pressures on hand/finger 33. No body part discomfort and no demand awkward posture 34. Avoid lack of tactile feeling (numbness) 35. Enough friction between hand and handle: provide adequate grip friction 36. No muscle cramp 37. No fatigue during workdays 38. Low handgrip force: require low force output 39. Avoid sharpness 40. No slippery handle and no sweaty handle 41. Comfortable working posture 42. No sore muscles and no blisters 43. Avoid roughness of handle surface 44. No interference from protective equipment 45. Be affective 46. Use to fun 47. Professional looks 48. Stylish 49. Nice color 50. Solid design 51. Look luxurious 52. Look simple 53. Look rigid 54. Look salient 55. Be attractive 56. Be balanced 57. Be stable 58. Reasonable price and maintenance cost 59. Provide personalization 60. Provide Identification

Table 4.6. Definitions of user satisfaction attributes

No	Attributes	Definition	From
1	Force/torque output	The tool provides the force/torque output required to perform the intended task	7/9/10
2	Precision	The tool provides the precision required to perform the intended task	11
3	Effectiveness	The tool provides the right function required to perform the intended task	12/14/15
4	Efficiency	The tool performs the intended task with minimum user effort	13/37/38
5	Productivity	The tool maximizes the work output during a work day	17
6	Durability	The tool maximizes the duration of product/part life; avoid damage to the working object and product itself with adequate handle/tip hardness	16/18
7	Multi-function	The tool provides different functions for a variety of tasks	22
8	Handle shape	The tool provides an adequate grip for different users and/or grip type	23/24/31
9	Handle size	The tool provides an adequate handle size to fit various hand sizes and/or grip type	25/27/31
10	Tool weight	The tool is as light as the function requires	19
11	Manipulation	The tool is easy to understand the intended use of the product, so as to be able to manipulate the product for performing the required task	1
12	Convenience/Portability	The tool is easy to carry/store/pick up & put down the product, the shape and size of the product is adequate for its function	2/20
13	Identification	The tool is easy to discriminate this product from other similar products	3/59/60
14	Maintenance	The tool is easy to maintain/clean/repair the product	4/6/58
15	All-weather proof	The tool provides the right function regardless of weather conditions	5
16	Safety	The tool is safe to use; the product does not harm the user	8
17	Feedback	The tool provides adequate feedback of task completion	26
18	Grip comfort	The tool provides a good fit in hand/fingers without pain/peak pressures on hand/fingers, irritation of tissue/blisters, numbness/lack of tactile feeling, muscle cramping/soreness, and interference from protective equipment such as gloves	28/29/30/32/34/36/39/41/42/43/44
19	Grip friction	The tool provides adequate grip friction between hand and handle; no slippery handle/ no sweaty handle	35/40
20	Luxurious	The product looks flashy, splendid, or extravagant	51
21	Harmony	The components of the product are well-matched, balanced, and in harmony	56
22	Neatness	The product looks clean, tidy, and well-arranged	52
23	Rigidity	The product looks solid, stable, and secure	50/53/57
24	Attractiveness	The product looks pleasing/charming and arouses interest/fun	46/55
25	Craftsmanship	The product is produced with great care and in fine detail	47
26	Prominence/Uniqueness	The product is outstanding, prominent, unique, and eye-catching	54
27	Shape	The shape of the tool integrates its components characteristics (ratio, length, area, etc.) well	45/52
28	Color	The conceptual image of the product is identified by its color/color combination	49
29	Texture	The image/impression of the product is developed by its texture (e.g., soft, coarse, etc.)	43
30	Design/Styling	The conceptual image of the product is identified by its design (e.g., conventional or innovative, traditional or modern, etc.)	48

4.3.2 Evaluation of User Satisfaction Attributes

Participants

A total of 57 participants from the Pennsylvania State University (male: 37, female: 13) and from industry (male: 3, female: 4) volunteered to participate in the questionnaire. They were divided into two groups representing novice and expert. The detailed information of participants was summarized in Table 4.7.

Table 4.7. Information of participants employed in questionnaire

Descriptive Statistics	Novice (n = 50)			Expert (n = 7)		
	Age	# of use /month	Hours /month	Age	# of use /month	Hours /month
Mean	28.9	3.6	1.52	44.0	16.5	41.6
Standard deviation	4.45	4.87	2.56	12.23	13.91	25.01
Maximum	37.0	22.5	13.5	60.0	45.0	90.0
Minimum	18.0	0.0	0.0	26.0	3.0	18.0

Materials

Questionnaire consisted of full set of pre-screened user satisfaction attributes. Each of questions consisted of a user satisfaction attribute and its functional definition. 5-point liner numeric rating scale was utilized to measure the relative importance of each user satisfaction attribute. In addition, open-ended question associated with each user satisfaction attribute was employed to capture the unrestricted voice of user. Figure 4.2 illustrates the example of questionnaire and full set of questionnaire is described in Appendix E.

INTRODUCTION

Assuming you are working for 8 hours a day with a screwdriver, how important to you is each of the following 30 user satisfaction factors considering your overall satisfaction in use of the screwdriver? Please pick a number from the scale and jot it in the bracket beside the question.

Rating Scale						
Extremely Unimportant	**1**	**2**	**3**	**4**	**5**	**Extremely Important**

Rating instruction*: if you feel the requirement is extremely important, pick a number from the far right side of the scale (e.g., 5). If you feel it is extremely unimportant, pick a number from the far left (e.g., 1), and if you feel the importance is between these extremes, pick a number from someplace in the middle of the scale to show your opinion.*

Q1 Force/torque output [scale: ________]
: The tool provides the force/torque output required to perform the intended task

If you have any specific requirement/needs with regard to the ***force/torque output****, please write down your needs. If not, you may skip this question.*

Figure 4.2. Example of questionnaire for user satisfaction

Data Analysis

Descriptive statistics were computed. After testing normality, nonparametric analysis such as Mann-Whitney U-test was utilized to analyze if attributes were rated differently between novice group and expert group. In addition, rank correlation analysis was conducted to examine if there exists significant rank difference between two groups.

Result of Questionnaire Survey

A total of 30 attributes were ranked on mean of their rating score. Among them, ratings of 11 attributes were significantly different between two groups (novice vs. expert) from the Mann-Whitney Test (α=0.05). Result of Spearman correlation analysis revealed that the ranks of two groups were significantly correlated ($\boldsymbol{r}$ = 0.911, P < 0.001). The results of questionnaire from each group were summarized in Table 4.8.

Table 4.8. Results of questionnaire survey

No.	User Satisfaction Attributes	Novice (n = 50)			Expert (n = 7)			P-value (α=0.05)
		Mean	SD.	Rank	Mean	SD.	Rank	
1	Force/torque output	4.38	0.85	4	4.29	0.49	1	0.378
2	Precision	4.22	0.79	7	4.29	0.76	2	0.905
3	Effectiveness	4.38	0.73	5	4.14	0.90	4	0.496
4	Efficiency	4.44	0.64	2	4.14	0.90	5	0.395
5	Productivity	4.00	1.05	9	3.43	0.98	8	0.159
6	Durability	4.02	0.89	8	3.29	1.11	10	0.077
7	**Multi-function**	2.92	1.12	26	2.00	0.82	20	**0.043***
8	Handle shape	3.92	1.14	10	3.29	0.95	11	0.119
9	Handle size	3.66	1.02	12	4.00	0.58	6	0.438
10	Tool weight	3.48	1.07	15	3.29	0.95	12	0.588
11	Manipulation	3.62	0.92	13	3.00	1.41	14	0.377
12	Convenience/Portability	3.82	0.92	11	2.86	1.57	16	0.110
13	Identification	3.06	1.20	24	2.14	1.46	19	0.058
14	Maintenance	3.42	1.11	17	3.14	1.57	13	0.831
15	**All-weather proof**	3.30	1.22	19	1.86	1.46	22	**0.009***
16	Safety	4.52	0.74	1	4.29	0.76	3	0.319
17	**Feedback**	3.30	1.13	20	1.86	1.21	23	**0.008***
18	**Grip comfort**	4.44	0.70	3	3.43	1.13	9	**0.013***
19	**Grip friction**	4.30	0.76	6	3.57	0.98	7	**0.050***
20	Luxurious	2.22	1.37	30	1.43	0.79	29	0.169
21	**Harmony**	3.06	1.10	25	1.71	0.76	25	**0.004***
22	Neatness	3.20	1.21	23	2.29	1.11	18	0.070
23	Rigidity	3.60	1.14	14	3.00	1.41	15	0.263
24	Attractiveness	2.74	1.37	28	1.71	1.11	26	0.063
25	**Craftsmanship**	3.28	1.25	21	2.00	1.41	21	**0.028***
26	**Prominence/Uniqueness**	2.72	1.21	29	1.57	1.13	27	**0.021***
27	Shape	3.44	1.01	16	2.57	1.13	17	0.059
28	**Color**	2.76	1.30	27	1.43	0.79	30	**0.011***
29	**Texture**	3.24	0.82	22	1.86	1.21	24	**0.005***
30	**Design/Styling**	3.36	1.06	18	1.57	1.13	28	**0.001***

Note: Attributes in bold were significant from the Mann-Whitney Test (α=0.05)

4.3.3 Classification of User Satisfaction Attributes

Factor Analysis

From the result of questionnaire survey, user satisfaction attributes were analyzed and classified into meaningful categories to be related to user satisfaction dimensions. Principal Component Analysis (PCA) with varimax rotation was utilized for classifying user satisfaction attributes. As a result, 30 user satisfaction attributes could be classified into 7 factors with criterion of eigenvalues greater than 1 (Table 4.9).

Table 4.9. Prior communality estimates

Eigenvalues of the Correlation Matrix				
No.	Eigenvalue	Difference	Proportion	Cumulative
1	8.8538	4.7705	0.2951	0.2951
2	4.0833	1.8536	0.1361	0.4312
3	2.2297	0.4487	0.0743	0.5056
4	1.7810	0.1114	0.0594	0.5649
5	1.6696	0.3981	0.0557	0.6206
6	1.2715	0.1826	0.0424	0.6630
7	**1.0888**	**0.1158**	**0.0363**	**0.6993**
8	0.9730	0.0709	0.0324	0.7317
. . .	. . .	. . .	. . .	. . .
29	0.0569	0.0209	0.0019	0.9988
30	0.0360		0.0012	1.0000

After the principal component analysis (PCA) with varimax rotation, the initial classification of user satisfaction attributes was derived and Table 4.10 shows the factor loadings.

Table 4.10. Factor matrix from the result of PCA (factor loadings > 0.4 are shown)

User satisfaction attributes	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7
Neatness	0.786						
Color	0.755						
Prominence/Uniqueness	0.734						
Identification	0.717						
Attractiveness	0.715						
Design/Styling	0.715						
Craftsmanship	0.700						
Harmony	0.681						
Maintenance	0.663						
Shape	0.650						
Convenience/Portability	0.629						
Luxurious	0.589						
Tool weight	0.559		0.419				
All-weather proof	0.559	0.429					
Texture	0.553						
Durability	0.542						
Rigidity	0.528						
Feedback	0.499						
Manipulation	0.468						
Multi-function	0.422						
Grip friction		0.640					
Efficiency		0.588					
Grip comfort	0.406	0.582		0.415			
Force/torque output		0.531					
Effectiveness		0.501					
Productivity		0.417					
Handle size		0.423	0.762				
Handle shape			0.741				
Precision				0.424	0.420		
Safety					(0.379)		

Classification of User Satisfaction Attributes

Regarding the result of PCA with varimax rotation, factor 6 and 7 were not further mentioned since they did not include any underlying attributes of which factor loading is larger than 0.4. Hence, the remaining five factors explain 62.06% of the internal variance. In order to classify the user satisfaction attributes into meaningful user satisfaction dimensions (described in chapter 3), the following adjustments for classification were conducted.

First, the first factor was divided in two dimensions, which consist of "affective image/impression (dimension 1)" and "physical interaction (dimension 2)" since their underlying user satisfaction attributes did not logically match. Second, the third factor was combined with the "physical interaction" dimension since its underlying attributes of "handle size" and "handle shape" corresponded to the physical dimension of screwdriver. Third, remaining factor containing "precision" was combined with the second factor since it corresponded to the "performance (dimension 3)". Finally, though the factor loading of "safety" was slightly lower than 0.4, "safety" was retained due to its higher rating score and it was included into "physical interaction" dimension since its functional definition corresponds to the physical property. As a result, 30 user satisfaction attributes were classified into three user satisfaction dimensions consisting of affective image/impression, physical interaction, and performance, respectively. Table 4.11 shows the result of classification of user satisfaction attributes.

Table 4.11. Classification of user satisfaction attributes

Dimension	User satisfaction attributes
Affective Image /Impression	Neatness, Color, Prominence/Uniqueness, Attractiveness, Design/Styling, Craftsmanship, Harmony, Shape, Luxurious, Texture, Rigidity
Physical Interaction	Identification, Maintenance, Convenience/Portability, Tool Weight, All-weather proof, Durability, Feedback, Safety, Manipulation, Multi-function, Handle size, Handle shape,
Performance	Efficiency, Force/torque output, Effectiveness, Productivity, Precision, Grip friction, Grip comfort

4.3.4 Screening of User Satisfaction Attributes

From the result of classification of user satisfaction attributes, their internal consistency reliability related to user satisfaction dimensions was tested with Cronbach's coefficient alpha. Cronbach's coefficient alpha is a measure of the overall reliability of the questionnaire. As the average inter-factor correlation increases, Cronbach's coefficient alpha increases as well. If Cronbach's coefficient alpha is high, then it can be accepted that the factors are measuring the same underlying feature. To identify which items are unreliable, it is needed to calculate what the Cronbach coefficient alpha would be if a particular item was deleted (Cronbach, 1990).

According to the published literature (Doll and Torkzadeh, 1988), there is no accepted standard of cutoff threshold. However, as a rule of thumb, Cronbach's coefficient alpha should be at least 0.7 before it can be said that the item is reliable (Nunnally, 1976).

Test for Reliability of User Satisfaction Attributes

Analysis of Cronbach's coefficient alpha was conducted using statistical analysis package (SAS v.9.1). In addition, item-total correlation was tested for assessing the correlation of each item with the three user satisfaction dimensions. The cutoff thresholds were 0.7 of Cronbach's coefficient alpha and 0.4 of item-total correlation coefficient.

Table 4.12 shows the result of internal consistency reliability test with Cronbach coefficient alpha and item-total correlation coefficient.

Table 4.12. Result of test for internal consistency reliability

User Satisfaction Dimension	No.	User Satisfaction Attributes	Item-Total Correlation	Alpha if Item deleted	Alpha with all items
Performance	1	Force/torque output	0.4227	0.7487	0.7649
	2	**Precision**	**0.3764**	0.7580	
	3	Effectiveness	0.4199	0.7492	
	4	Efficiency	0.5046	0.7316	
	5	**Productivity**	**0.3622**	0.7609	
	18	Grip comfort	0.6361	0.7030	
	19	Grip friction	0.6846	0.7020	
Physical Interaction	6	Durability	0.4303	0.7977	0.8092
	7	Multi-function	0.4740	0.7938	
	8	Handle shape	0.4735	0.7938	
	9	Handle size	0.4792	0.7933	
	10	**Tool weight**	**0.2652**	0.8121	
	11	**Manipulation**	**0.2152**	0.8164	
	12	Convenience/Portability	0.7427	0.7685	
	13	Identification	0.6640	0.7761	
	14	Maintenance	0.5699	0.7850	
	15	All-weather proof	0.5350	0.7882	
	16	**Safety**	**0.2024**	0.8174	
	17	Feedback	0.4647	0.7946	
Affective Image /Impression	20	Luxurious	0.7229	0.9109	0.9202
	21	Harmony	0.5821	0.9177	
	22	Neatness	0.7658	0.9088	
	23	**Rigidity**	**0.3823**	0.9270	
	24	Attractiveness	0.8012	0.9071	
	25	Craftsmanship	0.6540	0.9143	
	26	Prominence/Uniqueness	0.7998	0.9071	
	27	Shape	0.7377	0.9102	
	28	Color	0.7820	0.9080	
	29	Texture	0.5408	0.9197	
	30	Design/Styling	0.7718	0.9085	

Note: Item-total correlations of user satisfaction attributes in bold are below the cutoff threshold (0.4)

For the first user satisfaction dimension of “performance”, there existed a total of 7 user satisfaction attributes. With all items included, the standardized Cronbach alpha was 0.7649, which is above the cutoff threshold of 0.7. As a result, there was no item to be removed considering the alpha with deleted item. In addition, from the result of item-total correlation coefficient, all items were also above the cutoff threshold of 0.4, except for item 2 (precision) and 5 (productivity) which were below the threshold. However, their coefficient alpha with item 2 and 5 deleted (0.7580 and 0.7609) would not increase the coefficient alpha with all item (0.7649). For this reason, it was decided that item 2 and 5 were retained for the final list.

For the second user satisfaction dimension of "physical interaction", there existed a total of 12 user satisfaction attributes. With all items included, the standardized Cronbach alpha was 0.8092, which is above the cutoff threshold of 0.7. As a result, there was no item to be removed considering the alpha with deleted item. From the result of item-total correlation coefficient, all items were also above the cutoff threshold of 0.4, except for item 10 (tool weight), 11 (manipulation) and 16 (safety) which were lower than desirable. The result indicated that these items were unreliable and therefore would be dropped from the initial list.

The third user satisfaction dimension of "affective image/impression", there existed a total of 11 user satisfaction attributes. With all items included, the standardized Cronbach alpha was 0.9202, which is above the cutoff threshold of 0.7. As a result, there was no item to be removed considering the alpha with deleted item. From the result of item-total correlation coefficient, all items were also above the cutoff threshold of 0.4, except for item 23 (rigidity) which was lower than desirable. This result suggested that item 23 was unreliable and therefore would be removed from the initial list.

Final List of User Satisfaction Attributes

After internal consistency reliability test with Cronbach's coefficient alpha and item-total correlation coefficient, four user satisfaction attributes of item 10 (tool weight), 11 (manipulation), 16 (safety), and 23 (rigidity) were removed from the initial list of user satisfaction attributes. Based on this result, it is expected to utilize more reliable user satisfaction attributes for the following analysis. Consequently, a total of 26 user satisfaction attributes associated with user satisfaction dimensions were employed as an input of the following stages of design process. Table 4.13 shows the final list of user satisfaction attributes that was employed as input of a modified HoQ chart of QFD.

Table 4.13. Final list of user satisfaction attributes

User Satisfaction Dimension	No.	User Satisfaction Attributes	Importance Rating	
			Novice	Expert
Performance	1	Force/torque output	4.37	4.29
	2	Precision	4.23	4.29
	3	Effectiveness	4.35	4.14
	4	Efficiency	4.40	4.14
	5	Productivity	3.93	3.43
	18	Grip comfort	4.32	3.43
	19	Grip friction	4.21	3.57
Physical Interaction	6	Durability	3.93	3.29
	7	Multi-function	2.81	2.00
	8	Handle shape	3.84	3.29
	9	Handle size	3.70	4.00
	12	Convenience/Portability	3.70	2.86
	13	Identification	2.95	2.14
	14	Maintenance	3.39	3.14
	15	All-weather proof	3.12	1.86
	17	Feedback	3.12	1.86
Affective Image /Impression	20	Luxurious	2.12	1.43
	21	Harmony	2.89	1.71
	22	Neatness	3.09	2.29
	24	Attractiveness	2.61	1.71
	25	Craftsmanship	3.12	2.00
	26	Prominence/Uniqueness	2.58	1.57
	27	Shape	3.33	2.57
	28	Color	2.60	1.43
	29	Texture	3.07	1.86
	30	Design/Styling	3.14	1.57

4.4 IDENTIFICATION OF CRITICAL PRODUCT DESIGN AREA

4.4.1 Correlation Analysis

With the result of user satisfaction attributes, in this study correlation analysis between user satisfaction attributes and product design attributes was performed by both ergonomics and engineering knowledge. The initial rating was conducted by ergonomists and then its result was reviewed and confirmed by professional engineer who has experienced in product development such as hand tools. The ratings of correlation were evaluated by degree of how important a product design attribute is related to a user satisfaction attribute in that a well-designed product design attribute would satisfy user needs associated with the user satisfaction attribute. Table 4.14 shows the result of initial correlation analysis between user satisfaction attributes and product design attributes.

Table 4.14. Result of correlation analysis between user satisfaction attributes and product design attributes

User Satisfaction Attributes	Product Design Attributes																								
	Handle											Shaft				Bit (Blade/Tip)				Supplementary function					
	Dimension			Shape				Surface property				Dimension		Physical property		Dimension		Physical property							
	Dia-meter	Length	Weight	Crosssec-tional	Longitu-dinal	Front (thumb)	End (bolster)	Texture	Material /finish	Groove	Color	Length	Dia-meter	Material /finish	Color	type	size	Material /finish	Color	Rotation holder	Bit storage	Bit changer	Magnetic tip	Barcode/ tag/label	Hole (bolster)
Force/torque output	●	●	O	●	⊙	⊙	⊙	●	●	⊙		O				●	⊙	⊙		O					●
Precision	●	●	O	●	⊙	⊙	⊙	O	O	O		●	O			⊙	●	⊙					⊙		
Effectiveness	●	●	O	●	⊙	⊙	⊙	O	O	⊙		●	O			●	●	⊙		⊙	⊙	⊙	⊙		⊙
Efficiency	●	●	O	●	⊙	⊙	⊙	O	O	⊙		⊙	O			⊙	⊙	⊙		⊙	O	O	⊙		⊙
Productivity	●	●	O	●	⊙	⊙	⊙	O	O	O		●				●	●	⊙	⊙	●	⊙	●	●		⊙
Durability									●	O		O	●	●			⊙	●		O	O	⊙			O
Multi-function							⊙									●				●	●	●	⊙		●
Handle shape	●	●		●	●	●	●			●										O	O	O			O
Handle size		●	●	⊙	⊙	O	O			O										O	O	O			O
Convenience/Portability		●	●	⊙	⊙	O	O					●									●				●
Identification	O	O		⊙	⊙	O	O	O	O	⊙	●	●	O	⊙	●	⊙	⊙	⊙	●			O		●	O
Maintenance								●	●	⊙				⊙				⊙		⊙	⊙	⊙	O		⊙
All-weather proof								O	●					O				O							
Feedback																				●		●			
Grip comfort	●	●	O	●	●	O	⊙	⊙	●	●															O
Grip friction	●	●		●	●	O	O	●	●	●															O
Luxurious				O	O	O	O	O	⊙	O	●	O		●	●			O	●	O	O	O		O	O
Harmony	⊙	⊙		⊙	⊙	⊙	⊙					⊙	O	O	⊙	O	O	O	⊙	⊙	⊙	⊙			O
Neatness	O	O		⊙	⊙	⊙	⊙	O		O		⊙	O	O	⊙		O	O	⊙	O	O	O		●	O
Attractiveness	O	O		O	O	O	O		⊙		●			O	⊙			O	⊙	O	O	O		O	O
Craftsmanship				O	O	⊙	⊙	O	●	O				⊙		⊙	⊙	●		⊙	⊙	⊙	⊙	O	
Prominence/Uniqueness				O	O	O	O	O	O	O	●			⊙	●			O	⊙	⊙	⊙	⊙	O	⊙	⊙
Shape	⊙	⊙		●	●	●	●			●			O					O		⊙	⊙	⊙			O
Color									⊙		●			O	●			O	●						
Texture								●	⊙	●					●										
Design/Styling	⊙	⊙		●	●	●	●	⊙	●	⊙	●	⊙	O	O	●		O	⊙	⊙	O	●	●		●	O

Degree of correlation: O = 1, ⊙ = 3, ● = 5

4.4.2 Design Priority Analysis

Regarding the final stages of the case study, overall importance scores of product design attributes associated with user satisfaction were calculated by simple additive scoring method with respect to novice and expert, respectively. According to the result shown in Figure 4.3 and Table 4.15 ~ 4.16, it was revealed that design priority should go to the cross-sectional shape of handle, handle diameter, handle length, longitudinal shape of handle, and handle material/finish. Result of Spearman correlation analysis revealed that the ranks of two groups were significantly correlated (***r*** = 0.981, P < 0.001).

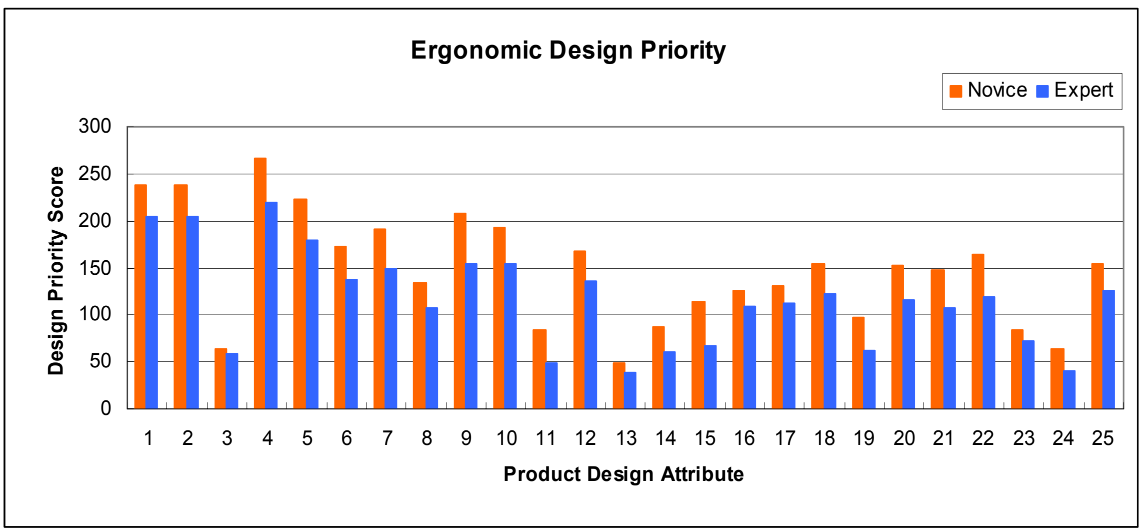


Figure 4.3. Ergonomic design priority of product design attributes

Table 4.15. Ergonomic design priority of product design attributes

Product Design Attributes	Novice		Expert	
	Score	Rank	Score	Rank
1. Handle diameter	238.5	2	204.3	2
2. Handle length	238.5	2	204.3	2
3. Handle weight	63.3	24	58.0	22
4. Cross-sectional shape of handle	265.8	1	219.3	1
5. Longitudinal shape of handle	222.9	4	178.7	4
6. Front shape of handle (thumb area)	173.4	8	136.7	8
7. End shape of handle	191.1	7	149.6	7
8. Handle texture	134.9	15	106.6	17
9. Handle material/finish	208.2	5	154.8	5
10. Handle groove	193.1	6	154.2	6
11. Handle color	84.3	21	49.3	23
12. Shaft length	167.4	9	135.3	9
13. Shaft diameter	49.3	25	39.3	25
14. Shaft material/finish	87.1	20	60.7	21
15. Shaft color	113.8	18	67.1	19
16. Bit type	126.5	17	108.7	15
17. Bit size	130.2	16	112.5	14
18. Bit material/finish	153.7	12	122.4	11
19. Bit color	97.4	19	61.8	20
20. Rotation holder	152.8	13	116.1	13
21. Bit storage (cap/compartment)	147.6	14	108	16
22. Bit changer (interchangeable bits)	164.1	10	118.6	12
23. Magnetic bit (tip)	83.9	22	71.6	18
24. Barcode/Tag/Label	64.5	23	39.9	24
25. Hole	153.9	11	126	10

Table 4.16. Result of design priority analysis between user satisfaction attributes and product design attributes

User Satisfaction Attributes			Product Design Attributes																											
			Handle											Shaft				Bit (Blade/Tip)				Supplementary function					
Name	Importance		Dimension			Shape				Surface property				Dimension		Physical property		Dimension		Physical property		Rotation holder	Bit storage	Bit changer	Magnetic tip	Barcode/tag/label	Hole (bolster)
	Novice	Expert	Dia-meter	Length	Weight	Crosssec-tional	Longitu-dinal	Front (thumb)	End (bolster)	Texture	Material/finish	Groove	Color	Length	Dia-meter	Material/finish	Color	type	size	Material/finish	Color						
Force/torque output	4.38	4.29	5	5	1	5	3	3	3	5	5	3		1				5	3	3		1					5
Precision	4.22	4.29	5	5	1	5	3	3	3	1	1	1		5	1			3	5	3					3		
Effectiveness	4.38	4.14	5	5	1	5	3	3	3	1	1	3		5	1			5	5	3		3	3	3	3		3
Efficiency	4.44	4.14	5	5	1	5	3	3	3	1	1	3		3	1			3	3	3		3	1	1	3		3
Productivity	4.00	3.43	5	5	1	5	3	3	3	1	1	1		5				5	5	3	3	5	3	5	5		3
Durability	4.02	3.29									5	1		1	5	5			3	5		1	1	3			1
Multi-function	2.92	2.00							3									5				5	5	5	3		5
Handle shape	3.92	3.29	3	3		5	5	5	5			5										1	1	1			1
Handle size	3.66	4.00	5	5	5	3	3	1	1			1										1	1	1			1
Convenience/Portability	3.82	2.86	5	5	5	3	3	1	1					5									5				5
Identification	3.06	2.14	1	1		3	3	1	1	1	1	3	5	5	1	3	5	3	3	3	5			1		5	1
Maintenance	3.42	3.14								5	5	3				3				3		3	3	3	1		3
All-weather proof	3.30	1.86								1	5					1				1							
Feedback	3.30	1.86																				5		5			
Grip comfort	4.44	3.43	5	5	1	5	5	1	3	3	5	5															1
Grip friction	4.30	3.57	5	5		5	5	1	1	5	5	5															1
Luxurious	2.22	1.43				1	1	1	1	1	3	1	5	1		5	5			1	5	1	1	1		1	1
Harmony	3.06	1.71	3	3		3	3	3	3					3	1	1	3	1	1	1	3	3	3	3			1
Neatness	3.20	2.29	1	1		3	3	3	3	1		1		3	1	1	3		1	1	3	1	1	1		5	1
Attractiveness	2.74	1.71	1	1		1	1	1	1		3		5			1	3			1	3	1	1	1		1	1
Craftsmanship	3.28	2.00				1	1	3	3	1	5	1				3		3	3	5		3	3	3	3	1	
Prominence/Uniqueness	2.72	1.57				1	1	1	1	1	1	1	5			3	5			1	3	3	3	3	1	3	3
Shape	3.44	2.57	3	3		5	5	5	5			5		5	1					1		3	3	3			1
Color	2.76	1.43									3		5			1	5			1	5						
Texture	3.24	1.86								5	3	5					5										
Design/Styling	3.36	1.57	3	3		5	5	5	5	3	5	3	5	3	1	1	5		1	3	3	1	5	5		5	1
Priority (Novice)	Overall score		238.5	238.5	63.3	265.8	222.9	173.4	191.1	134.9	208.2	193.1	84.3	167.4	49.3	87.1	113.8	126.5	130.2	153.7	97.4	152.8	147.6	164.1	83.9	64.5	153.9
	Rank		2	2	24	1	4	8	7	15	5	6	21	9	25	20	18	17	16	12	19	13	14	10	22	23	11
Priority (Expert)	Overall score		204.3	204.3	58.0	219.3	178.7	136.7	149.6	106.6	154.8	154.2	49.3	135.3	39.3	60.7	67.1	108.7	112.5	122.4	61.8	116.1	108.0	118.6	71.6	39.9	126.0
	Rank		2	2	22	1	4	8	7	17	5	6	23	9	25	21	19	15	14	11	20	13	16	12	18	24	10

Comparison of Novice and Expert

Figure 4.4 and Table 4.17 show the descriptive statistics of design priority score. Though result of Spearman correlation analysis revealed that the ranks of two groups (novice and expert) were significantly correlated (***r*** = 0.981, P < 0.001), priority of expert group was distinctly divided while that of novice group scattered across the product design attributes.

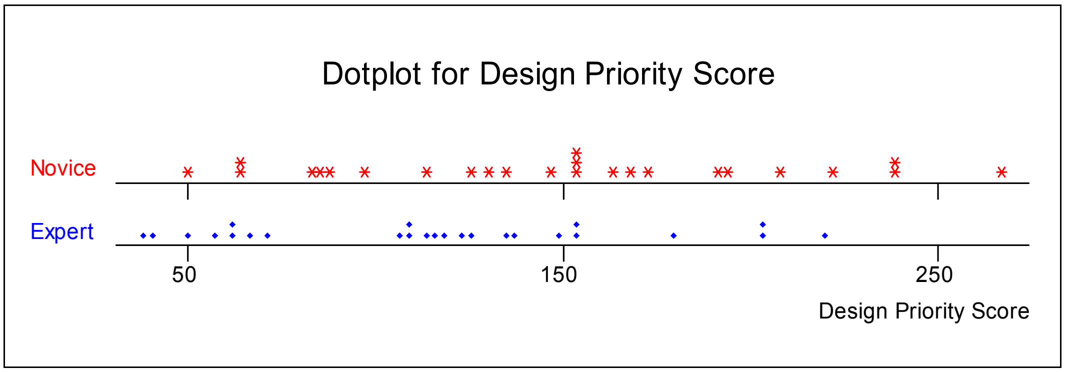


Figure 4.4. Dotplot for design priority score of product design attributes

Table 4.17. Descriptive Statistics of design priority score

Group	Descriptive Statistics						
	Mean	Median	SD	Min	Max	Q_1	Q_3
Novice	148.2	152.8	59.6	49.3	265.8	92.3	192.1
Expert	116.2	116.1	52.2	39.3	219.3	64.4	151.9

Table 4.18 compared novice group with expert group in terms of design priority. Regarding the high design priority above the 3rd Quartile (denoted by $\boldsymbol{Q_3}$), there was an agreement in the cross-sectional shape of handle (#3), handle diameter (#1), handle length (#2), longitudinal shape of handle (#4), handle material/finish (#9), and handle

groove (#10) between two groups. However, low design priority below the 1st Quartile (denoted by Q_1) slightly differed between two groups: shaft material/finish (#14), handle color (#11), barcode/tag/label (#24), handle weight (#3), and shaft diameter (#13) showed relatively low priorities in both groups. Interestingly, magnetized bit/tip (#23) was less favorable to novice group while bit/tip color (#19) was less important to expert group in terms of design priority score.

Table 4.18. Comparison of design priority (Novice vs. Expert)

Priority	Novice			Expert		
	No	Product Design Attributes	Score	No	Product Design Attributes	Score
High	4	Cross-sectional shape of handle	265.8	4	Cross-sectional shape of handle	219.3
	1	Handle diameter	238.5	1	Handle diameter	204.3
	2	Handle length	238.5	2	Handle length	204.3
	5	Longitudinal shape of handle	222.9	5	Longitudinal shape of handle	178.7
	9	Handle material/finish	208.2	9	Handle material/finish	154.8
	10	Handle groove	193.1	10	Handle groove	154.2
Low	14	Shaft material/finish	87.1	19	Bit color	61.8
	11	Handle color	84.3	14	Shaft material/finish	60.7
	23	Magnetic bit (tip)	83.9	3	Handle weight	58.0
	24	Barcode/Tag/Label	64.5	11	Handle color	49.3
	3	Handle weight	63.3	24	Barcode/Tag/Label	39.9
	13	Shaft diameter	49.3	13	Shaft diameter	39.3

Chapter 5

ERGONOMIC EVALUATION OF HAND TOOLS

5.1 INTRODUCTION

Since ergonomic evaluation of different design alternatives of hand tools should take into account the real effects during actual work (Strasser and Wang, 1998), the evaluation methodology using experimentation must include the objective assessments such as torque production capability and physiological load on the user in terms of electromyographic activities as well as user's subjective judgment to a hand tool such as discomfort ratings.

According to the published literature, a number of researchers have demonstrated that the torque production capability that is achieved by gripping and twisting a handle or object is dependent on a number of factors such as handle characteristics, task variables, and individual differences as followings:

- **Handle characteristics:** handle length (Magill and Konz, 1986; Mital and Sanghavi, 1986; Deivanayagam and Weaver, 1988), handle diameter (Swain et al., 1970; Pheasant and O'Neill, 1975; Huston et al., 1984; Cochran and Riley, 1986; Mital and Sanghavi, 1986; Adams and Peterson, 1988; Deivanayagam and Weaver, 1988; Imrhan and Loo, 1989; Habes and Grant, 1997; Shih and Wang, 1997; Peebles and Norris, 2003), handle shape (Pheasant and O'Neill, 1975; Cochran and Riley, 1986; Mital and Channaveeraiah, 1988; Mital et al., 1994; Shih and Wang, 1997), and handle surface properties (Pheasant and O'Neill, 1975; Imrhan and Loo, 1989; Imrhan and Jenkins, 1990)

- **Task variables:** grip type (Adams and Peterson, 1988), direction of rotation (Adams and Peterson, 1988, Imrhan and Jenkins, 1990; Imrhan et al., 1992; Timm et al., 1993; Strasser and Wang, 1998; O'Sullivan and Gallwey, 2002), arm posture (Huston et al., 1984; Mital, 1986; Adams and Peterson, 1988; Imrhan and Jenkins, 1990, Örtengren et al., 1991; Habes and Grant, 1997; O'Sullivan and Gallwey, 2002), handle orientation (Swain et al., 1970; Adams and Peterson, 1988; Deivanayagam and Weaver, 1988; Mital and Channaveeraiah, 1988; Imrhan and Farahmand, 1991; Imrhan et al., 1992; Habes and Grant, 1997; Strasser and Wang, 1998; Casey et al., 2002; Peebles and Norris, 2003), and use of gloves (Swain et al., 1970; Riley et al, 1985; Adams and Peterson, 1988; Cochran et al., 1988; Chen et al., 1989; Mital et al., 1994; Shih and Wang, 1997; Tsaousidis and Freivalds, 1998)
- **Individual differences:** age (Berns, 1981; Rohles et al., 1983; Imrhan and Loo, 1988; Crawford et al., 2002; Voorbij and Steenbekkers, 2002; Peebles and Norris, 2003), gender (Mital and Sanghavi, 1986; Mital and Channaveeraiah, 1987; Shih et al., 1997; Peebles and Norris, 2003), hand size (Grant et al., 1992; Yakou et al., 1997; Kong and Lowe, 2003), hand laterality (Imrhan and Jenkins, 1990; Strasser, 1991; Wang and Strasser, 1993; Strasser and Wang, 1998), and level of experience (Casey et al., 2002)

As listed above, there are a number of variables that have been considered in design and evaluation of hand tools associated with hand/wrist twisting torque tasks.

However, it should be emphasized that this experimental approach did not comprise all aspects of factors affecting functionality of a hand tool associated with screwdriving task. Unlike most of the previous studies, this thesis aims to present a comprehensive evaluation methodology which can be applied to the evaluation of design alternatives of a hand tool, rather than to the investigation of optimal level of design characteristics of a hand tool. While independent variables of this study may not encompass all the factors that affect muscular torque strength, experimental dependent measures are expected to be comprehensive and adequate for the controlled tasks so as to achieve a manageable experimental design.

The ergonomic evaluation methodology proposed in this study consists of two evaluation techniques: (1) experimental investigation including two experimentations (maximum torque task and constant torque task) and (2) subjective evaluation using a product-interactive questionnaire survey. Experiments were designed to evaluate different screwdriver handle designs with objective measures such as torque production, muscular activity (EMG), wrist posture in terms of ulnar deviation angle, and perceived discomfort associated with external pressure at the hand while the questionnaire survey was intended to assess users' subjective preferences to different screwdriver designs in terms of user satisfaction.

5.2 PILOT EXPERIMENT

5.2.1 Method

The pilot experiment aimed to demonstrate the applicability of the experimental method and to calculate the number of participants to be employed in the main study with statistical significance. A completely randomized single-factor experiment was conducted to collect the maximum torque production, subjective ratings of overall discomfort of the hand region and slipperiness using Borg's CR-10 scale, grip force distribution using FSRs, and EMG signals from flexor digitorum superficialis (FDS) and biceps brachii (BB) muscles during maximum voluntary contraction of supination (clockwise forearm rotation). A total of four male participants with no history of upper extremity disorders were recruited in the pilot experiment. All participants were right handed, aged from 26 to 31. Each participant was asked to follow the experimental procedure for the maximum torque task (completely described in section 5.3.5). The detailed information about the participants including anthropometric characteristics is summarized in Table 5.1.

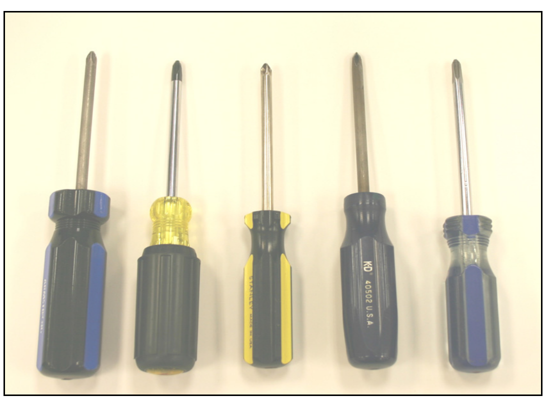
Table 5.1. Summary of the participants' characteristics

Participant code	Demographics			Anthropometry				
	Age	Gender	Hand laterality	Height (cm)	Weight (kg)	Hand length (cm)	Hand breadth (cm)	Elbow height (cm)
P01	26	Male	Right	171.0	64.0	18.1	8.6	99.0
P02	31	Male	Right	176.0	75.0	19.0	8.8	102.0
P03	26	Male	Right	172.0	59.0	18.5	8.3	97.0
P04	30	Male	Right	170.0	63.0	18.2	8.1	96.0
Descriptive statistics	Mean			172.3	65.3	18.5	8.5	98.5
	Standard Deviation			2.63	6.85	0.40	0.31	2.65
	Minimum			170.0	59.0	18.1	8.1	96.0
	Maximum			176.0	75.0	19.0	8.8	102.0

The experimental design for the pilot study consisted of one independent variable and five dependent variables. The independent variable is type of screwdriver handle design with five levels of A, B, C, D, and E as described in Table 5.2 and Figure 5.1.

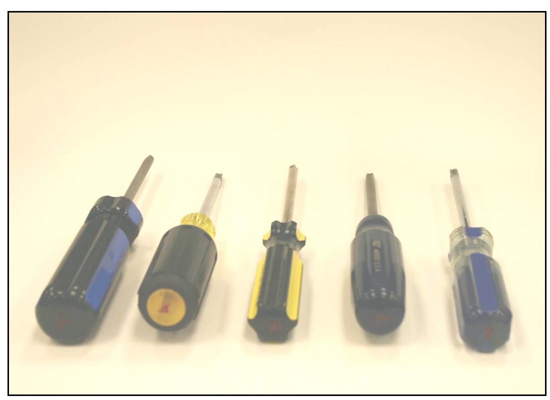
Table 5.2. Characteristics of screwdrivers

Code	Handle Shape	Surface Properties		Size (cm)		
		Texture	Material	Shaft length	Handle length	Handle diameter
A	Pentagonal round	5 grooves	Plastic	10.0	11.3	3.3
B	Octagonal round	8 small indentations	Rubber over plastic	10.2	10.8	3.3
C	Hexagonal round	6 grooves	Plastic	10.3	9.5	2.6
D	Tetragonal round	4 grooves	Plastic	10.3	10.7	3.2
E	Tetragonal round	4 grooves	Plastic	10.7	9.3	2.8



A B C D E

(a)



A B C D E

(b)

Figure 5.1. Five different handle designs of screwdriver
: a) front view, b) cross-sectional view

In each experimental condition, two trials were repeated so that a total of 10 data points were obtained from each subject. The order of 10 trials was completely randomized. The dependent variables studied in this pilot experiment were maximum torque exertion, two EMGs measured from FDS and BB, two subjective ratings of overall discomfort and slipperiness using Borg's CR-10 scale, four grip forces (#3 ~ #6 as shown in Figure 5.14) measured at the contact area in the hand. The experimental variables are summarized in Table 5.3.

Table 5.3. Experimental variables of the pilot study

Variables		Description	Unit
Independent	Handle type	- 5 levels (A, B, C, D, E)	N/A
Dependent	Torque	- Maximum exertion	Nm
	EMGs	- FDS - BB	nEMG (0 ~ 1)
	Subjective ratings	- Discomfort (overall) - Slipperiness	Borg's CR-10 (normalized)
	Grip force distribution	- Middle phalange (long finger) - Middle phalange (ring finger) - Metacarpal - Thenar	Normalized grip force (0 ~ 1)
	Wrist posture	- Ulnar deviation angle	Degree (º)

Analysis of variance (ANOVA) was performed on all dependent measures to investigate the effects of different screwdriver handle designs on maximum torque production capability, muscular activities, subjective ratings of discomfort and slipperiness, grip force distribution, and wrist posture, respectively. A post-hoc paired comparison test was used to further explore the statistical significance. Finally, correlation analysis was also utilized to evaluate the relationship between dependent variables. All statistical analyses were performed by MINITAB™ (release 13.1) statistical software.

5.2.2 Results of Pilot Study

Table 5.4 summarized the changes in dependent measures with respect to screwdriver handle designs using descriptive statistics such as mean and standard deviation.

Table 5.4. Summary of results (mean, standard deviation in parentheses)

Dependent measures		Screwdriver Handle type				
		A	B	C	D	E
Maximum Torque**		2.26 (0.44)	2.28 (0.36)	1.65 (0.22)	1.81 (0.17)	1.68 (0.14)
Normalized EMG	FDS**	0.81 (0.11)	0.76 (0.09)	0.89 (0.12)	0.80 (0.13)	0.90 (0.11)
	BB	0.76 (0.16)	0.82 (0.13)	0.67 (0.15)	0.67 (0.21)	0.81 (0.09)
Subjective Ratings	Discomfort**	0.31 (0.13)	0.24 (0.13)	0.73 (0.16)	0.67 (0.20)	0.68 (0.21)
	Slipperiness**	0.44 (0.14)	0.05 (0.09)	0.72 (0.17)	0.79 (0.19)	0.86 (0.18)
Grip force Distribution	#3[a] *	0.38 (0.22)	0.39 (0.21)	0.43 (0.25)	0.33 (0.18)	0.28 (0.24)
	#4[b]	0.36 (0.12)	0.36 (0.11)	0.40 (0.26)	0.30 (0.13)	0.32 (0.17)
	#5[c]	0.58 (0.27)	0.40 (0.11)	0.55 (0.09)	0.47 (0.26)	0.37 (0.17)
	#6[d] **	0.19 (0.22)	0.13 (0.16)	0.10 (0.11)	0.34 (0.35)	0.14 (0.13)
Wrist Angle	Ulnar deviation	29.6 (5.21)	28.8 (4.03)	27.0 (4.43)	26.1 (5.75)	25.7 (4.49)

Note * : Significant at $P < 0.05$
**: Significant at $P < 0.01$
3[a]: Middle phalanx area of middle finger
4[b]: Middle phalanx area of ring finger
5[c]: Metacarpal area of middle finger
6[d]: Thenar area.

Analysis of Variance (ANOVA)

As shown in Figure 5.2 and Table 5.5, the handle types of screwdriver had a statistically significant effect on maximum torque production (P < 0.001). However, change of maximum torque production capabilities was not statistically significant across subjects and trials.

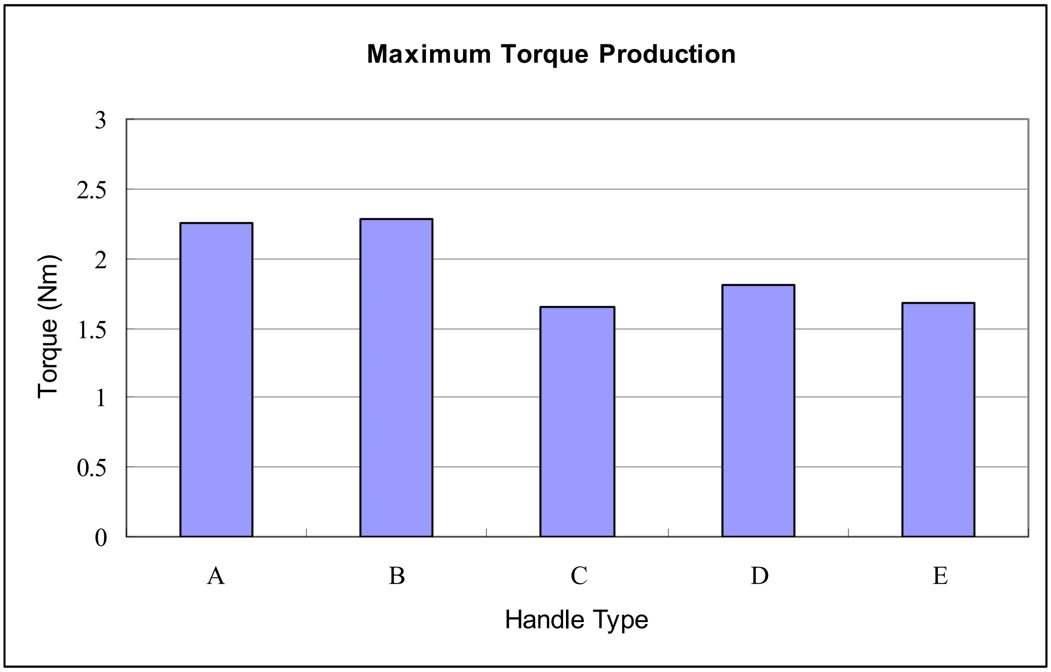


Figure 5.2. Results of maximum torque production

Table 5.5. Result of ANOVA for maximum torque production

Source	DF	SS	MS	F	P
Handle Type	4	3.15194	0.78799	10.01	0.000**
Subject	3	0.32584	0.10861	1.38	0.267
Trial	1	0.21609	0.21609	2.74	0.108
Error	31	2.44077	0.07873		
Total	39	6.13464			

The normalized EMG values of FDS and BB for the various handle types are shown in Figure 5.3. According to the result of ANOVA as shown in Table 5.6, the EMG activity of FDS differed significantly (P < 0.01) across the handle types while muscular activity of BB did not reflect any significant change due to handle types. Interestingly, based on the results of maximum torque production, a lower muscular exertion of FDS with a greater muscular exertion of BB was shown in using the handle type B.

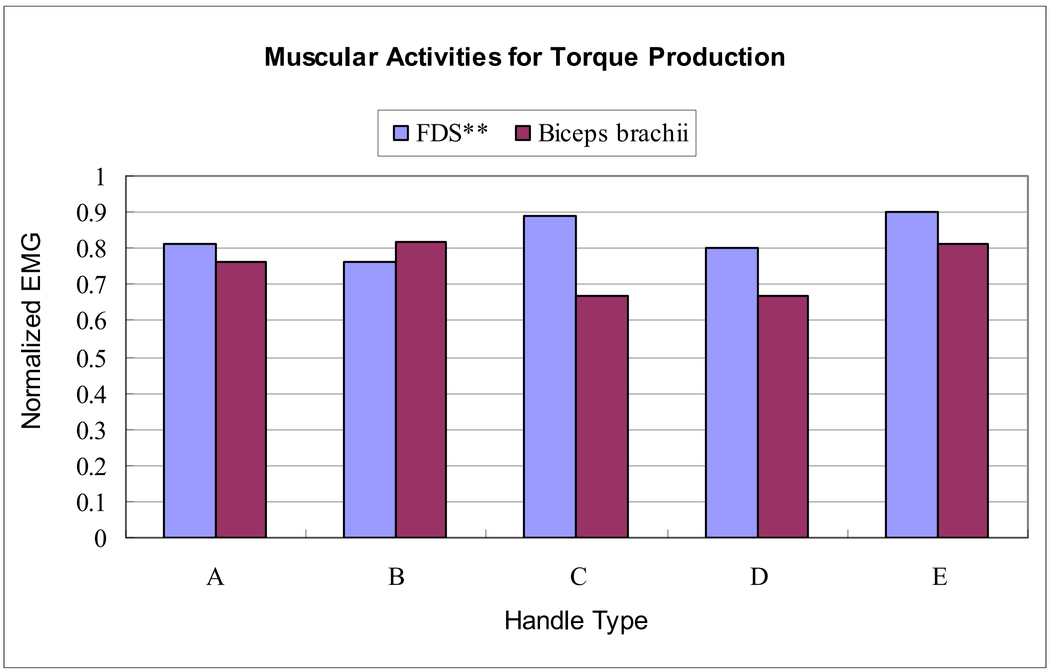


Figure 5.3. Results of normalized EMGs of FDS and BB

(**: Significant at P < 0.01)

Table 5.6. Result of ANOVA for normalized EMG (FDS)

Source	DF	SS	MS	F	P
Handle Type	4	0.11815	0.02954	4.45	0.006**
Subject	3	0.24498	0.08166	12.31	0.000**
Trial	1	0.00036	0.00036	0.05	0.817
Error	31	0.20571	0.00664		
Total	39	0.56920			

Figure 5.4 shows the normalized subjective ratings of overall discomfort and slipperiness averaged across the five handle types. These are on a scale of 0 ~ 1 with a lower value being more comfortable or acceptable. The results of ANOVA for discomfort (Table 5.7) and slipperiness (Table 5.8) indicated that the effects of handle types on the subjective ratings of overall discomfort and slipperiness were significant ($P < 0.001$). In this regard, it can be claimed that the handle type B is the most comfortable and most acceptable handle design in terms of overall discomfort and slipperiness.

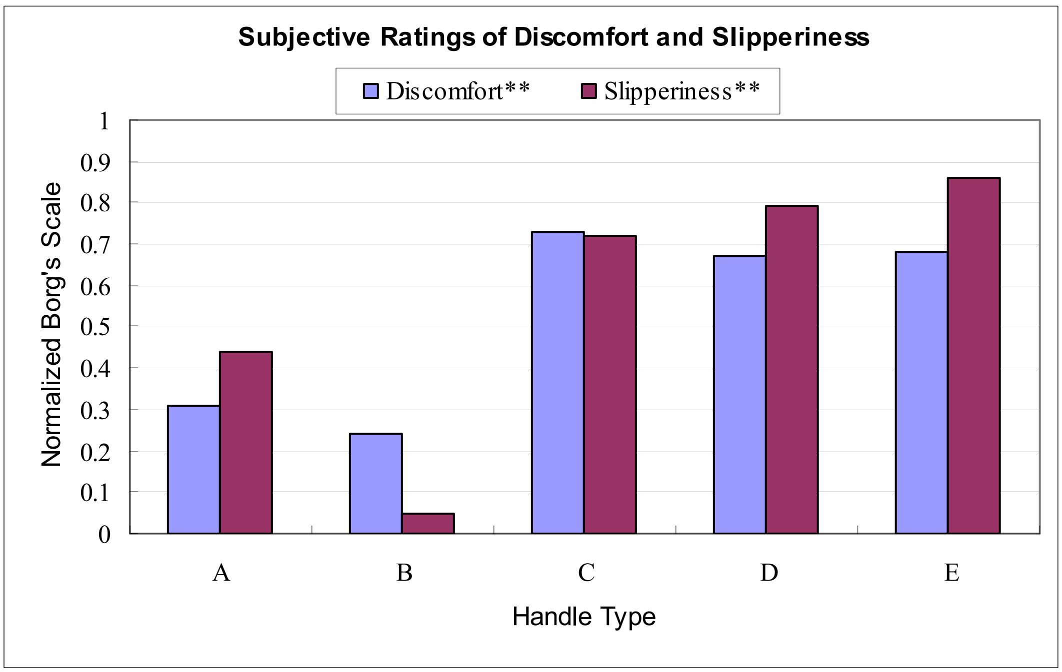


Figure 5.4. Results of subjective ratings on discomfort and slipperiness
(**: Significant at $P < 0.001$)

Table 5.7. Result of ANOVA for subjective discomfort ratings

Source	DF	SS	MS	F	P
Handle Type	4	1.67462	0.41866	16.15	0.000**
Subject	3	0.13869	0.04623	1.78	0.171
Trial	1	0.06806	0.06806	2.63	0.115
Error	31	0.80356	0.80356		
Total	39	2.68494			

Table 5.8. Result of ANOVA for subjective slipperiness ratings

Source	DF	SS	MS	F	P
Handle Type	4	3.53663	0.88416	39.92	0.000**
Subject	3	0.15319	0.05106	2.31	0.096
Trial	1	0.03306	0.03306	1.49	0.231
Error	31	0.68656	0.02215		
Total	39	4.40944			

According to the results of ANOVA (Table 5.9 and Table 5.10), the effects of handle types on the normalized grip forces measured at the area of middle phalanx of middle finger ($P < 0.05$) and thenar area ($P < 0.001$) were significant. However, the handle types did not have any significant effects on the normalized grip forces measured at the middle phalanx area of ring finger and metacarpal area. Although the difference of grip forces measured was not statistically significant across the handle types, it can be claimed that metacarpal area is the most compressed area while thenar area is the least compressed area in the hand. Furthermore, it should be emphasized that there was significant individual difference in terms of grip force ($P < 0.001$). Figure 5.5 illustrates the grip force distribution at the contact area in the hand.

Table 5.9. Result of ANOVA for grip force at the middle finger area

Source	DF	SS	MS	F	P
Handle Type	4	0.10292	0.02573	3.69	0.014*
Subject	3	1.51817	0.50606	72.62	0.000**
Trial	1	0.00048	0.00048	0.07	0.795
Error	31	0.21603	0.00697		
Total	39	1.83760			

Table 5.10. Result of ANOVA for grip force at the thenar area

Source	DF	SS	MS	F	P
Handle Type	4	0.28522	0.07131	5.86	0.001**
Subject	3	1.16222	0.38741	31.83	0.000**
Trial	1	0.02310	0.02310	1.90	0.178
Error	31	0.37732	0.01217		
Total	39	1.84787			

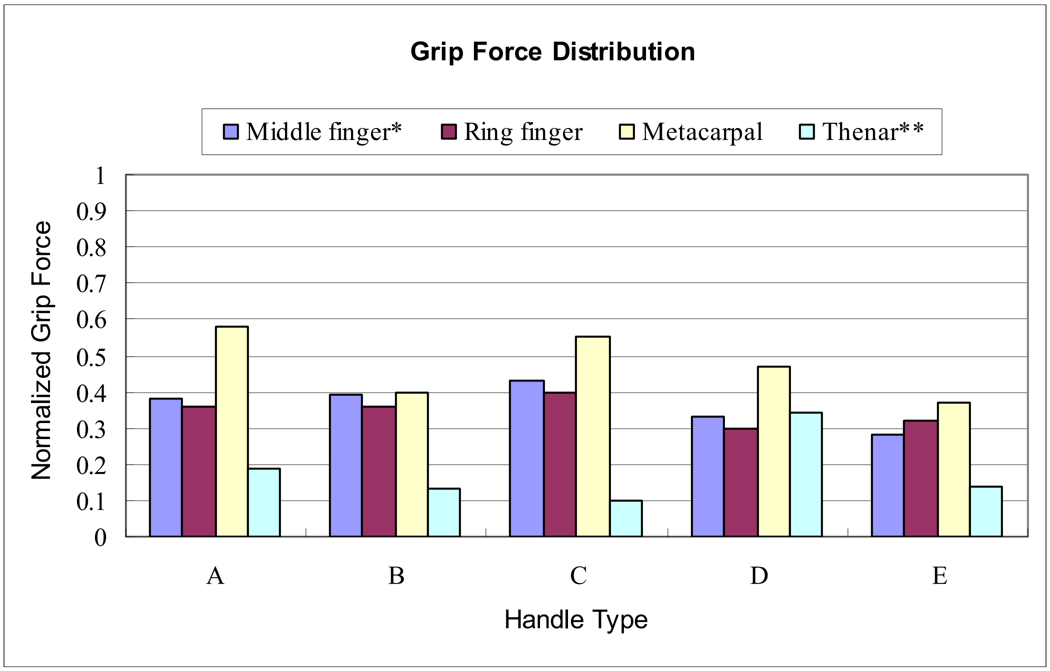


Figure 5.5. Results of grip force distribution
(*: Significant at P < 0.05, **: Significant at P < 0.01)

According to the result of ANOVA for wrist ulnar deviation angle, there was no significant difference of wrist posture during simulating screwdriving task.

Post-hoc Analysis (Tukey's Test)

For the post-hoc paired comparison analysis, a series of Tukey's tests were performed to further explore the statistical significance. The results of Tukey's test on the means of significantly different dependent measures are summarized in Table 5.11. The results of Tukey's test revealed that torque production capabilities of handle type B and A were significantly higher ($P < 0.05$) than other handle types. In addition, it can be claimed that handle type B is the most acceptable handle design in terms of subjective ratings of slipperiness.

Table 5.11. Results of Tukey's test on means for handle types

Responses	Handle Types (mean in parentheses)				
Maximum Torque	B (2.28)	A (2.26)	D (1.81)	E (1.68)	C (1.65)
EMG activity of FDS	E (0.90)	C (0.89)	A (0.81)	D (0.80)	B (0.76)
Subjective Ratings - Overall Discomfort	C (0.73)	E (0.68)	D (0.67)	A (0.31)	B (0.24)
- Slipperiness	E (0.86)	D (0.79)	C (0.72)	A (0.44)	B (0.05)

- Handle types underlined by the same line are not significantly different from each other ($\alpha = 0.05$).
- Means are ordered from highest to lowest.

Correlation Analysis

Finally, correlation analysis using Pearson's correlation coefficients (*r*) was performed in order to investigate the association between dependent measures of torque, EMGs, subjective ratings, and wrist ulnar deviation angle. Table 5.12 summarized the results of correlation analysis. According to the results, there was a close correlation between normalized EMG of FDS and wrist ulnar deviation angle. This result indicated that muscular activity of flexor muscle decreased as the wrist ulnar deviation angle increased. In addition, torque production capability correlated closely with muscular activity of FDS ($P < 0.01$) as well as subjective ratings of discomfort ($P < 0.01$) and slipperiness ($P < 0.01$), respectively. Interestingly, normalized EMG of BB correlated negatively ($P < 0.05$) with subjective discomfort ratings. However, there was no significant evidence of correlations between normalized EMG of FDS and subjective ratings of discomfort, and between normalized EMG of FDS and subjective ratings of slipperiness. However, subjective feelings of slipperiness significantly correlated with the subjective discomfort ratings ($P < 0.01$).

Table 5.12. Results of correlation analysis (Pearson correlation coefficient)

	Torque	EMG (FDS)	EMG (BB)	Wrist angle	Discomfort
EMG (FDS)	-0.423**				
EMG (BB)	0.167	0.064			
Wrist angle	0.330*	-0.664**	0.041		
Discomfort	-0.502**	0.191	-0.321*	-0.194	
Slipperiness	-0.499**	0.244	-0.211	-0.164	0.750**

Note: Significant at $P < 0.05$ (*), Significant at $P < 0.01$ (**).

5.2.3 Sample Size Determination

From the results of the pilot experiment, the number of participants to be recruited in the main study was determined by considering type I error rate (α), type II error rate (β), variability of measurement (σ), and expected difference between two treatment means (D). The parameter of equation was used to determine the sample size (Montgomery, 1997).

$$\Phi^2 = \frac{nD^2}{2a\sigma^2}$$

Given a minimum acceptable power of 0.80 with a significance level ($\alpha = 0.05$), an expected maximum difference ($D = 0.45$ Nm) determined by using the results of Tukey's test on mean torques for screwdriver handle types from the pilot experiment. The variability of measurement (σ = 0.31 Nm) was also based on the mean standard deviation of the torque production from the result of the pilot study. The result of power analysis was shown in Table 5.13. As a result, a minimum sample size of 13 participants was determined with statistical significance (α = 0.05).

Table 5.13. Result of power analysis for sample size determination

Sample size (n)	Parameters		Degree of freedom	Error		Power (1-β)
	Φ^2	Φ	a(n-1)	α	β	
7	1.475	1.215	30	0.05	0.507	0.493
8	1.686	1.298	35	0.05	0.435	0.565
9	1.896	1.377	40	0.05	0.369	0.631
10	2.107	1.452	45	0.05	0.310	0.690
11	2.318	1.522	50	0.05	0.258	0.742
12	2.529	1.590	55	0.05	0.213	0.787
13	2.739	1.655	60	0.05	0.174	**0.826**
14	2.950	1.718	65	0.05	0.142	0.859
15	3.161	1.778	70	0.05	0.114	0.886
16	3.371	1.836	75	0.05	0.092	0.909

5.2.4 Discussion

As mentioned earlier, the main objective of evaluation experiment was not to identify the optimum level of design characteristics such as shape, diameter, length, surface properties and materials of the handle but to present a comprehensive evaluation technique that can quantify the objective measures such as torque production, muscular activity, grip force distribution, and wrist posture as well as subjective aspects of users such as discomfort and slipperiness during screwdriving task so as to evaluate various handle designs. With regard to torque production, the results of existing screwdrivers in this pilot experiment were compatible with the recommendations of the previous studies in the literature as described in chapter 2.4. The handle types (C and E) that have smaller handle diameter than the recommended size of 30mm (Hall, 1997; Yakou et al., 1997) showed low torque production capability due to the reduced mechanical advantage, while handle types (B and A) with larger diameter produced significantly higher torque ($P < 0.05$) than other handle types. According to the results of correlation analysis, EMG analyses seemed not to support torque results in that EMG is an indirect measure of muscle forces. However, as mentioned earlier, there are a number of factors affecting torque production capability. Therefore, it is recommended that an efficiency measure (Torque/EMG) should be utilized in the main study. As expected, there was no significant difference of wrist posture in terms of ulnar deviation angle since there was no variant in terms of tool grip type and angle across the five handle designs tested in this pilot experiment.

With regard to user satisfaction, the participants in this pilot experiment had considerable complaint about discomfort and slipperiness in use of smaller and plastic handles. Although the objective measurement of friction on hand-handle interfaces was not available in this study, intuitively rubber material with softer grip would be preferred to hard plastic in terms of comfort and slipperiness. The result of correlation analysis indicated that there was a strong association between subjective ratings of discomfort and slipperiness ($r = 0.75$, $P < 0.001$). In this regard, subjective judgment used in the pilot experiment seemed a relevant and meaningful measure that showed the superiority of handle type B with a larger handle diameter and rubber surface material. Thus, user satisfaction by reducing slipperiness seems to be something that should be extensively investigated in the main study.

5.3 EXPERIMENTS

5.3.1 Participants

A total of fifteen right-handed volunteers were recruited from the student population of the Pennsylvania State University and they participated in both experimentations and subjective evaluation using a product-interactive questionnaire. The number of participant was determined with statistical significance calculated by result of pilot experiment (n=15, Power = 0.886). There was a diversity of anthropometric sizes, ages, and gender except hand laterality. All participants were in good health and have no history of upper extremity pain or musculoskeletal injuries, which can limit their physical activities. Thus, they were screened for any hand and wrist injuries or any hand surgery using the participant screening questionnaire in Appendix G. A coding scheme was used to maintain confidentiality of participants (e.g. participant 1= P01). Participants were compensated for their time and participation. In addition, they were allowed to withdraw from the study at any time. The following anthropometric characteristics of the experimental subjects were measured and listed. Descriptions of each measure were adapted from the established anthropometry literature (Webb Associates, 1978).

- Height (cm): vertical distance from the top of the head to the floor
- Weigh (kg): body weight with light cloth
- Hand length (cm): distance from the base of the hand to the top of middle finger measured along the long axis of the hand
- Hand breadth (cm): breadth of the hand as measured across the distal ends of the metacarpal bones

- Elbow height (cm): vertical distance from the floor to the lower edge of the hand while the upper arm is put downward naturally with the elbow bending at a right angle, palm inside and forearm stretched forward horizontally.

After screening procedure, a total of 15 participants including ten males and five females participated in both experimentations and questionnaire survey. The detailed information about participants was summarized in Table 5.14.

Table 5.14. Summary of the participants' characteristics

Participant code	Demographics			Anthropometry				
	Age (yr)	Gender	Hand laterality	Height (cm)	Weight (kg)	Hand length (cm)	Hand breadth (cm)	Elbow height (cm)
P01	26	M	Right	172	74.5	18.5	8.8	103.0
P02	35	M	Right	174	65.0	17.8	8.3	108.2
P03	29	M	Right	173	79.0	18.3	8.4	107.5
P04	29	M	Right	182	73.0	19.8	9.1	114.5
P05	25	F	Right	162	42.0	15.2	6.8	102.5
P06	26	M	Right	167	60.5	17.4	8.4	100.0
P07	27	M	Right	178	70.0	17.9	8.6	107.7
P08	32	M	Right	184	78.0	19.5	9.1	113.0
P09	34	M	Right	175	66.0	18.2	8.1	103.0
P10	28	M	Right	176	65.0	18.5	8.8	106.0
P11	27	F	Right	172	55.0	18.1	7.4	109.5
P12	34	M	Right	178	75.0	19.0	8.8	109.0
P13	26	F	Right	168	59.0	17.5	8.0	105.0
P14	34	F	Right	160	54.4	16.9	7.4	102.0
P15	18	F	Right	157	48.9	16.6	7.4	98.5
Descriptive statistics	Mean (age: 28.7yrs)			171.9	64.49	17.83	8.01	104.4
	Standard Deviation			7.82	11.01	1.16	0.70	4.57
	Minimum			157.0	42.0	15.2	6.8	98.5
	Maximum			184.0	79.0	19.8	9.1	114.5

5.3.2 Experimental Tasks

Maximum Torque Task

Participants were asked to apply a series of isometric maximum torque exertions to a Phillips head screwdriver with its bit inserted into the female to female socket adapter fitted onto the male square drive of the torque tester. With respect to the evaluation of screwdriver handle designs, the following two factors varied during the simulated screwdriving task. The detailed information about these factors was described in the following experimental design section.

- Handle type : five different screwdrivers in terms of handle characteristics
- Rotation direction: supination (clockwise) and pronation (counter clockwise)

Constant Torque Task

Since one of the objectives of this study is to evaluate the optimal screwdriver handle design that can minimize muscular effort while producing a desired level of torque output, it is needed to simulate real working situation in practice as close as possible. In fact, users may not be required to exert their maximum muscular capacity in their daily uses of screwdriver. In this respect, it could be a better way for evaluating the handle designs to compare the muscular efforts required to produce a constant level of torque output. The level of torque requirement was determined with respect to the published torque production data associated with screwdriving task. Since the value of maximum torque strength from the literature (described in Table 5.15) varied greatly with regard to various factors such as handle characteristics, task condition, and individual differences, it might be difficult to determine a constant level of torque requirement to be used in this experiment. In this experiment, a constant level of torque exertion was determined as 0.5 Nm in order to encompass the range of published maximum torque strength data extracted from the almost same experimental conditions (standing, elbow height, horizontal tool orientation) compared to experimental setup in this study. This value of 0.5 Nm is also below the range of maximum acceptable torque (1.25 Nm and 1.30 Nm) suggested by Armstrong et al. (1999) and Ciriello et al. (2002), respectively. The same participants who participated in the maximum torque experiment were employed in a constant torque task. In addition, the same experimental variables of the maximum torque experiment except torque production were tested in the constant torque experiment.

Table 5.15. Maximum torque strength data from the published literature

Reference	Tool Type (dimension: cm)	Torque Strength (Nm.)		Direction of Rotation
		Male	Female	
Mital (1986)	4 different types	N=36	N=14	
	Type 1 (L:15.5, D:3.5)	4.42 (1.53)	3.08 (1.12)	Supination
	Type 2 (L:18.0, D:2.3)	2.16 (1.04)	1.69 (0.68)	Supination
	Type 3 (L:24.0, D:1.8)	2.92 (1.09)	2.29 (0.89)	Supination
	Type 4 (L:25.3, D:3.0)	3.85 (1.27)	2.75 (1.26)	Supination
Mital and Sanghavi (1986)	2 different types	N=30	N=25	
	Type 1 (L:15.2, D:2.9)	3.24 (N/A)	2.11 (N/A)	Supination
	Type 2 (L:5.1, D:3.7)	3.71 (N/A)	2.42 (N/A)	Supination
Habes and Grant (1997)	2 different types	N=15	N/A	
	Type 1 (D: 2.9)	3.16 (N/A)		Supination
	Type 2 (D: 3.7)	3.89 (N/A)		Supination
Mital and Kumar (1998)	2 different types	N=30	N=25	
	Short (N/A)	4.3 (1.7)	3.0 (1.2)	Supination
			3.4 (1.1)	Pronation
	Long (N/A)	3.0 (1.0)	1.8 (0.6)	Supination
			2.1 (0.6)	Pronation
Strasser and Wang (1998)	6 different types	N=10	N/A	
	Overall average (N/A)	3.8 (N/A)		Supination
		4.6 (N/A)		Pronation

Note: L (length), D (diameter), standard deviations of torque strength are in parenthesis

5.3.3 Experimental Design

The experimental designs used in both torque exertion tasks are a completely randomized design. In two experiments, handle type and rotation direction are fixed-effects factors and subject is a random-effect factor. Five different types of screwdriver handle design were prepared and they had different characteristics of hand-handle interface in terms of shape, size, and surface characteristics. For simulating the screwdriving task, two different levels of forearm rotation direction (supination: clockwise rotation and pronation: counter-clockwise rotation) were selected. In nature, the use of a screwdriver has two purposes; insert a screw and unscrew a tightened screw. Driving a screw is performed by outward forearm rotations (supination) of the right arm while inward forearm rotations (pronation) are required to unscrew a screw.

Other factors affecting torque strength were controlled via experimental procedure. For instance, the types of grip employed in screwdriving task vary widely with respect to force and precision requirement of the task (Kadefors et al., 1993). Based on the published hand grip classification scheme as described in Appendix B (Napier, 1956; Kadefors et al., 1993; Yun, 1994), the following definition of precision grip was controlled for the experiment and shown in Figure 5.6.

- The precision grip (diagonal hand grip): an intermediate stage between power grip and pinch. While the hand postures are maintained as a power grip posture, the action is very similar to pinch tasks. Force is applied on the finger tips for holding the grip and additional force is applied through the thumb and index finger for turning the screwdriver to one direction (clockwise or counter clockwise).

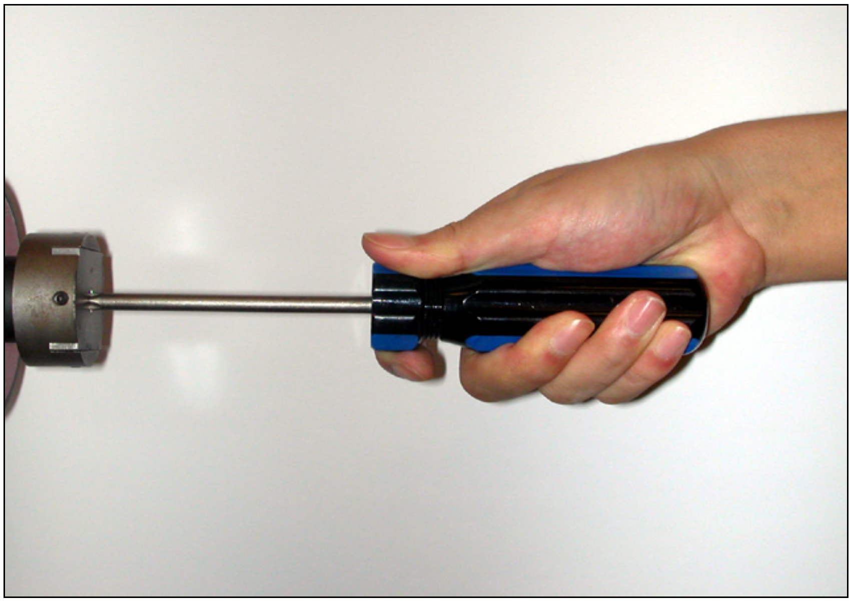


Figure 5.6. Precision grip of the right hand employed in screwdriving task

For both maximum torque and constant torque experiments, three repetitions for each of 10 different experimental conditions (5 handle designs × 2 rotation directions) were run in a completely randomized experimental design, respectively. As dependent variables, the following measurements were collected and analyzed on a group of subjects.

- Torque production was monitored and measured by electronic torque tester (ARM64-632, Armstrong Tools) for maximum torque task and a purpose built torque measurement system for constant torque task.
- Electromyograms (EMGs) of appropriate muscle groups were recorded by MyoScan-Pro™ EMG sensors (SA9401M, Thought Technology) and the FlexComp Infiniti™ data collection system (Thought Technology). These EMGs are an indirect measure of the muscular exertion in use of screwdriver.

- Grip force distribution in the hand was investigated using force sensing resistors (FlexiForce™ A201, Tekscan). This data provided a quantitative measure of the hand-handle interface.
- Wrist posture in terms of ulnar deviation angle was monitored by biaxial electrogoniometer (XM110, Biometrics). This data provided a quantitative measure of the hand tool-induced postures.
- Subjective ratings of discomfort were collected using Borg's CR-10 rating scale (Borg, 1990) associated with hand map.

While torques exerted during the trials of maximum torque task were collected by readings of electronic torque tester (ARM64-632, Armstrong Tools), BioGraph Infiniti™ software (version 2.1, Thought Technology) was utilized to monitor and acquire the data from EMG, electrogoniometer, and FSRs, simultaneously. Experimental variables of both experiments are summarized in Table 5.16 and Table 5.17, respectively.

Table 5.16. Experimental variables of maximum torque task

Variables		Description	Unit
Independent	Screwdriver type	- 5 levels (A, B, C, D, E)	N/A
	Rotation direction	- 2 levels (supination/pronation)	N/A
Dependent	Torque	- Maximum torque production	Nm
	EMGs	- FDS - BB	Normalized EMG (0 ~ 1)
	Subjective ratings	- Discomfort (6 areas & overall) - Slipperiness	Normalized Borg's CR-10
	Grip force Distribution	FSR (6 areas in grip/finger) - Thumb - Index finger - Middle phalange (long finger) - Middle phalange (ring finger) - Metacarpal - Thenar	Normalized grip force (0 ~ 1)
	Wrist posture	- Ulnar deviation angle	Degree (°)

Table 5.17. Experimental variables of constant torque task

Variables		Description	Unit
Independent	Screwdriver type	- 5 levels (A, B, C, D, E)	N/A
	Rotation direction	- 2 levels (supination/pronation)	N/A
Dependent	EMGs	- FDS - BB	Normalized EMG (0 ~ 1)
	Subjective ratings	- Discomfort (6 areas & overall) - Slipperiness	Normalized Borg's CR-10
	Grip force Distribution	FSR (6 areas in grip/finger) - Thumb - Index finger - Middle phalange (long finger) - Middle phalange (ring finger) - Metacarpal - Thenar	Normalized grip force (0 ~ 1)
	Wrist posture	- Ulnar deviation angle	Degree (°)

5.3.4 Instrumentation and Apparatus

Screwdrivers

According to the published literature, functional characteristics of screwdriver mainly influence the workload and the risk of injuries so that the selection of screwdrivers is very important. One interesting research finding showed that Phillips type screws demanded 36% higher axial force compared to TORX screws (Arnkvaern, 1985)., For the experimental investigation, five screwdriver handle designs were selected from the various Phillips head screwdrivers. Each screwdriver differs from another in terms of handle size, weight, handle shape, and handle surface properties. The characteristics of screwdrivers employed in the experimentation are summarized in Table 5.18 and shown in Figure 5.7.

Table 5.18. Characteristics of screwdrivers

Code	Handle Characteristics	Surface Properties		Size (cm)		
		Finish	Material	Shaft length	Handle length	Handle diameter
A	Pentagonal round shank Black (red)/black tip	6 grooves /Brand	Plastic	10.1	11.3	3.1
B	Tri-lobe round shank Grey (blue)/ black tip	Barcode/Hole	Dual plastic	10.2	11.5	3.7
C	Tri-lobe round shank Blue/Black/ black tip	Hole	Dual plastic	10.2	12.5	3.3
D	Round shank Black (blue)/black tip	Hole/Interlock ing finger area	Plastic/ Sticky area	10.1	11.1	3.3
E	Octagonal round shank only Black (yellow)/black tip	8 small indentations	Rubber over plastic	10.2	10.8	3.3

A B C D E A B C D E

(a) (b)

Figure 5.7. Five different screwdriver designs
: a) front view, b) cross-sectional view

<u>Workstation</u>

The experimental environment simulates standing work. An adjustable workstation was used to alter the work surface height as necessary to accommodate elbow height of participants so as to allow for a standard working posture between different sized participants in a laboratory setting. According to the published recommendations (Putz-Anderson, 1988; Habes and Grant, 1997; Chaffin et al., 1999), work surfaces should be positioned at or slightly below elbow height. Figure 5.8 illustrates the height-adjustable workstation for simulating screwdriving task in the experiment.

Figure 5.8. A height-adjustable workstation for simulating screwdriving task

<u>Data Collection System</u>

Regarding experimental investigation, during screwdriving task simulation, five measurement instruments were utilized to investigate physiological and psychophysical responses in the experiment; EMG, Torque, grip force distribution, wrist posture in terms of ulnar deviation angle, and perceived discomfort of the participant using a questionnaire with hand map. Among them, EMG, grip force distribution, and wrist deviation angle were gathered via FlexComp Infiniti™ data collection system (Thought Technology). FlexComp Infiniti™ system can collect the data up to ten sensors. FlexComp Infiniti™ system consists of three hardwares (FlexComp Infiniti™ encoder unit, TT-USB interface unit, and fiber optic cable) and operating software (BioGraph Infiniti™ Ver. 2.1.). The FlexComp Infiniti™ encoder is a multi-modality device for real time data acquisition with ten channels. The FlexComp Infiniti™ encoder can render a wide and comprehensive range of objective physiological signs used in ergonomics, clinical observation, and biofeedback. Figure 5.9 illustrates the FlexComp Infiniti™ data collection system. The detailed specifications and features of FlexComp Infiniti™ system are summarized in Appendix C.1.

Figure 5.9. FlexComp Infiniti™ data collection system (Thought Technology)

EMG Measurement System

Electromyography (EMG) study on human muscle has extensively been used to study the function of hand muscles in use of hand tool (Habes and Grant, 1997). In the experiment, sets of MyoScan-Pro™ sensors (Thought Technology) and disposal Ag/AgCl electrodes were used for EMG measurement. The MyoScan-Pro™ sensors are the surface EMG sensors that can be placed on the skin surface. The MyoScan-Pro™ sensors can automatically convert the EMG signal to a root mean square (RMS) value. The EMG signals collected by MyoScan-Pro™ sensors are integrated by the FlexComp

Infiniti™ encoder and BioGraph Infiniti™ software. Since the MyoScan-Pro™ sensor uses internal electronic circuit to perform RMS rectification within the sensor, it is likely that slight offsets can occur in the sensor reading. For this reason, it is necessary to calibrate the MyoScan-Pro™ sensors before the measurement. Calibration can be simply done by connecting a zeroing cable to the FlexComp Infiniti™ encoder while recording. While zeroing MyoScan-Pro™ sensors, the reading can be adjusted within the operating software (BioGraph Infiniti™ Ver. 2.1). Appendix C.5 summarizes the detailed technical specifications and features of MyoScan-Pro™ sensors. Figure 5.10 shows MyoScan-Pro™ sensors and Ag/AgCl surface electrodes.

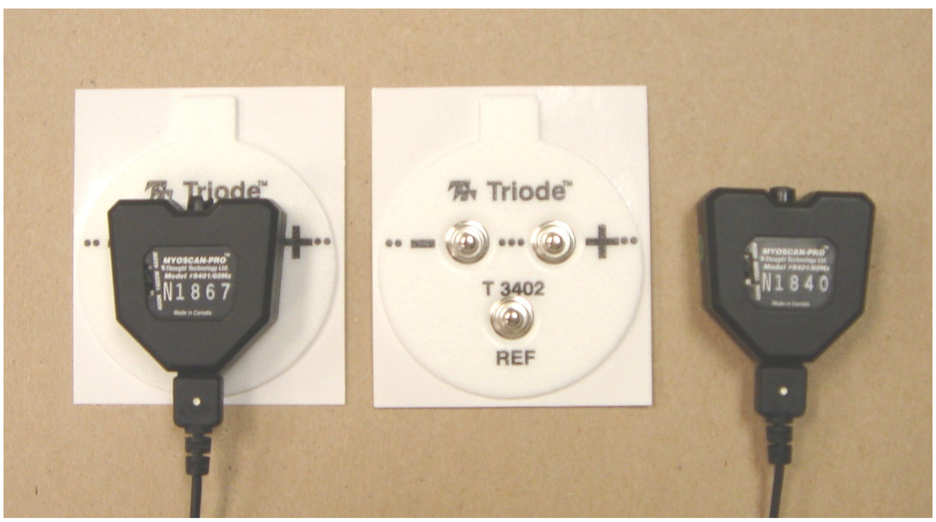


Figure 5.10. MyoScan-Pro™ EMG sensors and surface electrodes

The selection of muscles groups for investigating muscular activity in torque exertion tasks varied across the published literature with respect to their study objectives and applications. According to the literature summarized in Table 5.19, among the forearm muscles groups (Appendix A.2), the following muscle groups were identified as the principal forearm muscle groups, which are involved in forearm rotation actions in screwdriving task:

- The flexor muscle groups as grip musculature
- The extensor muscle groups as grip musculature
- The biceps brachii as powerful supinator

However, due to the limited number of channel of FlexComp Infiniti™ data collection system, two principal forearm muscle groups were chosen in this experimental investigation since they are expected to be intensively involved in supination/pronation actions with screwdrivers. Based on the literature (Strasser, 1991), flexor digitorum superficialis (FDS) and biceps brachii (BB) were used to explore electromyographic activities of appropriate muscle groups during the simulated screwdriving task. Surface electrodes were placed in pairs over each muscle groups to be investigated. Placement of the electrodes was determined as follows, based on the standard techniques provided by literature (Zipp, 1982):

- Flexor digitorum superficialis (FDS): one fourth of a line from medial epicondyle of the humerus to the skin fold at the wrist
- Biceps brachii (BB): one third of a line from tendon of the biceps muscle in the cubital fossa to the acromion

Table 5.19. Summary of EMG studies on forearm rotation task

Reference	Measure	Muscle groups	Applications
Mital and Channaveeraiah (1988)	EMG Force/torque	- Flexor muscles - Extensor muscles	Screwdriver
Örtengren et al. (1991)	EMG Torque	- Extensor carpi radialis brevis - Flexor digitorum superficialis - Trapezius pars descendens	Wrist twisting
Strasser (1991)	EMG Torque	- Flexor digitorum superficialis - Biceps brachii	Screwdriver
Wang and Strasser (1993)	EMG Torque	- Flexor digitorum superficialis - Brachioradialis - Biceps brachii - Deltoideus p. clavicularis	Screwdriver
Kendall et al. (1994)	EMG Torque	- Flexor digitorum superficialis - Extensor digitorum - Biceps brachii	Screwdriver
Mital et al. (1994)	EMG Force/torque	- Flexor muscles - Extensor muscles	Screwdriver (with glove)
Habes and Grant (1997)	EMG/Torque	- Flexor digitorum superficialis - Flexor pollicis longus - Extensor digitorum - Triceps brachii - Anterior deltoid - Biceps brachii	Screwdriver
Strasser and Wang (1998)	EMG Torque	- Flexor digitorum superficialis - Brachioradialis - Biceps brachii - Deltoideus p. clavicularis	Screwdriver
Naito et al. (2002)	EMG	- Brachioradialis - Biceps brachii - Triceps brachii	Supination
O'Sullivan and Gallwey (2002)	EMG	- Pronator teres - Pronator quadratus - Extensor carpi radialis brevis - Brachioradialis - Biceps brachii - Mid deltoid	Supination Pronation

Torque Measurement System

For the maximum torque experiment, torque output was measured with a portable electronic torque tester (ARM64-632, Armstrong Tools). Electronic torque tester can hold the highest torque value applied to the tester in each trial using peak hold data mode. For measuring torque production, the bit of screwdriver to be tested was placed on the female to female socket adapter fitted onto the male square drive of the torque tester. Figure 5.11 shows a picture of electronic torque tester. The detailed technical specifications and features of electronic torque tester are summarized in Appendix C.2.

Figure 5.11. Electronic torque tester (ARM64-632, Armstrong Tools)

Regarding the constant torque experiment, torque output was monitored and recorded using a purpose built torque measurement system. The torque measurement system consists of a purpose built strain gauge, digital indicator (3270, Daytronic Corporation), and strip-chart recorder (Linear, Serco). Voltage signals from the strain gauge are interfaced with the strip-chart recorder (Linear, Serco) via digital indicator so that torque signals are configured within strip-chart recorder and then can display the torque output on the recorder in real time. Figure 5.12 shows a picture of the purpose built torque measurement system.

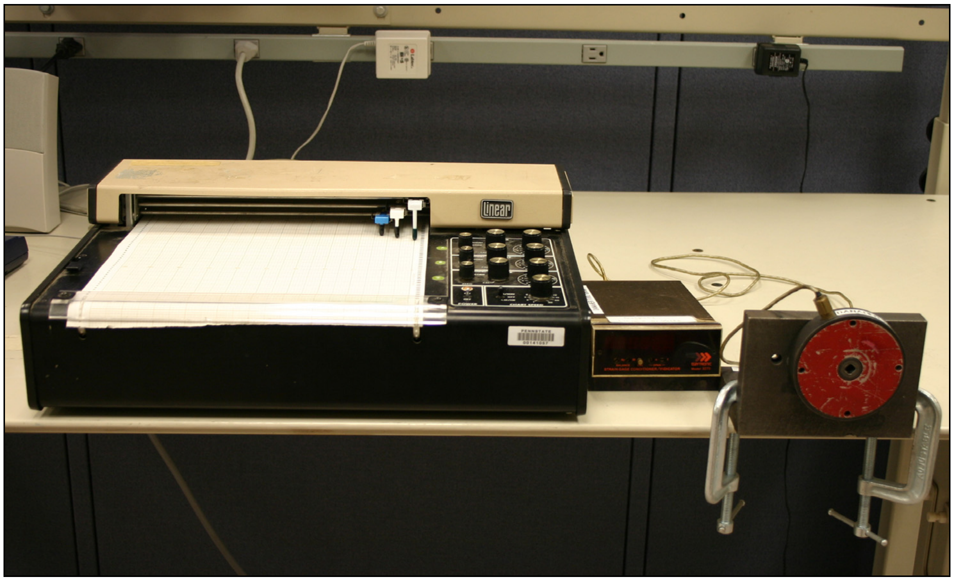


Figure 5.12. A purpose built torque measurement system for constant torque task
(Strip-chart recorder, digital indicator, and strain gauge from left to right)

Grip Force Distribution Measurement System

Since a conductive polymer sensor that can be attached to the palmer surface of the hand has been developed (Jensen et al., 1991), force sensitive resistors (FSRs) have been alternatives to measure force and pressure distributions at the hand-handle interface (Fellows and Freivalds, 1989; Yun et al., 1992; Yun and Freivalds, 1995; Hall, 1997; Kong and Freivalds, 2003; Kong and Lowe, 2003). The published literature as above mentioned has demonstrated that the FSR is a simple, relatively inexpensive, and durable force measurement device compared to load cells and strain gauge devices. FSRs also have made it possible to measure the force distribution pattern in the hand during various activities. Furthermore, FSRs have been well suited for the evaluation of the force or pressure distributions associated with different handle shapes and textures (Fellows and Freivalds, 1989; Yun et al., 1992; Yun and Freivalds, 1995; Hall, 1997; Chang et al., 1999; McGorry, 2001).

In this study, the same type of FSRs, FlexiForce™ resistance sensor (A201, Tekscan) was utilized since its flexibility and reliability of force measurement has been successfully demonstrated in the area of ergonomics (Park, 1999; Jang, 2002). Figure 5.13 shows a picture of FlexiForce™ resistance sensor. The detailed information about specifications, features, and calibration of FlexiForce™ sensor are described in Appendix C.3.

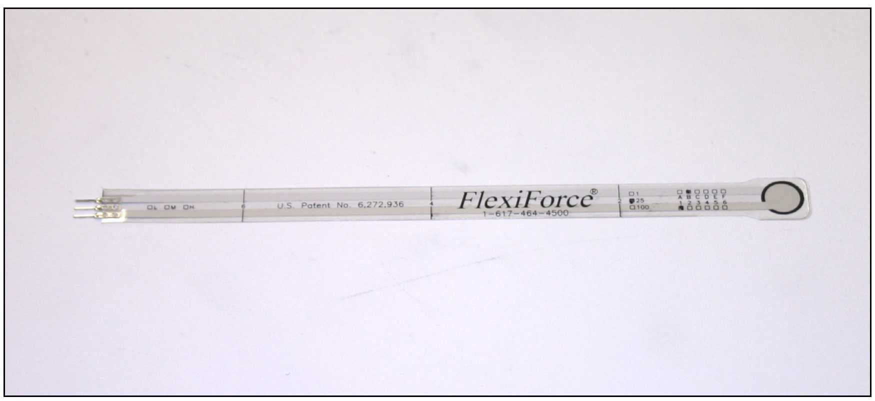


Figure 5.13. FlexiForce™ resistance sensor (A201, Tekscan)

When a screwdriver is used to produce a torque about the long axis, a large tangential or shearing force component might be expected at the hand-handle interface. The distribution and direction of application of gripping forces can vary due to the shape of handle, size of handle (length, diameter), the type of grip employed, and individual differences such as hand size. According to the published literature, screwdriver gripping forces were not evenly distributed along the long axis of the handle (Yun, 1994; Hall, 1997). Their findings indicated that force distribution pattern is required to investigate the high local force in the hand for the evaluation of the hand-handle interface.

In this study, a portable hand-handle force distribution measurement system was developed by overlaying force sensing resistors (FSRs) to measure contact forces between hand and handle. After following the procedures utilized by Fellow and Freivalds (1991), a contact area of hand-handle interface can be obtained by grasping a screwdriver handle treated with a water-soluble paint. Due to the limitation of channels available in FlexComp Infiniti™ data collection system, it was necessary to carefully determine the limited number of locations of FSRs on the contact parts of the hand. Based on the simple test, a total of six locations were determined as shown in Figure 5.14. These locations to be attached with FSRs were supported by the published grip force distribution data in use of screwdrivers (Yun, 1994; Hall, 1997).

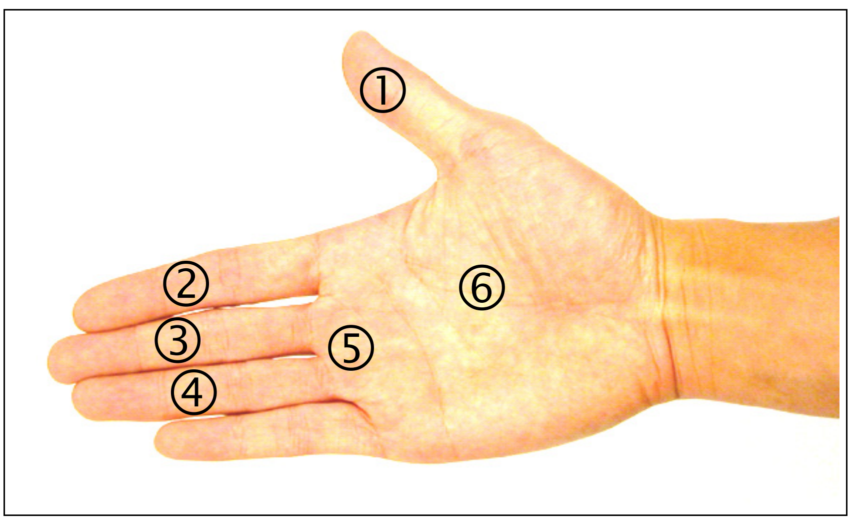


Figure 5.14. Six locations of FSRs on the contact area in the hand

Wrist Posture Measurement System

One of the most common complaints in using hand tools is biomechanical stress on the wrist due to the awkward postures such as ulnar deviation. While repetitive ulnar deviation is combined with forceful supination, it may inflame wrist tendons and can cause significant hand pain as well as tenosynovitis (Armstrong et al., 1982; Putz-Anderson, 1988). Hence, the postural stress on the wrist combined with forceful exertion should be monitored during work (Kadefors et al., 1993). In this respect, in order to investigate postural stress on the wrist in use of hand tools, a number of researchers have commonly utilized biaxial electrogoniometer for measuring the wrist joint motions such as flexion/extension and radial/ulnar deviation simultaneously. Over the last decades, the use of electrogoniometer has been demonstrated as a simple, relatively inexpensive, and objective measurement of wrist posture (Nicole 1987; Ojima et al., 1991; Hansson et al., 1996; Buchholz and Wellman, 1997).

In this study, a flexible biaxial electrogoniometer (XM110, Biometrics) was used to continuously monitor and record the wrist deviation angle in using a screwdriver. As followed by published literature (Buchholz and Wellman, 1997), an electrogoniometer was attached to the participants' right wrist using two points; the third metacarpal and the dorsal center of the wrist. Figure 5.15 shows a picture of electrogoniometer mounted on a wrist. The detailed technical specifications and features of biaxial electrogoniometer are summarized in Appendix C.4.

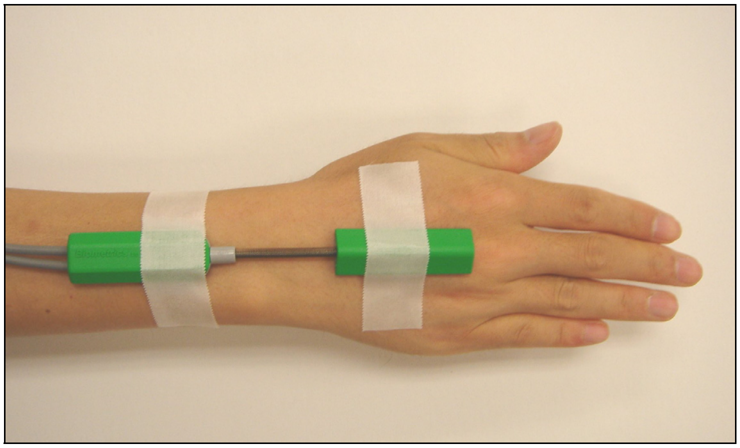


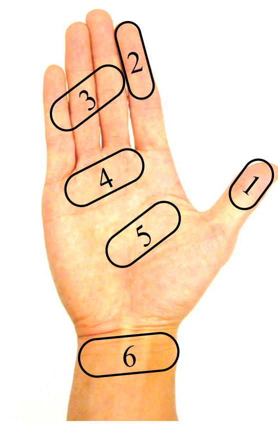
Figure 5.15. Biaxial electrogoniometer mounted on the wrist

Discomfort Measurement System

Participants' perceived ratings on discomfort and handle slipperiness in use of screwdriver were investigated for a qualitative measure of the hand-handle interface. These subjective ratings were correlated with the aforementioned objective measures such as Torque, EMG, grip force distribution, and wrist deviation angle. For a purpose built discomfort measurement system, a questionnaire using the Borg's CR-10 scale (Borg, 1990) combined with hand map was developed and utilized to investigate the Participant's perceived discomfort at six hand/wrist regions of hand map in use of each screwdriver handle design (Appendix C.6).

Level of discomfort at each hand region was rated with the Borg's CR-10 rating scales. For the data analysis, Participants' discomfort ratings were normalized by the maximum ratings for each participant in order to reduce the effect of individual variations (Chang et al., 1999; O'Sullivan and Gallwey, 2002). Based on the published grip force distribution data associated with screwdriving task (Yun, 1994; Hall, 1997), six regions (thumb, index finger, middle phalange of fingers, metacarpals, thenar, and wrist) in the hand map was determined to be utilized for subjective discomfort ratings as shown in Table 5.20.

Table 5.20. Subjective ratings using Borg's CR-10 scale combined with hand map

<table>
<tr><th colspan="2">Criteria</th><th>Rating</th><th>Rating Scales</th><th>Hand Map</th></tr>
<tr><td rowspan="6">Area code</td><td>1 Thumb</td><td></td><td rowspan="8">0. No discomfort
0.5 Barely noticeable discomfort
1. Very mild discomfort
2. Mild discomfort
3. Moderate discomfort
4.
5. Strong discomfort
6.
7. Very strong discomfort
8.
9.
10. Unbearable discomfort</td><td rowspan="8">
</td></tr>
<tr><td>2 Index finger</td><td></td></tr>
<tr><td>3 Middle phalange</td><td></td></tr>
<tr><td>4 Metacarpal</td><td></td></tr>
<tr><td>5 Thenar</td><td></td></tr>
<tr><td>6 Wrist</td><td></td></tr>
<tr><td colspan="2">Overall discomfort</td><td></td></tr>
<tr><td colspan="2">Slipperiness</td><td></td></tr>
</table>

5.3.5 Experimental Procedure

At the beginning of each experiment session, all participants were provided with a brief description of the goals and procedures of the experiment and informed consents were obtained. A coding scheme was used to maintain anonymity of participants (e.g. participant 1= P01). Using a questionnaire (Appendix G), the participant's demographic information (age, gender, musculoskeletal disorder history of the upper extremities) was surveyed. Then, anthropometric data (height, weight, elbow height, hand length, hand breadth) of participant were measured. The work surface height for the simulated screwdriving task was individually adjusted to each participant's elbow height in such a way that the longitudinal axis of the screwdrivers was aligned with the participant's forearm.

For each trial, participant was asked to stand in front of the workstation with the handle positioned in a frontal plane. Participant was also instructed to grip the handle with precision grip, and to turn the handle in a clockwise (supination) or counter clockwise (pronation), with elbow angle at approximately 90º with screwdrivers. While performing experimental tasks, participants were not permitted to use their left hand to guide or support the shaft of the screwdriver. All participants were asked to use the grip force distribution measurement system, which was attached with 6 FSRs to evaluate grip force distributions in the hand. After shaving and scrubbing the recording muscle sites with alcohol, disposal Ag/AgCl surface electrodes were attached to the recommended locations for the selected muscles in the literature (Zipp, 1982).

Next, biaxial electrogoniometer was attached on a participant's right wrist and hand using two points, the third metacarpal and the dorsal center of the wrist (Buchholz and Wellman, 1997). Simple calibration procedures for zeroing of EMGs, electrogoniometer, and FSRs were performed using BioGraph Infiniti™ software before each trial.

For the maximum torque task, participants were asked to exert as much torque as possible for 3-5 seconds as followed by the established procedure (Caldwell et al., 1974). Electromyograms (EMGs) of the selected muscle groups, grip force distribution in the hand, and wrist deviation angle were recorded by the FlexComp Infiniti™ data collections system. At the same time, the readings of maximum torque output were obtained by electronic torque tester. Maximum voluntary torque exertion was repeated three times for each experimental condition in random order.

For the constant torque task, participants were asked to exert a constant level of torque (0.5Nm) for 5 repetitions during each trial in order to simulate real screwdriving task while monitoring the level of torque production displayed by strip-chart recorder. EMGs of the selected muscle groups, grip force distribution in the hand, and wrist deviation angle were recorded by the FlexComp Infiniti™ data collections system. At the same time, the level of torque exerted was continuously monitored and recorded by a purpose built torque meter and strip-chart recorder. A trial of constant torque exertion was repeated three times for each experimental condition like maximum torque task.

After finishing each trial of two experimentations, subjective ratings of perceived discomfort were evaluated using Borg's CR-10 rating scale associated with hand maps. Regarding the evaluation of perceived discomfort in using a screwdriver, it has been reported that discomfort ratings can be dominated by impressions of torque performance (Magill and Konz, 1986; Strasser, 1991). Therefore, during maximum torque experiment, the torque output of each trial was not shown to subjects in order to avoid this transfer effect. Each participant was allowed at least 2 minutes resting time between trials so as to recover from the onset of fatigue (Caldwell et al., 1974). A total of 30 trials (5 screwdrivers × 2 rotation directions × 3 trials) for each experimentation were completely randomized. Figure 5.16 shows the schematic diagram of experimental setup and illustrates a picture of experimental trial.

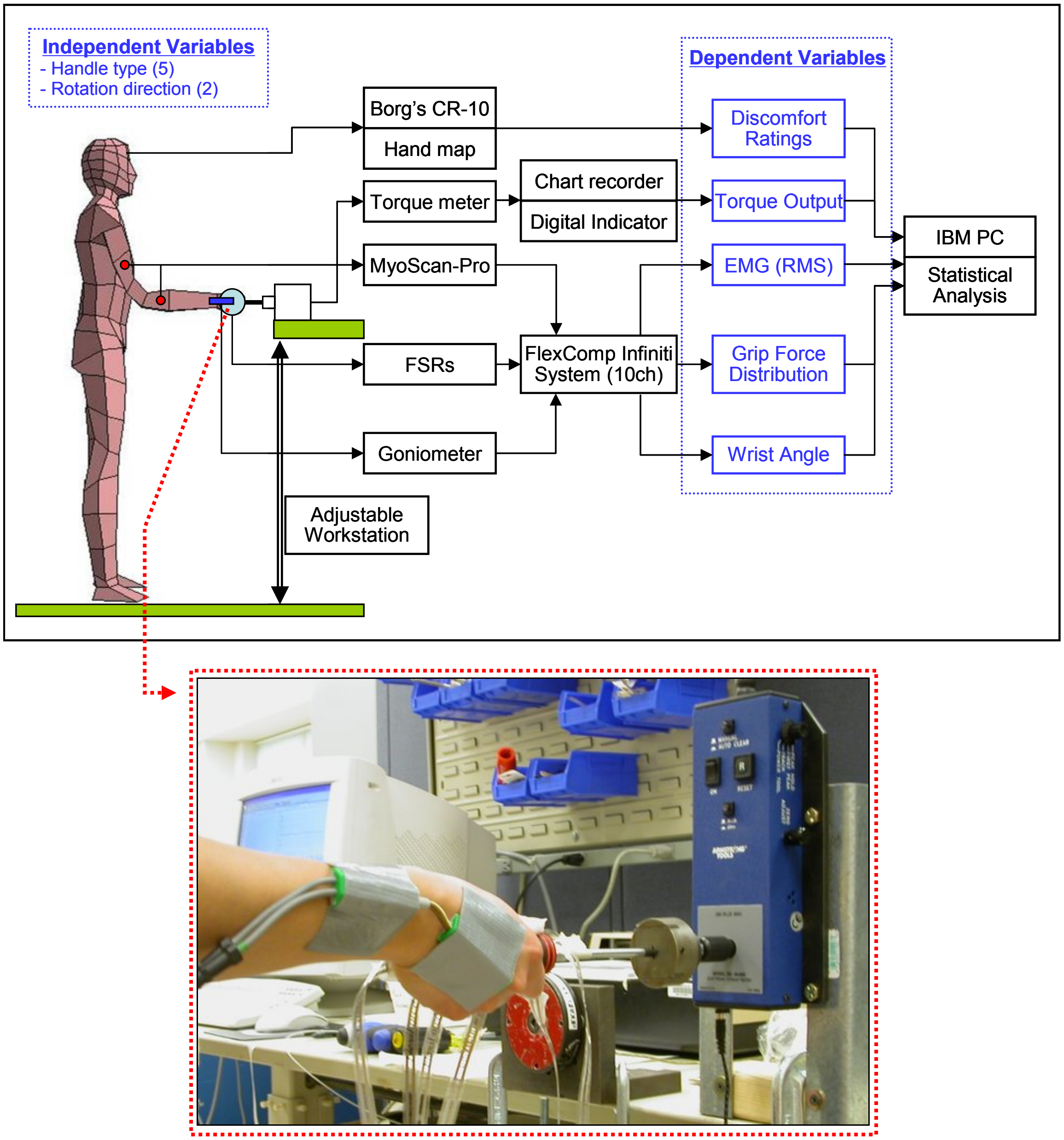


Figure 5.16. Schematic diagram of experimental setup

5.3.6 Data Analysis

In order to compare the muscle activities across both experimental trials and participants, a normalization procedure was performed (Mirka, 1991). The RMS (root mean square) EMG amplitude was normalized relative to its maximal and minimal values using the following equation:

$$\text{Normalized EMG (\%)} \ (NEMG) = \frac{EMG_{read} - EMG_{\min}}{EMG_{\max} - EMG_{\min}}$$

EMG_{read} is the measured EMG value, EMG_{max} is the EMG measured under maximal voluntary contraction at neutral posture of the wrist, and EMG_{min} is the EMG at rest condition. Normalization is a technique used to quantify an EMG signal so that a muscle's relative activity can be assessed. When the EMG values obtained from the different experimental conditions were compared in this experiment, the normalized EMG (NEMG) value can reflect a relative activation level of a muscle as a percentage of that muscle's maximum voluntary contraction (MVC) with a specific condition. For the same reason, discomfort ratings were also normalized by the maximum ratings for each participant in order to reduce the effect of individual variations (Chang et al., 1999).

A series of analysis of variance (ANOVA) tests were used to assess the main effects for both maximum torque and constant torque experiments. Furthermore, a post-hoc paired comparison test such as Tukey's test was utilized to further explore the statistical significance. In situation where the normality assumption is unjustified, nonparametric methods would be conducted for an alternative procedure. Pearson's correlation analysis was used to evaluate the relationship between dependent variables. All statistical analyses were performed using MINITAB^{TM} (release 13.1) statistical software.

5.4 SUBJECTIVE EVALUATION

5.4.1 Method

In order to develop a comprehensive ergonomic evaluation technique, a product-interactive questionnaire was developed and employed to assess users' subjective and affective preference or expectation related to given a screwdriver design. Subjective evaluation using a product-interactive questionnaire aimed to evaluate different design alternatives of screwdriver using subjective evaluation criteria associated with user satisfaction attributes.

Questionnaire consisted of the same list of user satisfaction attributes which was developed. For the subjective evaluation, 5-point interval rating scale was also utilized to measure users' relative preference across five different screwdriver designs with regard to each user satisfaction attribute. Figure 5.17 illustrates an example of questionnaire. The same participants with same screwdriver designs were employed in both experimentations and questionnaire survey. Consequently, it is assumed that participants had at least 2-hour experience of the screwdrivers to be assessed if they completed the two experimental sessions. During the subjective evaluation session, participants were allowed to test five screwdriver designs using torque measurement system.

5.4.2 Subjective Assessment of Design Priority

In order to quantify the priority of screwdriver designs in terms of subjective evaluation, participants' subjective ratings on the different designs related to each of user satisfaction attributes were synthesized into a one-dimensional measure of design priority. Design priorities represented by the overall score may indicate which screwdriver design is the best in terms of user satisfaction. Overall score of each screwdriver design associated with user satisfaction is calculated by the following equation.

$$D_k = \frac{\sum_i \sum_j U_i R_{ijk}}{N}$$

Where, $\boldsymbol{D_k}$: weighted design priority overall score of the $\boldsymbol{k^{th}}$ screwdriver design
$\boldsymbol{U_i}$: weight of $\boldsymbol{i^{th}}$ user satisfaction attribute obtained in chapter 4
$\boldsymbol{R_{ijk}}$: rating score of the $\boldsymbol{j^{th}}$ participant on the $\boldsymbol{k^{th}}$ screwdriver design related to the $\boldsymbol{i^{th}}$ user satisfaction attribute
$\boldsymbol{N}$: total number of participant

INTRODUCTION

This questionnaire is intended to evaluate different design of screwdriver in terms of user satisfaction. User satisfaction means that products should have the right function required to perform the intended tasks, correspond to users' subjective taste and preference, and provide pleasure in use of the product.

Assuming you are working for 8 hours a day with a screwdriver, how important to you is each of the following 30 user satisfaction factors considering your over please rate your level of satisfaction or preference with respect to the each satisfaction factor. Please pick a number from the scale for each screwdriver design based on your subjective evaluation and jot it in the space beside the each design, respectively.

Rating Scale						
Not at all	1	2	3	4	5	Perfectly satisfied or prefered

***Rating instruction**: if you feel the given design is perfectly satisfied or preferred, pick a number from the far right side of the scale (e.g., 5). If you feel it is extremely unsatisfied, pick a number from the far left (e.g., 1), and if your level of preference or satisfaction is between these extremes, pick a number from someplace in the middle of the scale to show your opinion*

Q1 Force/torque output
: The tool provides the force/torque output required to perform the intended task

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

Figure 5.17. Example of questionnaire for subjective evaluation

5.4.3 Integrated Design Priority

In order to quantify the overall priority of design alternatives of a hand tool including users' subjective evaluation and objective assessment of the functionality of the hand tool, this study proposed an integrated evaluation technique incorporating objective performance measures such as torque production and EMGs into the subjective evaluation measures in terms of overall user satisfaction. Regarding the subjective evaluation technique using a questionnaire survey, some evaluation criteria (user satisfaction attributes) such as force/torque output and efficiency are generally accepted as objective measures by their functional definitions (described in chapter 4). Accordingly, once the evaluation data from objective assessment can substitute for participants' subjective ratings related to those objective criteria, it is expected that more reasonable design priority might be obtained from a holistic perspective. In fact, among the 30 user satisfaction attributes used in subjective evaluation, it is possible to obtain the objective measurements corresponding to the torque production, efficiency, grip comfort, and grip friction using the results of dependent measures employed in the experimental investigations. Consequently, an integrated measure is developed by normalization of four objective measurements from the experimentations and 5-point subjective ratings related to the final-screened 26 user satisfaction attributes, respectively.

$$NT_k = \frac{T_k - T_{\min}}{T_{\max} - T_{\min}}$$

Where, NT_k : normalized average torque output of the k^{th} screwdriver design
T_k : average torque output of the k^{th} screwdriver design
T_{max} : maximum average torque output from all screwdriver designs
T_{min} : minimum average torque output from all screwdriver designs

For an objective measure of efficiency, the ratio of torque level to the muscular activity (EMG) has been demonstrated as an efficiency measure in the literature (Kong and Freivalds, 2003; Kong and Lowe, 2003). The larger efficiency (Torque/EMG ratio), the less muscular activity required to produce a constant torque level. Thus, the results of experimentations in this study can be utilized to calculate the efficiency.

$$E_k = \frac{NT_k}{NEMG_k}$$

Where, E_k : efficiency of the k^{th} screwdriver design
NT_k : normalized average torque output of the k^{th} screwdriver design
$NEMG_k$: normalized EMG of the k^{th} screwdriver design

Regarding the grip comfort, the result of average ratings on discomfort from the experiments may directly substitute for the subjective measure of grip comfort in questionnaire survey since they were already normalized by the data analysis method. Even though both grip comfort of questionnaire and overall discomfort rating of the experiments rely on participant's subjective judgment, it is assumed that overall discomfort ratings from experimentations are less subjective than data from questionnaire survey since the experimental findings are closely associated with objective external force at the hand. For the same reason, subjective ratings on slipperiness of experiments also directly substitute for the subjective evaluation of grip friction in questionnaire survey.

Consequently, four objective measurements from the experiments substitute for subjective ratings related to the corresponding user satisfaction attributes so that they can be embedded with subjective evaluation attributes for developing an integrated measure of design priority.

Chapter 6

RESULTS OF ERGONOMIC EVALUATION

6.1 RESULTS OF EXPERIMENTS

6.1.1 Results of Maximum Torque Experiment

Table 6.1 summarized the changes in all dependent measures with respect to screwdriver handle designs using descriptive statistics such as mean and standard deviation.

According to the result of ANOVA, among dependent measures, maximum torque production, muscular activity of bicep brachii (BB), grip force on all the hand area (except index finger area), subjective discomfort ratings on all six areas at hand and wrist, overall discomfort, and slipperiness were significantly changed by screwdriver types. Regarding the effect of rotation direction, maximum torque production, muscular activities of Flexor digitorum superficialis (FDS) and bicep brachii (BB), wrist posture in terms of ulnar deviation angle, subjective discomfort ratings on thumb and wrist area, overall discomfort, and slipperiness, and grip force on all area in hand (expect thumb area) were significantly different between directions of rotation.

Table 6.1. Summary of results from maximum torque task

Dependent measures			A	B	C	D	E
			Screwdriver Handle Type				
Maximum Torque Production (Nm)**		Supination	2.34	2.19	2.42	2.11	2.26
		Pronation	2.01	2.09	2.19	1.93	2.01
		Overall	2.17	2.14	2.30	2.02	2.14
NEMG (FDS)		Supination	0.74	0.71	0.76	0.71	0.74
		Pronation	0.74	0.69	0.73	0.70	0.70
		Overall	0.74	0.70	0.75	0.70	0.72
NEMG (BB)*		Supination	0.82	0.69	0.74	0.70	0.80
		Pronation	0.09	0.10	0.11	0.09	0.09
		Overall	0.46	0.40	0.43	0.39	0.45
Wrist Angle (Ulnar Deviation)		Supination	24.57	26.45	26.75	24.03	25.22
		Pronation	33.68	33.11	32.99	34.39	34.63
		Overall	29.12	29.78	29.87	29.21	29.92
Grip Force Distribution	Supination	Thumb	0.46	0.38	0.34	0.46	0.54
		Index finger	0.36	0.42	0.41	0.44	0.41
		Middle finger	0.50	0.67	0.64	0.48	0.46
		Ring finger	0.45	0.42	0.48	0.26	0.26
		Metacarpal	0.30	0.20	0.19	0.25	0.31
		Thenar	0.50	0.45	0.58	0.47	0.70
	Pronation	Thumb	0.44	0.40	0.43	0.43	0.46
		Index finger	0.34	0.27	0.30	0.31	0.25
		Middle finger	0.36	0.31	0.45	0.32	0.39
		Ring finger	0.48	0.59	0.51	0.31	0.41
		Metacarpal	0.27	0.16	0.15	0.15	0.15
		Thenar	0.32	0.22	0.32	0.34	0.32
Subjective Ratings**	Supination	Thumb	0.44	0.43	0.43	0.56	0.54
		Index finger	0.49	0.48	0.47	0.58	0.60
		Middle Phalange	0.55	0.63	0.61	0.68	0.66
		Metacarpal	0.64	0.62	0.70	0.74	0.70
		Thenar	0.67	0.68	0.66	0.84	0.72
		Wrist	0.60	0.56	0.63	0.74	0.67
		Overall	0.62	0.67	0.70	0.84	0.70
		Slipperiness	0.51	0.74	0.72	0.72	0.70
	Pronation	Thumb	0.45	0.51	0.48	0.55	0.55
		Index finger	0.48	0.51	0.54	0.62	0.61
		Middle Phalange	0.58	0.66	0.66	0.70	0.61
		Metacarpal	0.63	0.70	0.72	0.72	0.67
		Thenar	0.64	0.70	0.73	0.79	0.68
		Wrist	0.64	0.69	0.68	0.77	0.70
		Overall	0.64	0.72	0.77	0.83	0.74
		Slipperiness	0.56	0.69	0.74	0.72	0.69

Note: significant at $P < 0.05$ (*) and significant at $P < 0.001$ (**) across screwdriver handle types

Maximum Torque Production

As shown in Table 6.2 and Figure 6.1, the handle designs of screwdriver had a statistically significant effect on the maximum torque production ($P < 0.001$). In addition, change of maximum torque production capabilities was statistically significant across subjects. However, there was no significant interaction effect of handle type and rotation direction. In terms of torque production capacity, it was revealed that screwdriver type C was the best while screwdriver type D was the worst design among the 5 different types of screwdriver.

Table 6.2. Result of ANOVA for maximum torque production

Source	DF	SS	MS	F	P
Direction	1	554.0	554.00	46.92	**0.000****
Handle Type	4	264.23	66.06	5.59	**0.000****
Subject	14	4505.60	321.83	27.25	**0.000****
Trial	2	13.25	6.62	0.56	0.571
Type×Direction	4	35.79	8.95	0.76	0.553
Error	424	5042.54	11.78		
Total	449	10379.62			

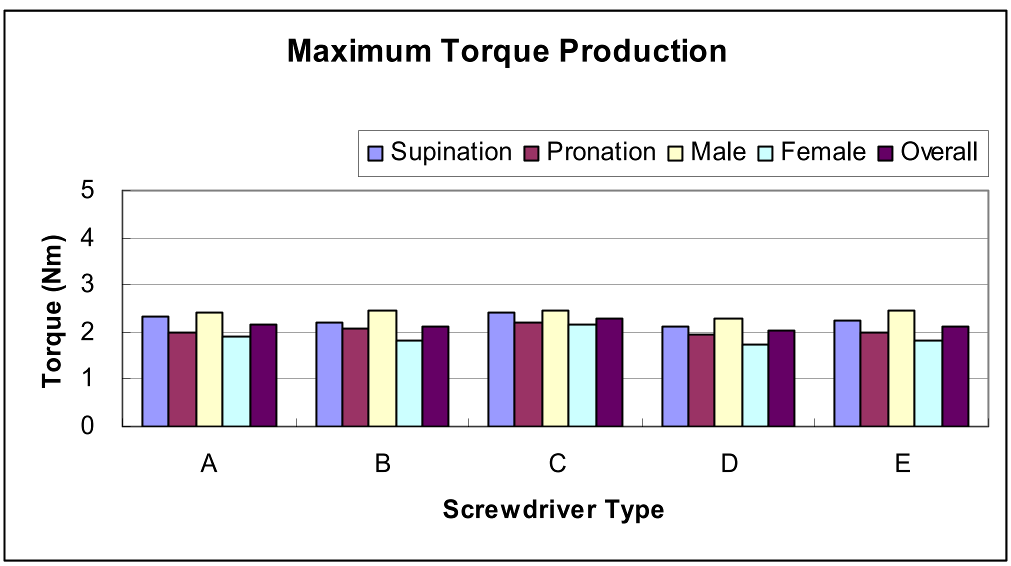


Figure 6.1. Results of maximum torque production

Muscular Activities

The normalized EMG values of FDS and BB for the various handle types are shown in Figure 6.2 and Figure 6.3. According to the results of ANOVA as shown in Table 6.3 and Table 6.4, the muscular activity of BB differed significantly across the handle types while muscular activity of FDS did not reflect any significant change due to handle types. There was significant interaction effect of the handle type and rotation direction on the muscular activity of BB. However, the direction of rotation had a statistically significant effect on both muscular activities of FDS ($P < 0.001$) and BB ($P < 0.001$). Regarding the muscular activity of BB in pronation (NEMG = 0.098), the average level of EMG was extremely low compared with that of supination (NEMG = 0.741). This result supported that BB acts as not pronator but powerful supinator.

Table 6.3. Result of ANOVA for EMG (FDS)

Source	DF	SS	MS	F	P
Direction	1	0.25016	0.25016	18.62	**0.000****
Handle Type	4	0.10987	0.02747	2.04	0.087
Subject	14	1.10889	0.07921	5.90	**0.000****
Trial	2	0.02209	0.01104	0.82	0.440
Type×Direction	4	0.00923	0.00231	0.17	0.953
Error	424	5.70562	0.01343		
Total	449	7.19663			

Table 6.4. Result of ANOVA for EMG (BB)

Source	DF	SS	MS	F	P
Direction	1	46.5162	46.5162	3878.87	**0.000****
Handle Type	4	0.2143	0.0536	4.47	**0.002****
Subject	14	1.7166	0.1226	10.22	**0.000****
Trial	2	0.0369	0.0184	1.54	0.216
Type×Direction	4	0.2283	0.0571	4.76	**0.001****
Error	424	5.3130	0.0124		
Total	449	53.7970			

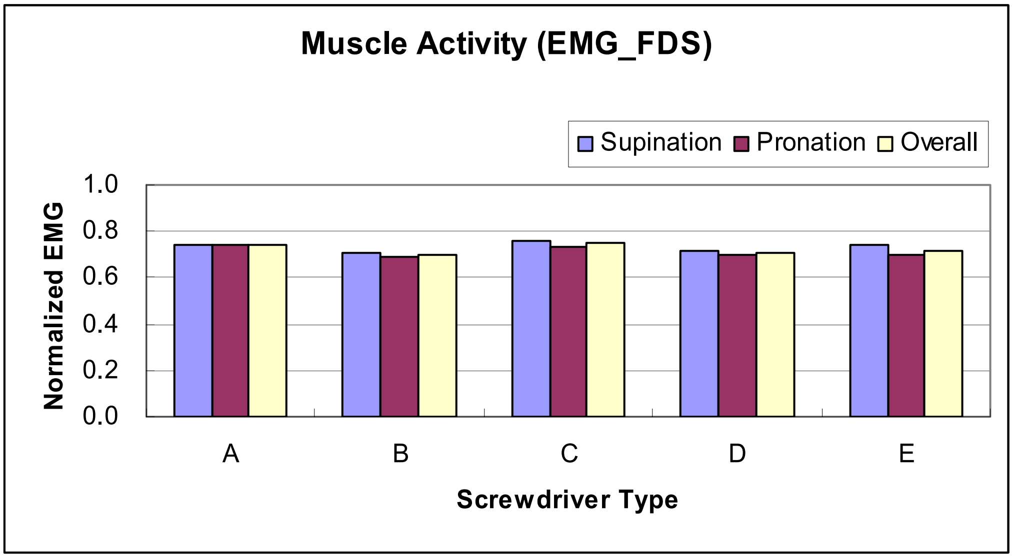


Figure 6.2. Results of the normalized EMG of FDS

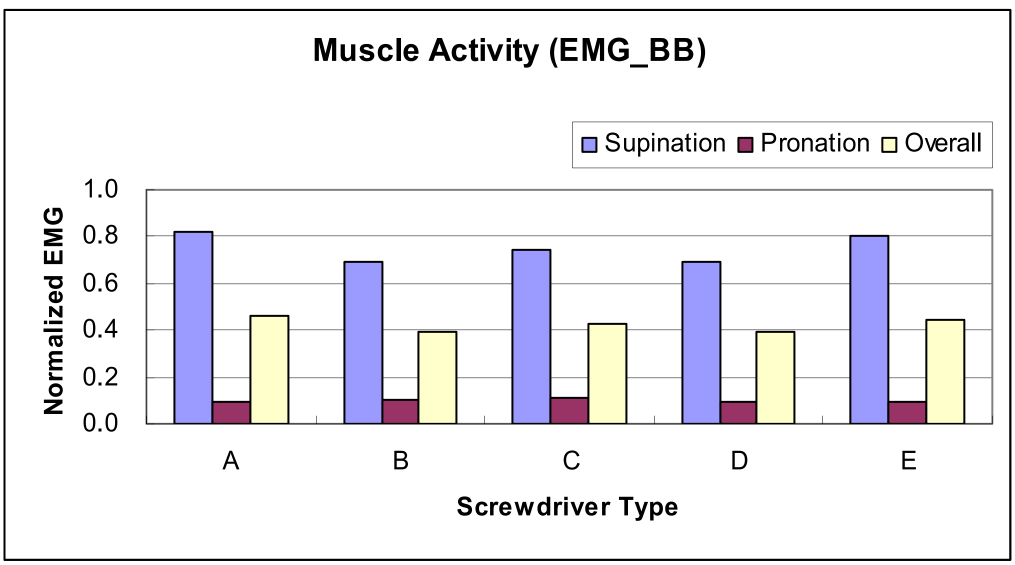


Figure 6.3. Results of the normalized EMG of BB

Wrist Posture

Figure 6.4 shows the change of wrist posture in terms of ulnar deviation angle across the various screwdriver handle types. According to the result of ANOVA as shown in Table 6.5, the wrist posture differed significantly between supination and pronation ($P < 0.001$) while it did not reflect any significant change due to handle types. However, there was marginal significant interaction effect of the handle type and rotation direction on the wrist posture ($P < 0.05$).

Table 6.5. Result of ANOVA for wrist posture (ulnar deviation angle)

Source	DF	SS	MS	F	P
Direction	1	7527.64	7527.64	416.48	**0.000****
Handle Type	4	40.91	10.23	0.57	0.688
Subject	14	3568.30	254.88	14.10	**0.000****
Trial	2	2.92	1.46	0.08	0.922
Type×Direction	4	176.02	44.00	2.43	**0.047***
Error	424	7839.58	18.32		
Total	449	18979.35			

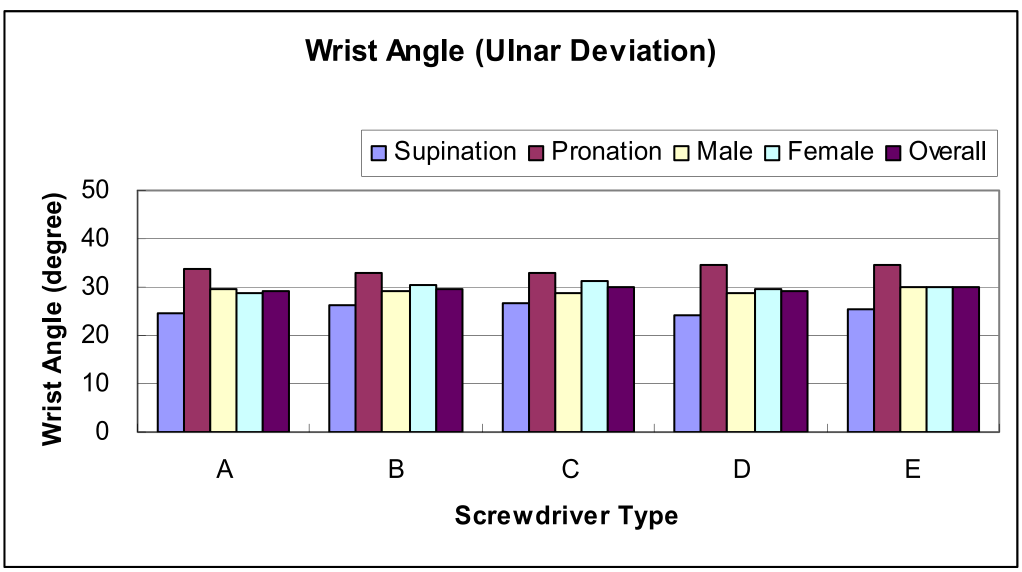


Figure 6.4. Results of ulnar deviation angle

<u>Subjective Ratings on Discomfort and Slipperiness</u>

Figure 6.5 shows the normalized subjective ratings of overall discomfort and Figure 6.6 shows slipperiness averaged across the five handle types. Their values are on a scale from 0 to 1 with a lower value being more comfortable or acceptable. The results of ANOVA for overall discomfort (Table 6.6) and slipperiness (Table 6.7) indicated that the effects of handle types on the subjective ratings of overall discomfort ($P < 0.05$) and slipperiness were significant ($P < 0.001$). Moreover, the direction of rotation did not significantly affect on user's subjective feelings of discomfort and slipperiness. Based on the results, handle type A (hexagonal round shape and 6 grooves) might be the most comfortable and the most acceptable handle design among the 5 different screwdrivers in terms of overall discomfort and slipperiness.

Table 6.6. Result of ANOVA for subjective ratings on overall discomfort

Source	DF	SS	MS	F	P
Direction	1	0.10734	0.10734	7.41	**0.007***
Handle Type	4	1.22394	0.30599	21.12	**0.000***
Subject	14	4.44875	0.29420	20.31	**0.000***
Trial	2	0.00955	0.00477	0.33	0.719
Type×Direction	4	0.07509	0.01877	1.30	0.271
Error	424	6.21792	0.01453		
Total	449	11.67749			

Table 6.7. Result of ANOVA for subjective ratings on slipperiness

Source	DF	SS	MS	F	P
Direction	1	0.00062	0.00062	0.03	0.860
Handle Type	4	1.82218	0.45555	22.83	**0.000***
Subject	14	5.36787	0.38342	19.21	**0.000***
Trial	2	0.08152	0.04076	2.05	0.131
Type×Direction	4	0.06671	0.01668	0.84	0.503
Error	424	8.52876	0.01993		
Total	449	15.80096			

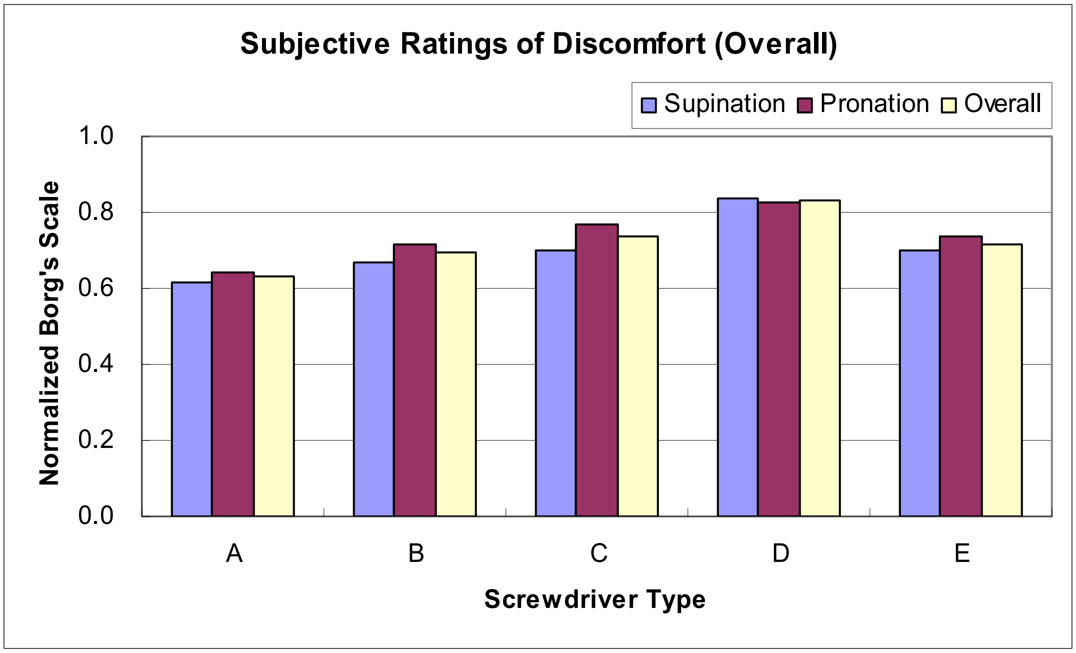


Figure 6.5. Results of subjective ratings on overall discomfort

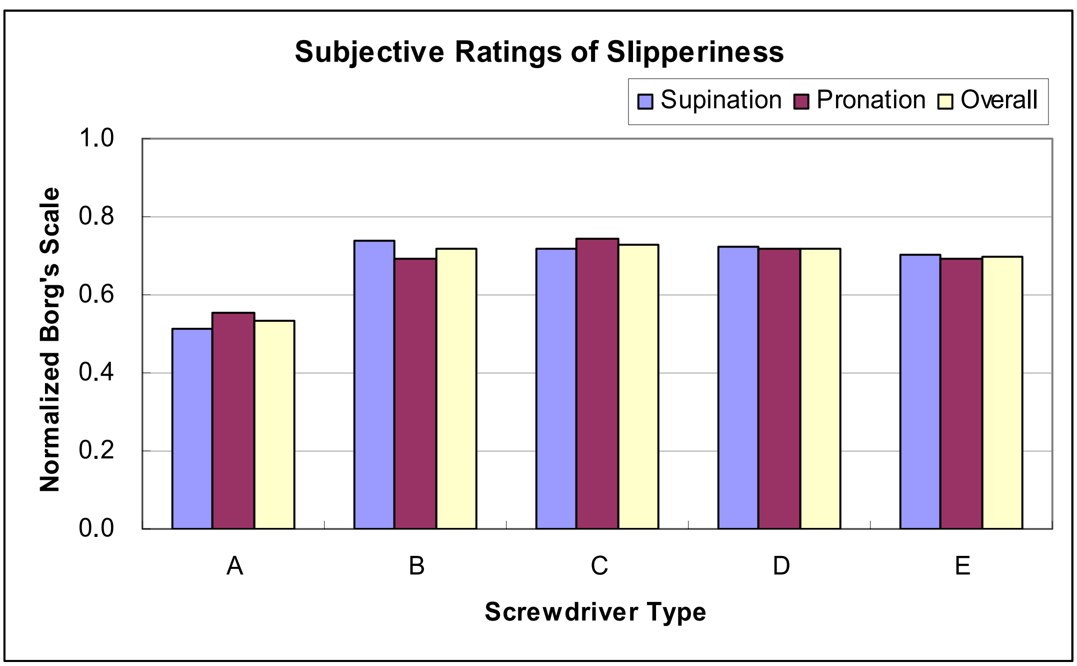


Figure 6.6. Results of subjective ratings on slipperiness

According to the results of ANOVA for subjective ratings on 6 different hand areas as shown in from Table 6.8 to Table 6.13, discomfort ratings on all six areas at hand and wrist were significantly different across screwdriver types (all Ps < 0.001). However, regarding the effect of rotation direction, only thumb ($P < 0.05$) and wrist area ($P < 0.001$) were significantly different. Figure 6.7 and Figure 6.8 illustrate the distribution of subjective discomfort ratings on hand and wrist area for supination and pronation, respectively. According to the results, subjective feelings of discomfort on thumb and index finger areas were relatively lower than those of other grip areas. This result may result from the nature of precision grip type employed in this study.

Table 6.8. Result of ANOVA for subjective ratings on thumb area

Source	DF	SS	MS	F	P
Direction	1	0.08053	0.08053	6.77	**0.010****
Handle Type	4	0.57020	0.14255	11.99	**0.000****
Subject	14	6.04433	0.43174	36.30	**0.000****
Trial	2	0.01943	0.00971	0.82	0.443
Type×Direction	4	0.07344	0.01836	1.54	0.189
Error	424	5.11621	0.01195		
Total	449	11.83069			

Table 6.9. Result of ANOVA for subjective ratings on index finger area

Source	DF	SS	MS	F	P
Direction	1	0.03957	0.03957	3.81	0.520
Handle Type	4	0.97840	0.24460	23.52	**0.000****
Subject	14	4.30444	0.30746	29.57	**0.000****
Trial	2	0.01923	0.00962	0.92	0.397
Type×Direction	4	0.05791	0.01448	1.39	0.236
Error	424	4.40860	0.01040		
Total	449	9.80816			

Table 6.10. Result of ANOVA for subjective ratings on middle phalange area

Source	DF	SS	MS	F	P
Direction	1	0.00231	0.00231	0.14	0.712
Handle Type	4	0.40048	0.10012	5.89	**0.000****
Subject	14	3.36886	0.24063	14.16	**0.000****
Trial	2	0.00670	0.00335	0.20	0.821
Type×Direction	4	0.12152	0.03038	1.79	0.130
Error	424	7.20532	0.01699		
Total	449	11.10518			

Table 6.11. Result of ANOVA for subjective ratings on metacarpal area

Source	DF	SS	MS	F	P
Direction	1	0.00657	0.00657	0.50	0.478
Handle Type	4	0.48979	0.12237	9.39	**0.000****
Subject	14	3.70750	0.26482	20.32	**0.000****
Trial	2	0.00325	0.00162	0.12	0.883
Type×Direction	4	0.20852	0.05213	4.00	**0.003***
Error	424	5.52621	0.01303		
Total	449	9.94154			

Table 6.12. Result of ANOVA for subjective ratings on thenar area

Source	DF	SS	MS	F	P
Direction	1	0.00493	0.00493	0.29	0.587
Handle Type	4	0.86648	0.21662	12.95	**0.000****
Subject	14	5.26420	0.37601	22.47	**0.000****
Trial	2	0.00840	0.00420	0.25	0.778
Type×Direction	4	0.16875	0.04219	2.52	**0.041***
Error	424	7.09489	0.01673		
Total	449	13.40762			

Table 6.13. Result of ANOVA for subjective ratings on wrist area

Source	DF	SS	MS	F	P
Direction	1	0.41770	0.41770	23.78	**0.000****
Handle Type	4	0.62628	0.15657	8.91	**0.000****
Subject	14	4.98688	0.35621	20.28	**0.000****
Trial	2	0.01992	0.00996	0.57	0.568
Type×Direction	4	0.12007	0.03002	1.71	0.147
Error	424	7.44692	0.01756		
Total	449	13.61776			

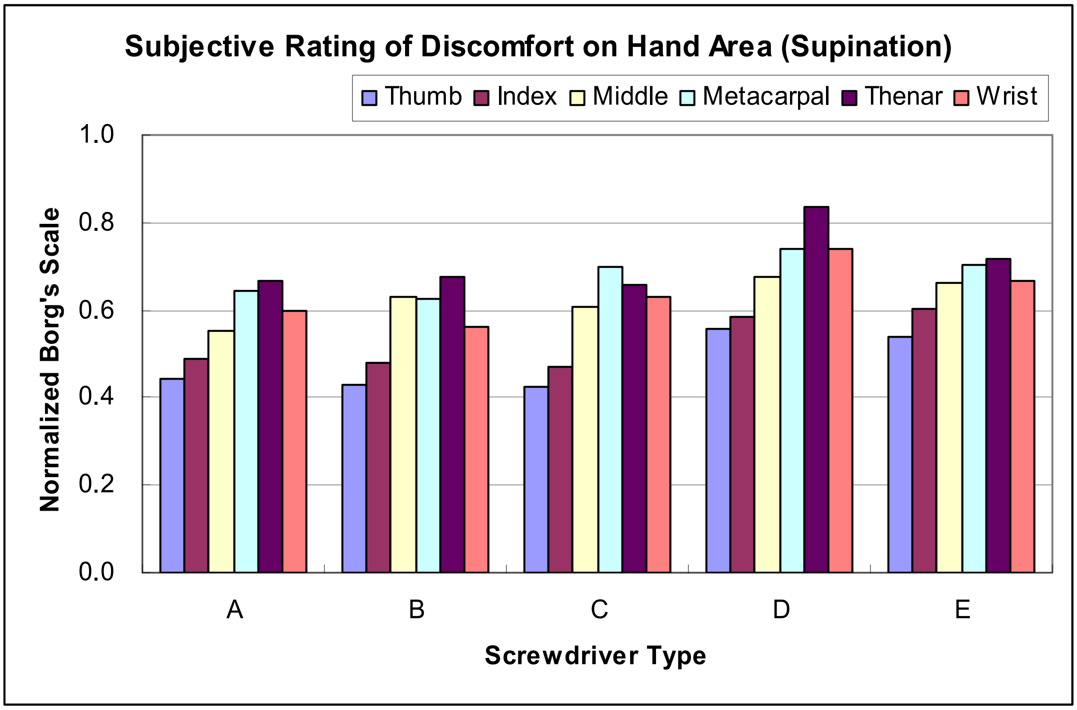


Figure 6.7. Distribution of subjective ratings on hand area for supination

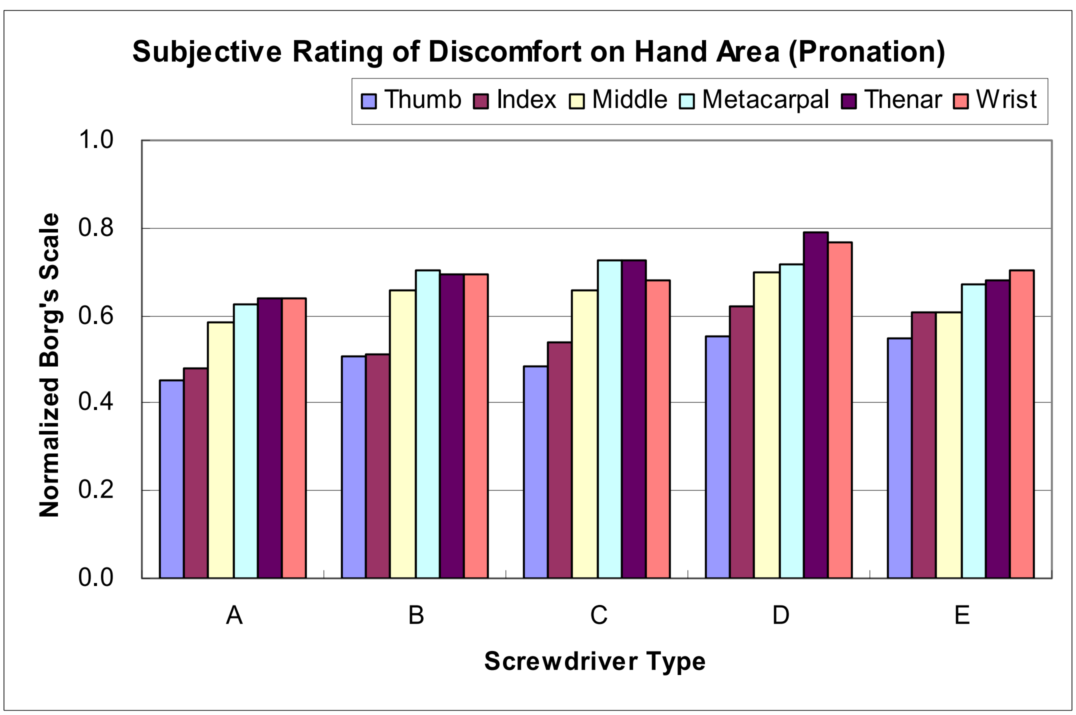


Figure 6.8. Distribution of subjective ratings on hand area for pronation

Grip Force Distribution (FSR)

According to the results of ANOVA (completely described in Appendix I), except thumb area (P = 0.601) as shown in Table 6.14, the effect of rotation directions were significant on the other hand areas (all Ps < 0.001). In addition, the effects of handle types on the normalized grip forces measured at the areas of hand-handle interface, except index finger area (P = 0.600) as shown in Table 6.15, were significantly different across screwdriver types (all Ps < 0.001). Furthermore, it should be emphasized that there were significant individual differences in all six areas in terms of grip force (all Ps < 0.001). Figure 6.9 and Figure 6.10 illustrate the grip force distribution at the contact area in the hand during supination and pronation, respectively.

Table 6.14. Result of ANOVA for grip force at thumb area (FSR1)

Source	DF	SS	MS	F	P
Direction	1	0.00811	0.00811	0.27	0.601
Handle Type	4	0.82910	0.20728	7.00	**0.000****
Subject	14	5.93623	0.42402	14.32	**0.000****
Trial	2	0.09480	0.04740	1.60	0.203
Type×Direction	4	0.26635	0.06659	2.25	0.063
Error	424	12.55055	0.02960		
Total	449	19.68514			

Table 6.15. Result of ANOVA for grip force at index finger area (FSR2)

Source	DF	SS	MS	F	P
Direction	1	1.57472	1.57472	71.11	**0.000****
Handle Type	4	0.06098	0.01525	0.69	0.600
Subject	14	4.51675	0.32263	14.57	**0.000****
Trial	2	0.05911	0.02955	1.33	0.264
Type×Direction	4	0.17969	0.04492	2.03	0.090
Error	424	9.38897	0.02214		
Total	449	15.78023			

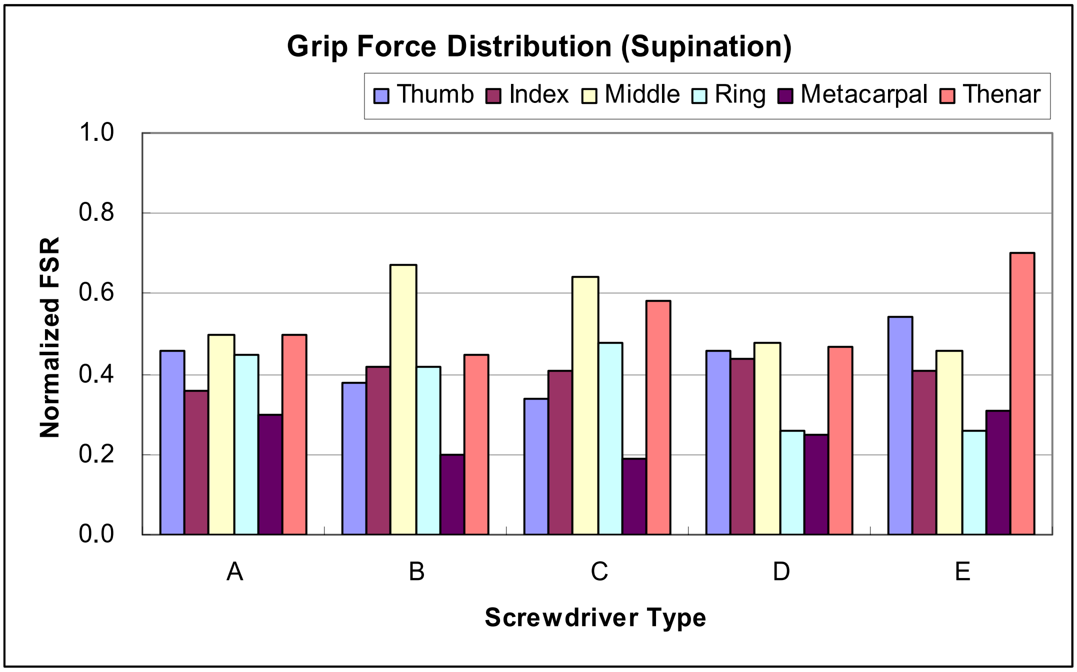


Figure 6.9. Distribution of grip contact force in hand area for supination

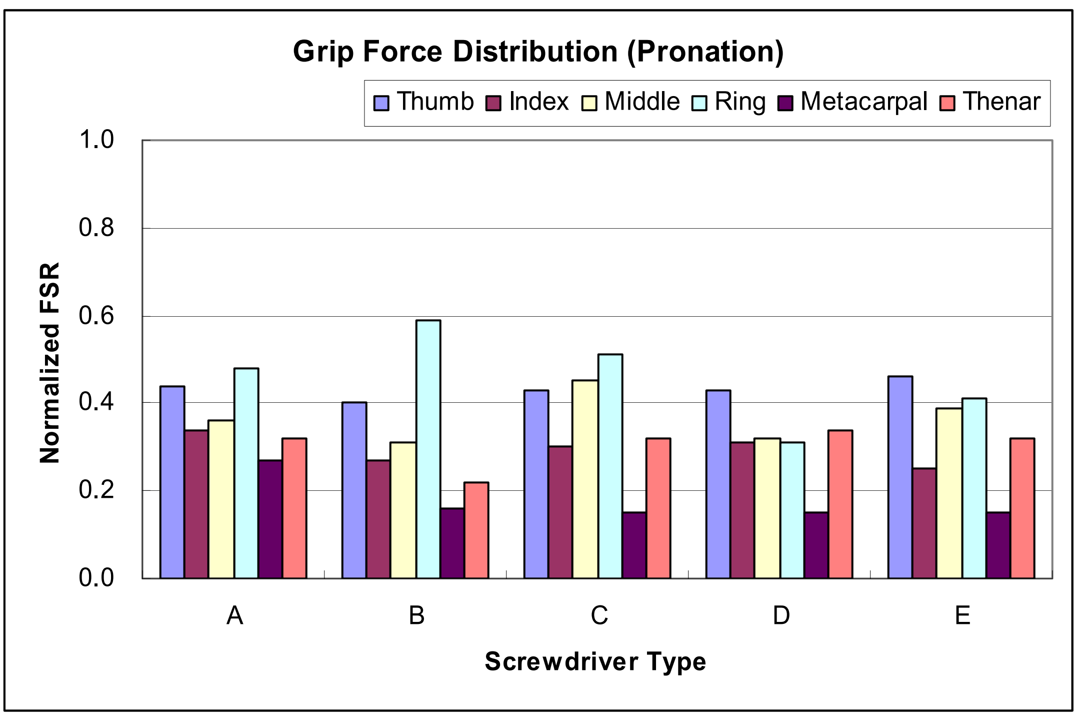


Figure 6.10. Distribution of grip contact force in hand area for pronation

Post-hoc Analysis (Tukey's Test)

For the post-hoc analysis, a series of Tukey's paired comparison tests were performed to further explore the statistical significance. The results of Tukey's test on the means of significantly different dependent measures are summarized in Table 6.16.

The results of Tukey's test revealed that torque production of handle type D was significantly lower ($P < 0.05$). Regarding muscular activity of BB, it is difficult to claim that the lower is the better since this result did not support the efficiency measure (ratio of Torque/EMG). In terms of subjective ratings on overall discomfort and slipperiness, it can be claimed that handle type A is the most acceptable handle design.

Table 6.16. Results of Tukey's test for handle types (maximum torque task)

Responses	Handle Types (mean in parentheses)				
Maximum Torque	C (2.30)	A (2.17)	B (2.14)	E (2.14)	D (2.02)
EMG activity of BB	A (0.82)	E (0.80)	C (0.74)	D (0.70)	B (0.69)
Subjective Ratings - Overall Discomfort	D (0.83)	C (0.74)	E (0.72)	B (0.69)	A (0.63)
- Slipperiness	C (0.73)	D (0.72)	B (0.72)	E (0.70)	A (0.53)

- Handle types underlined by the same line are not significantly different from each other ($\alpha = 0.05$).
- Means are ordered from highest to lowest.

6.1.2 Results of Constant Torque Experiment

Regarding constant torque task, Table 6.17 summarized the results of dependent measures with respect to screwdriver handle designs using descriptive statistics such as mean and standard deviation. However, the grip force distribution could not be analyzed since FSRs failed to read all 6 grip/finger areas due to the small amount of contact force.

From the results of ANOVA, except muscular activities of flexor digitorum superficialis ($P = 0.116$), all dependent measures were significantly changed across the different screwdriver handle types (all $Ps < 0.001$). With regard to the effect of rotation direction, muscular activities of flexor digitorum superficialis (FDS) and bicep brachii (BB), wrist deviation angle, subjective discomfort ratings on middle phalange and wrist area, and subjective ratings on slipperiness were significantly different between directions of rotation.

Table 6.17. Summary of results from constant torque task

Dependent measures			Screwdriver Handle Type				
			A	B	C	D	E
EMG (FDS)		Supination	0.29	0.28	0.27	0.28	0.28
		Pronation	0.25	0.25	0.25	0.27	0.28
		Overall	0.27	0.26	0.26	0.28	0.28
EMG (BB)**		Supination	0.11	0.10	0.07	0.11	0.10
		Pronation	0.05	0.04	0.04	0.05	0.05
		Overall	0.08	0.07	0.06	0.08	0.07
Wrist Angle** (Ulnar Deviation)		Supination	25.47	25.44	30.08	26.75	27.48
		Pronation	28.50	30.41	31.19	29.41	30.53
		Overall	26.99	27.93	30.64	28.08	29.01
Subjective Ratings**	Supination	Thumb	0.39	0.36	0.37	0.44	0.46
		Index finger	0.40	0.40	0.44	0.50	0.49
		Middle Phalange	0.44	0.46	0.48	0.53	0.49
		Metacarpal	0.49	0.49	0.49	0.64	0.54
		Thenar	0.48	0.54	0.56	0.62	0.59
		Wrist	0.49	0.49	0.51	0.56	0.56
		Overall	0.55	0.52	0.56	0.69	0.59
		Slipperiness	0.48	0.54	0.47	0.50	0.46
	Pronation	Thumb	0.37	0.36	0.39	0.48	0.48
		Index finger	0.44	0.40	0.42	0.51	0.47
		Middle Phalange	0.45	0.50	0.49	0.56	0.51
		Metacarpal	0.48	0.55	0.53	0.60	0.54
		Thenar	0.51	0.54	0.53	0.66	0.55
		Wrist	0.49	0.50	0.55	0.67	0.59
		Overall	0.52	0.56	0.54	0.71	0.63
		Slipperiness	0.51	0.55	0.57	0.51	0.45

Note: significant at $P < 0.001$ (**) across screwdriver handle types

Muscular Activities

According to the results of ANOVA as shown in Table 6.18 and Table 6.19, the muscular activity of BB differed significantly across the handle types while muscular activity of FDS (P = 0.116) did not reflect any significant change due to handle types. The direction of rotation had a statistically significant effect on both muscular activities of FDS (P < 0.001) and BB (P < 0.001). The normalized EMG values of FDS and BB for the various handle types are shown in Figure 6.11 and Figure 6.12.

Table 6.18. Result of ANOVA for EMG (FDS)

Source	DF	SS	MS	F	P
Direction	1	0.04560	0.04560	15.36	**0.000****
Handle Type	4	0.02225	0.00556	1.87	0.114
Subject	14	4.17443	0.29817	100.46	**0.000****
Trial	2	0.01941	0.00970	3.27	**0.039***
Type×Direction	4	0.02071	0.00518	1.74	0.139
Error	424	1.25847	0.00297		
Total	449	5.54087			

Table 6.19. Result of ANOVA for EMG (BB)

Source	DF	SS	MS	F	P
Direction	1	0.301088	0.301088	401.67	**0.000****
Handle Type	4	0.037896	0.009474	12.64	**0.000****
Subject	14	0.197696	0.014121	18.84	**0.000****
Trial	2	0.000723	0.000362	0.48	0.618
Type×Direction	4	0.010368	0.002592	3.46	**0.009***
Error	424	0.317825	0.000750		
Total	449	0.865596			

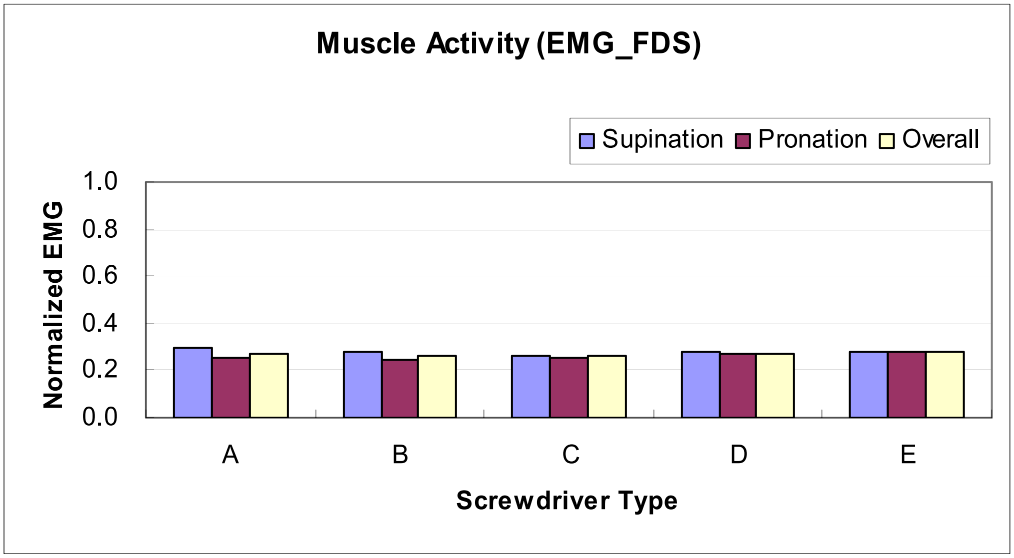


Figure 6.11. Results of the normalized EMG of FDS (constant torque task)

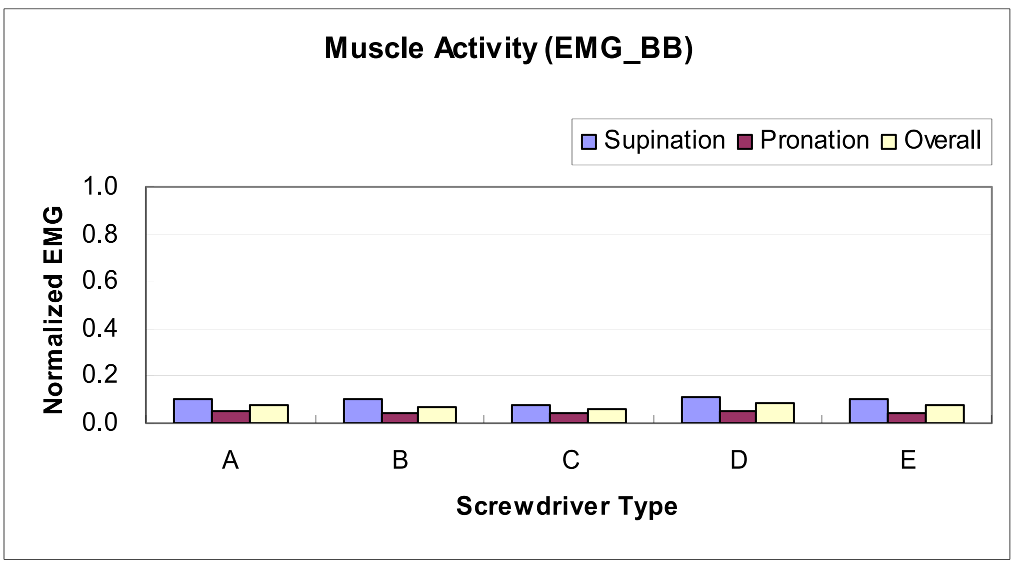


Figure 6.12. Results of the normalized EMG of BB (constant torque task)

Wrist Posture

Figure 6.13 shows the change of wrist posture in terms of ulnar deviation angle across the various screwdriver handle types. According to the result of ANOVA as shown in Table 6.20, the wrist posture differed significantly between supination and pronation ($P < 0.001$) as well as handle types ($P < 0.001$). However, there was no significant interaction effect of the handle type and rotation direction on the wrist posture.

Table 6.20. Result of ANOVA for wrist posture (ulnar deviation angle)

Source	DF	SS	MS	F	P
Direction	1	848.72	848.72	37.38	**0.000****
Handle Type	4	548.34	137.08	6.04	**0.000****
Subject	14	6091.95	435.14	19.16	**0.000****
Trial	2	45.30	22.65	1.00	0.370
Type×Direction	4	191.88	47.97	2.11	0.078
Error	424	9627.32	22.71		
Total	449	17353.51			

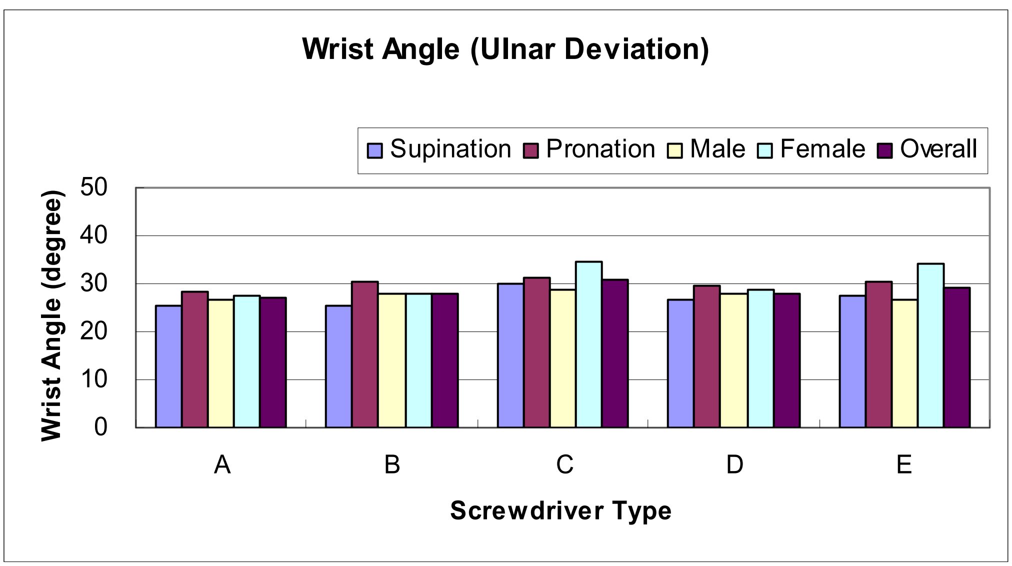


Figure 6.13. Result of wrist posture (constant torque task)

Subjective Ratings on Discomfort and Slipperiness

The results of normalized subjective ratings of overall discomfort and slipperiness averaged across the five handle types were shown in Figure 6.14 and Figure 6.15. According to the results of ANOVA for overall discomfort and slipperiness as shown in Table 6.21 and Table 6.22, the effects of handle types on the subjective ratings of overall discomfort ($P < 0.001$) and slipperiness ($P < 0.001$) were significant. However, the direction of rotation did not significantly affect on user's subjective ratings on overall discomfort while subjective ratings on slipperiness were significantly different between supination and pronation ($P < 0.05$).

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Table 6.21. Result of ANOVA for subjective ratings on overall discomfort

Source	DF	SS	MS	F	P
Direction	1	0.02785	0.02785	1.67	0.197
Handle Type	4	1.68983	0.42246	25.36	**0.000****
Subject	14	6.25877	0.44706	26.84	**0.000****
Trial	2	0.06380	0.03190	1.92	0.149
Type×Direction	4	0.07300	0.01825	1.10	0.358
Error	424	7.06243	0.01666		
Total	449	15.17569			

Table 6.22. Result of ANOVA for subjective ratings on slipperiness

Source	DF	SS	MS	F	P
Direction	1	0.09159	0.09159	6.60	**0.012***
Handle Type	4	0.55634	0.13909	10.02	**0.000****
Subject	14	8.54572	0.61041	43.97	**0.000****
Trial	2	0.09516	0.04758	3.43	**0.033***
Type×Direction	4	0.24610	0.06153	4.43	**0.002***
Error	424	5.88561	0.01388		
Total	449	15.42053			

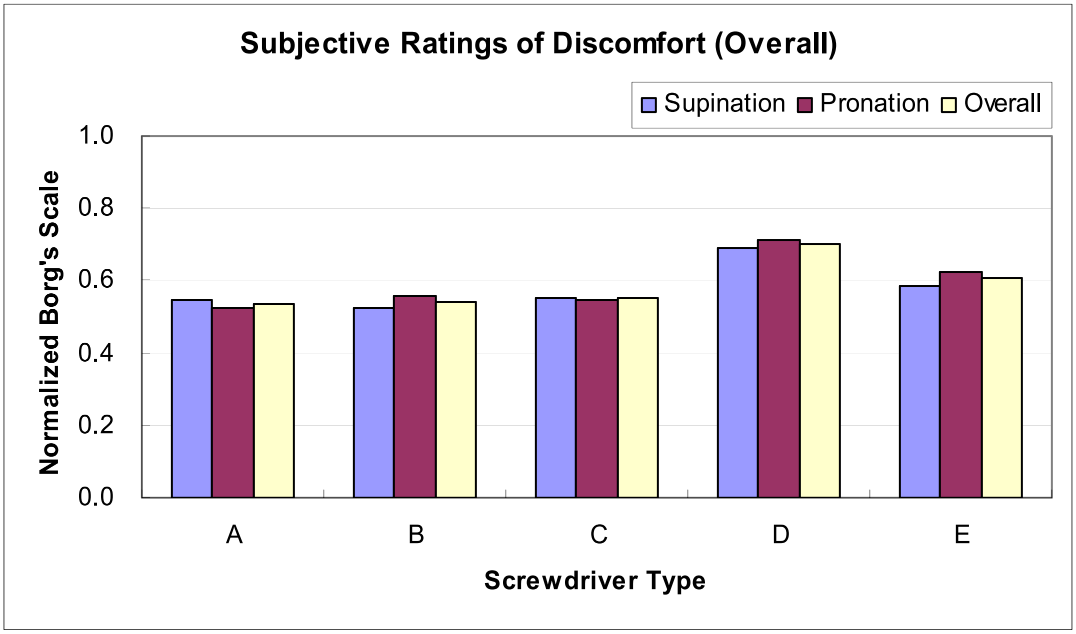

Figure 6.14. Results of overall discomfort ratings (constant torque task)

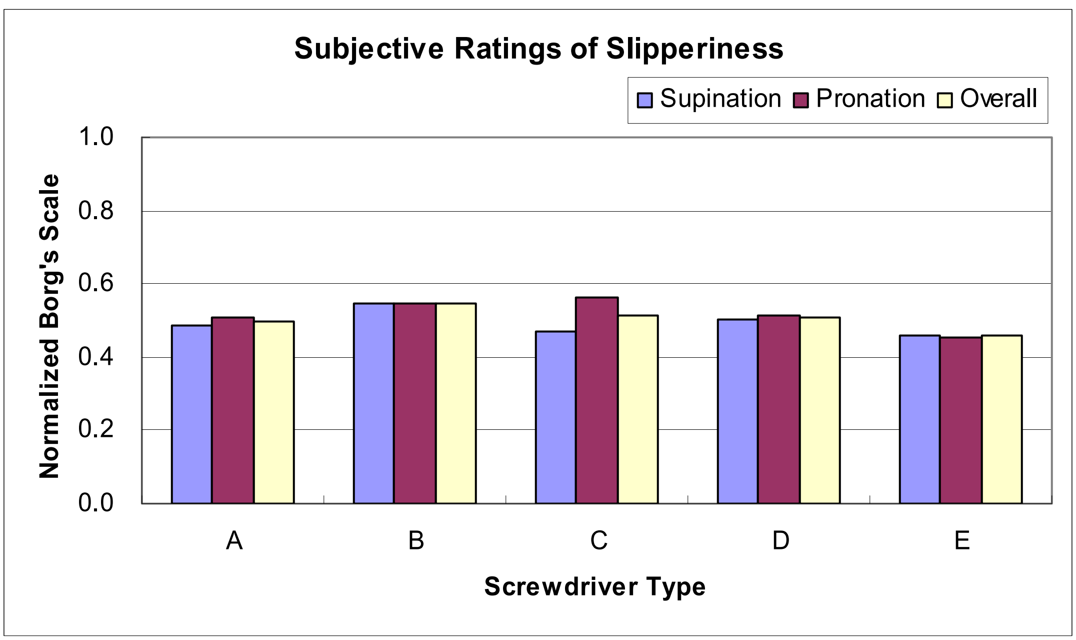

Figure 6.15. Results of subjective ratings on slipperiness (constant torque task)

According to the results of ANOVA for subjective ratings on 6 different hand areas (completely shown in Appendix I), subjective ratings of discomfort on all six areas at hand area were significantly different across screwdriver types (all Ps < 0.001). Regarding the effect of rotation direction as shown in Table 6.23 and Table 6.24, only middle phalange area (P < 0.01) and wrist area (P < 0.01) were significantly different. Figure 6.16 and Figure 6.17 illustrate the distribution of subjective discomfort ratings on hand and wrist area for supination and pronation, respectively. According to the results, subjective feelings of discomfort on thumb and index finger areas were relatively low. These findings also supported the results from maximum torque task.

Table 6.23. Result of ANOVA for discomfort ratings on middle phalange area

Source	DF	SS	MS	F	P
Direction	1	0.10611	0.10611	7.16	**0.008****
Handle Type	4	0.33488	0.08372	5.65	**0.000****
Subject	14	8.18859	0.58490	39.46	**0.000****
Trial	2	0.08684	0.04342	2.93	0.055
Type×Direction	4	0.01405	0.00351	0.24	0.917
Error	424	6.28539	0.01482		
Total	449	15.01586			

Table 6.24. Result of ANOVA for discomfort ratings on wrist area

Source	DF	SS	MS	F	P
Direction	1	0.12836	0.12836	8.30	**0.005****
Handle Type	4	0.99810	0.24952	16.13	**0.000****
Subject	14	9.46317	0.67594	43.69	**0.000****
Trial	2	0.01158	0.00579	0.37	0.688
Type×Direction	4	0.23103	0.05776	3.73	**0.005***
Error	424	6.55934	0.01547		
Total	449	17.39157			

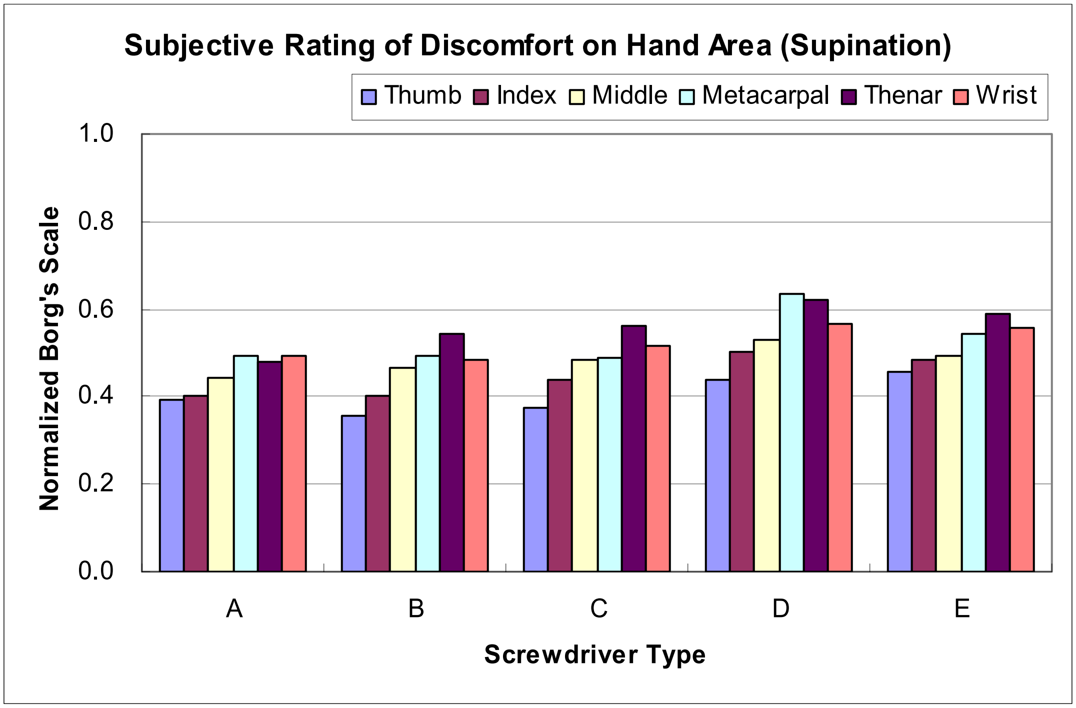

Figure 6.16. Distribution of subjective discomfort (supination, constant torque task)

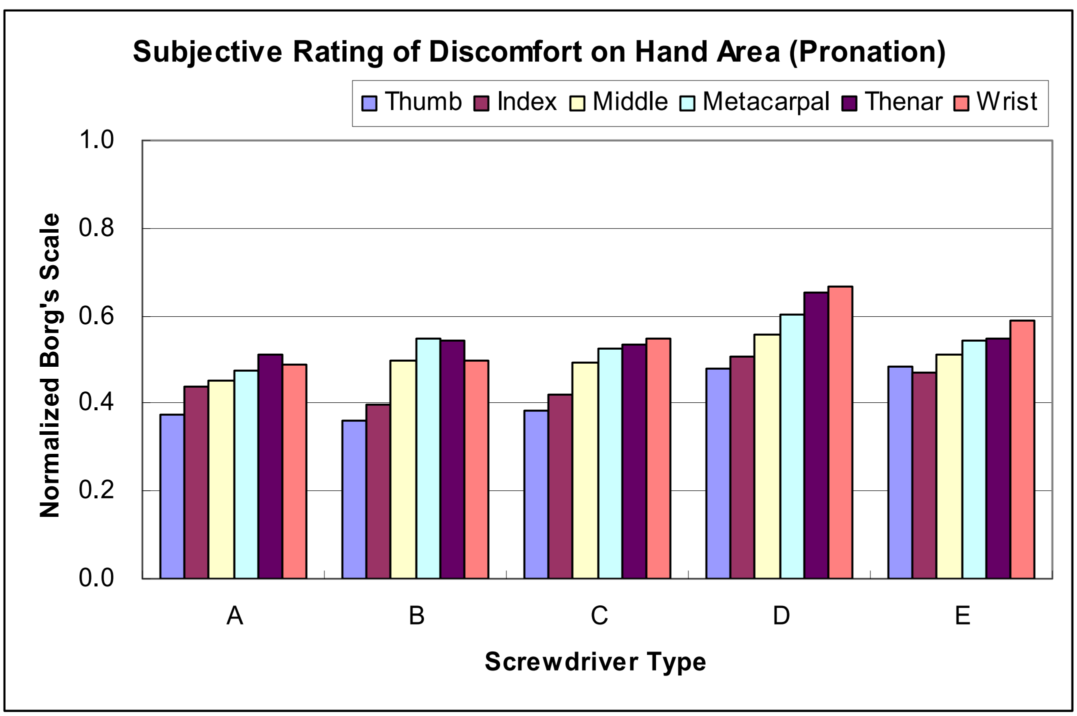

Figure 6.17. Distribution of discomfort (pronation, constant torque task)

Post-hoc Analysis (Tukey's Test)

For the post-hoc analysis, a series of Tukey's paired comparison tests were performed to further explore the statistical significance. The results of Tukey's test on the means of significantly different dependent measures are summarized in Table 6.25. The results of Tukey's test revealed that muscular activity of BB of handle type C was significantly lower ($P < 0.05$). In terms of the efficiency measure (ratio of Torque/EMG), it can be claimed that the lower is the better since a constant level of torque exertion was used in this constant torque experiment. Regarding the wrist posture in terms of ulnar deviation angle, screwdriver type C seems the worst design while other types were not significantly different. In terms of subjective ratings on overall discomfort and slipperiness, it is difficult to assert which one is the best screwdriver design. However, it might be claimed that handle type A is the most acceptable handle design with regard to both criteria.

Table 6.25. Results of Tukey's test for handle types (constant torque task)

Responses	Handle Types (mean in parentheses)				
EMG activity of BB	D (0.11)	A (0.11)	E (0.10)	B (0.10)	C (0.07)
Wrist Angle	C (30.6)	E (29.0)	D (28.1)	B (27.9)	A (27.0)
Subjective Ratings - Overall Discomfort	D (0.70)	E (0.61)	C (0.55)	B (0.54)	A (0.54)
- Slipperiness	B (0.55)	C (0.52)	D (0.51)	A (0.49)	E (0.46)

- Handle types underlined by the same line are not significantly different from each other ($\alpha = 0.05$).
- Means are ordered from highest to lowest.

6.2 RESULTS OF SUBJECTIVE EVALUATION

6.2.1 Results of Questionnaire Survey

From a total of 15 participants employed in the subjective evaluation of screwdriver design using questionnaire survey, their ratings on each screwdriver type by each of user satisfaction attributes were collected and calculated by the simple additive scoring method described in section 5.3.2.

Table 6.26 shows the average of rating scores from 15 participants and overall scores representing their subjective preference in terms of user satisfaction. As a result, screwdriver type A (overall score = 327.06) was the most favorable or acceptable design while type B (overall score = 300.31) was the worst design in terms of user satisfaction. Table 6.27 shows the results with regard to the user satisfaction dimensions including "performance", "physical interaction", and "affective image/impression", respectively. According to the result, screwdriver type E was the best design in terms of "performance" user satisfaction dimension. However its overall score deteriorated due to the worst score of "affective image/impression" dimension. In other words, screwdriver type E could be accepted as the best design with respect to the functional needs or requirements of users while its appearance did not appeal the users' subjective and affective feelings or preference. Result of overall score indicated that screwdriver type A was the most acceptable design with intermediate ranks from all three user satisfaction dimensions.

After checking the normality of rating data, a series of Kruskal-Wallis Tests (α = 0.05) were performed for the subjective ratings on screwdriver designs across all user satisfaction attributes. As a result, it was revealed that 5 screwdriver designs were significantly differently rated on 12 user satisfaction attributes: force/torque output, precision, efficiency, productivity, maintenance, grip friction, luxurious, neatness, attractiveness, prominence/uniqueness, color, and design/styling. An adjusted overall score with only 12 ratings on the significant attributes showed that screwdriver type A was the most acceptable design while type E was the worst.

Table 6.26. Results of subjective evaluation using questionnaire

User Satisfaction Attributes			Screwdriver Type					P-value (α=0.05)
No	Criteria	Weight	A	B	C	D	E	
1	**Force/torque output**	4.38	3.67	3.00	3.13	3.13	**4.40**	**0.000**
2	**Precision**	4.22	**3.73**	3.00	3.40	3.33	**3.73**	**0.042**
3	Effectiveness	4.38	3.60	3.00	3.27	3.27	3.73	0.075
4	**Efficiency**	4.44	3.47	2.93	2.87	3.27	**4.20**	**0.001**
5	**Productivity**	4.00	3.60	3.00	3.00	3.20	**3.73**	**0.032**
6	Durability	4.02	3.27	3.27	3.33	3.67	3.40	0.233
7	Multi-function	2.92	2.93	2.73	2.73	2.93	3.00	0.865
8	Handle shape	3.92	3.33	3.00	3.27	3.20	3.60	0.734
9	Handle size	3.66	3.60	2.93	3.13	3.67	3.53	0.079
12	Convenience/Portability	3.82	3.73	3.13	3.13	3.40	3.60	0.206
13	Identification	3.06	3.20	3.60	3.67	3.80	3.20	0.132
14	**Maintenance**	3.42	3.87	**4.00**	3.87	3.33	3.40	**0.020**
15	All-weather proof	3.30	3.80	3.47	3.47	4.07	3.60	0.196
17	Feedback	3.30	3.33	3.33	3.33	3.67	3.73	0.357
18	Grip comfort	4.44	3.53	2.87	3.27	3.40	3.87	0.151
19	**Grip friction**	4.30	**3.93**	2.73	2.93	3.80	3.67	**0.003**
20	**Luxurious**	2.22	3.40	**3.80**	3.67	**3.80**	1.60	**0.000**
21	Harmony	3.06	3.80	3.53	3.67	3.60	2.93	0.079
22	**Neatness**	3.20	3.40	**4.13**	3.93	3.53	2.27	**0.000**
24	**Attractiveness**	2.74	3.67	**4.13**	3.73	3.73	1.87	**0.000**
25	Craftsmanship	3.28	3.67	3.40	3.53	3.87	3.27	0.377
26	**Prominence/Uniqueness**	2.72	3.13	3.67	3.53	**4.33**	2.27	**0.000**
27	Shape	3.44	3.87	3.53	3.60	3.60	3.20	0.432
28	**Color**	2.76	**4.00**	3.53	3.40	3.67	2.20	**0.000**
29	Texture	3.24	3.40	3.53	3.47	3.60	2.47	0.008
30	**Design/Styling**	3.36	3.67	3.67	3.60	**3.87**	2.00	**0.000**
Overall score (with 26 USAs)			**327.06**	301.68	307.20	324.29	300.31	
Rank			**1**	4	3	2	5	

- User satisfaction attributes are denoted by USAs
- Criteria in bold were significantly different over screwdriver types (α=0.05)

Table 6.27. Results of subjective evaluation related to user satisfaction dimension

User Satisfaction Dimension		Screwdriver Type				
		A	B	C	D	E
26 USAs	Performance	109.96	88.43	94.24	100.84	**117.88**
	Rank	2	5	4	3	**1**
	Physical Interaction	108.74	102.69	104.49	**110.83**	108.82
	Rank	3	5	4	**1**	2
	Affective Image/Impression	108.36	110.56	108.46	**112.62**	73.61
	Rank	4	2	3	**1**	5
	Overall Score	**327.06**	301.68	307.20	324.29	300.31
	Rank	**1**	4	3	2	5
12 USAs	Performance and Physical Interaction	91.76	76.23	78.63	82.81	**95.99**
	Rank	2	5	4	3	**1**
	Affective Image/Impression	60.37	**65.02**	62.03	64.86	34.91
	Rank	4	**1**	3	2	5
	Overall Score	**152.13**	141.25	140.66	147.67	130.90
	Rank	**1**	3	4	2	5

- Note: User satisfaction attributes are denoted by USAs

6.2.2 Results of Integrated Design Priority

Using the simple additive scoring method described in the section 5.3.3, an integrated design priority was calculated and five screwdriver designs were ranked by their overall design priority scores. For the preparation of overall score calculation, some data manipulation was performed as below.

- Data of dependent measures were calibrated for the same interval range from 0 to 1. In addition, subjective ratings on overall discomfort and slipperiness, which were supposed to substitute for “grip comfort (#18)” and “grip friction

(#19)", were calibrated for the change of importance rating direction in accordance with other measures and then averaged for both maximum torque experiment and constant torque experiment.

- For the calculation of an efficiency measure (ratio of Torque/EMG), only EMGs of BB from maximum torque experiment and constant torque experiment was averaged and then utilized since EMGs of FDS was not significantly different between screwdriver designs. In addition, EMGs of BB in pronation were excluded in this calculation since the result of maximum torque experiment revealed that the data of bicep brachii (BB) during pronation was not reliable

According to the result as shown in Table 6.28, it was revealed that screwdriver design A was the best and screwdriver design D was the worst design among five different screwdriver designs in terms of the integrated design priority.

Table 6.28. Results of integrated design priority analysis

No	User Satisfaction Attributes		Screwdriver Type				
	Criteria	Weight	A	B	C	D	E
1	**Force/torque output**	0.97	0.95	0.93	**1.00**	0.88	0.93
2	Precision	0.93	**0.92**	0.73	0.87	0.62	0.85
3	Effectiveness	0.97	**0.88**	0.73	0.83	0.61	0.85
4	**Efficiency**	0.98	0.91	0.98	**1.00**	0.93	0.91
5	Productivity	0.88	**0.88**	0.73	0.76	0.60	0.85
6	Durability	0.89	0.80	0.79	**0.85**	0.69	0.77
7	Multi-function	0.65	**0.72**	0.66	0.69	0.55	0.68
8	Handle shape	0.87	0.82	0.73	**0.83**	0.60	0.82
9	Handle size	0.81	**0.88**	0.71	0.80	0.69	0.80
12	Convenience/Portability	0.85	**0.92**	0.76	0.80	0.64	0.82
13	Identification	0.68	0.79	0.87	**0.93**	0.71	0.73
14	Maintenance	0.76	0.95	0.97	**0.98**	0.62	0.77
15	All-weather proof	0.73	**0.93**	0.84	0.88	0.76	0.82
17	Feedback	0.73	0.82	0.81	**0.85**	0.69	**0.85**
18	**Grip comfort**	0.98	**1.00**	0.83	0.71	0.45	0.76
19	**Grip friction**	0.95	**1.00**	0.61	0.58	0.60	0.65
20	Luxurious	0.49	0.84	0.92	**0.93**	0.71	0.36
21	Harmony	0.68	**0.93**	0.85	**0.93**	0.68	0.67
22	Neatness	0.71	0.84	**1.00**	**1.00**	0.66	0.52
24	Attractiveness	0.61	0.90	**1.00**	0.95	0.70	0.43
25	Craftsmanship	0.73	**0.90**	0.82	**0.90**	0.73	0.74
26	Prominence/Uniqueness	0.60	0.77	0.89	**0.90**	0.81	0.52
27	Shape	0.76	**0.95**	0.85	0.92	0.68	0.73
28	Color	0.61	**0.98**	0.85	0.87	0.69	0.50
29	Texture	0.72	0.84	0.85	**0.88**	0.68	0.56
30	Design/Styling	0.74	0.90	0.89	**0.92**	0.73	0.45
Adjusted overall score (with 26 USAs)			**18.04**	16.71	17.48	13.76	14.70
Rank			**1**	3	2	5	4

- User satisfaction attributes are denoted by USAs
- Attributes (criteria) in bold were substituted by objective measurements from experiments

6.3 COMPARISON OF EVALUATION METHODS

Correlation analysis using Spearman correlation coefficients (***r***) was performed in order to investigate the association between all measures used in objective experiments and subjective evaluation. Table 6.29 summarizes the results and design priorities ranked by each measure. In addition, Table 6.30 shows the results of rank correlation analysis.

Table 6.29. Summary of ergonomic evaluation results and design priority

Ergonomic Evaluation		Screwdriver Type				
Method	Measure	A	B	C	D	E
Maximum Torque Experiment	Torque**	2.17 (2)	2.14 (3)	**2.30 (1)**	2.02 (5)	2.14 (4)
	EMG_FDS	0.742	0.699	0.747	0.704	0.720
	Efficiency (FDS)	0.949	0.992	**1.000**	0.931	0.962
	EMG_BB**	0.824	0.691	0.744	0.696	0.803
	Efficiency (BB)	0.852	0.999	**1.000**	0.938	0.860
	Average Efficiency	0.901 (5)	0.995 (2)	**1.000 (1)**	0.934 (3)	0.911 (4)
	Wrist angle	**29.12 (1)**	29.78 (3)	29.87 (4)	29.21 (2)	29.92 (5)
	Discomfort**	**0.63 (1)**	0.69 (2)	0.74 (4)	0.83 (5)	0.72 (3)
	Slipperiness**	**0.53 (1)**	0.72 (3)	0.73 (5)	0.72 (4)	0.70 (2)
Constant Torque Experiment	EMG_FDS	0.275	0.264	0.260	0.275	0.278
	Efficiency (FDS)	0.946	0.984	**1.000**	0.944	0.936
	EMG_BB**	0.105	0.099	0.072	0.112	0.104
	Efficiency (BB)	0.688	0.735	**1.000**	0.647	0.699
	Average Efficiency	0.817 (3)	0.859 (2)	**1.000 (1)**	0.795 (5)	0.817 (3)
	Wrist angle**	**26.99 (1)**	27.9 (2)	30.64 (5)	28.08 (3)	29.01 (4)
	Discomfort**	**0.54 (1)**	0.54 (2)	0.55 (3)	0.70 (5)	0.61 (4)
	Slipperiness**	0.49 (2)	0.55 (5)	0.52 (4)	0.51 (3)	**0.46 (1)**
Subjective Evaluation	Performance	109.96 (2)	88.43 (5)	94.24 (4)	100.84 (3)	**117.88 (1)**
	Physical Interaction	108.74 (3)	102.69 (5)	104.49 (4)	**110.83 (1)**	108.82 (2)
	Affective Image/Impression	108.36 (4)	110.56 (2)	108.46 (3)	**112.62 (1)**	73.61 (5)
	Overall (26 USAs)	**327.06 (1)**	301.68 (4)	307.20 (3)	324.29 (2)	300.31 (5)
	Performance and Physical Interaction**	91.76 (2)	76.23 (5)	78.63 (4)	82.81 (3)	**95.99 (1)**
	Affective Image/Impression**	60.37 (4)	**65.02 (1)**	62.03 (3)	64.86 (2)	34.91 (5)
	Overall (12 USAs)	**152.13 (1)**	141.25 (3)	140.66 (4)	147.67 (2)	130.90 (5)
Integrated Priority (26 USAs)		**18.04 (1)**	16.71 (3)	17.48 (2)	13.76 (5)	14.70 (4)

Note: Ranks of priority are in parenthesis, (**): significant at P < 0.001

Table 6.30. Result of rank correlation analysis between measures (Spearman correlation coefficient)

	Torque	M_FDS	M_BB	M_AE	M_Wrist	M_Dis	M_Slip	C_FDS	C_BB	C_AE	C_Wrist	C_Dis	C_Slip	USD 1	USD 2	USD 3	USA	US 1	US 2	US	INT
Torque	1.00																				
M_FDS	0.70	1.00																			
M_BB	0.30	0.70	1.00																		
M_AE	0.30	0.70	1.00***	1.00																	
M_Wrist angle	0.00	-0.60	-0.40	-0.40	1.00																
M_Discomfort	0.40	0.10	-0.50	-0.50	0.30	1.00															
M_Slipperiness	-0.10	-0.40	-0.90*	-0.90*	0.30	0.80	1.00														
C_FDS	0.80	0.70	0.70	0.70	0.10	0.10	-0.50	1.00													
C_BB	0.70	1.00***	0.70	0.70	-0.60	0.10	-0.40	0.70	1.00												
C_AE	0.82	0.97**	0.67	0.67	-0.41	0.21	-0.36	0.82	0.97**	1.00											
C_Wrist angle	-0.10	-0.50	-0.60	-0.60	0.80	0.70	0.70	-0.10	-0.50	-0.36	1.00										
C_Discomfort	0.70	0.30	-0.20	-0.20	0.40	0.90*	0.50	0.50	0.30	0.46	0.60	1.00									
C_Slipperiness	-0.30	-0.50	-0.80	-0.80	-0.10	0.10	0.60	-0.80	-0.50	-0.56	0.00	-0.20	1.00								
USD 1	-0.30	-0.50	-0.80	-0.80	-0.10	0.10	0.60	-0.80	-0.50	-0.56	0.00	-0.20	1.00***	1.00							
USD 2	-0.70	-0.80	-0.50	-0.50	0.10	-0.50	0.10	-0.80	-0.80	-0.87	-0.10	-0.70	0.70	0.70	1.00						
USD 3	-0.30	-0.20	0.50	0.50	0.40	-0.50	-0.60	0.30	-0.20	-0.15	0.10	-0.30	-0.70	-0.70	0.00	1.00					
USA	0.20	-0.50	-0.30	-0.30	0.90*	0.10	0.10	0.20	-0.50	-0.31	0.50	0.30	0.00	0.00	0.20	0.30	1.00				
US 1	-0.30	-0.50	-0.80	-0.80	-0.10	0.10	0.60	-0.80	-0.50	-0.56	0.00	-0.20	1.00***	1.00***	0.70	-0.70	0.00	1.00			
US 2	-0.10	0.10	0.60	0.60	0.30	-0.20	-0.50	0.50	0.10	0.15	0.20	0.00	-0.90*	-0.90*	-0.40	0.90*	0.10	-0.90*	1.00		
US	0.00	-0.60	-0.40	-0.40	1.00***	0.30	0.30	0.10	-0.60	-0.41	0.80	0.40	-0.10	-0.10	0.10	0.40	0.90*	-0.10	0.30	1.00	
INT	0.90*	0.40	-0.10	-0.10	0.30	0.70	0.30	0.60	0.40	0.56	0.30	0.90*	-0.10	-0.10	-0.60	-0.40	0.40	-0.10	-0.20	0.30	1.00

Note: Significant at $P < 0.05$ (*), $P < 0.01$ (**), and $P < 0.001$ (***)

M_FDS : Efficiency of FDS in maximum torque experiment,
M_AE : Average efficiency of FDS and BB in maximum torque experiment,
C_BB : Efficiency of BB in constant torque experiment (supination only),
USD 1 : 1st user satisfaction dimension (performance),
USD 3 : 3rd user satisfaction dimension (affective image/impression),
US 1 : Significant user satisfaction attributes in performance/physical interaction,
US : Overall user satisfaction dimension including 12 user satisfaction attributes,
M_BB : Efficiency of BB in maximum torque experiment (supination only)
C_FDS : Efficiency of FDS in constant torque experiment
C_AE : Average efficiency of FDS and BB in constant torque experiment
USD 1 : 2nd user satisfaction dimension (physical interaction)
USA : Overall user satisfaction dimension including 26 user satisfaction attributes
US 2 : Significant user satisfaction attributes in affective image/impression
INT : Integrated measure substituted for 4 out of 26 user satisfaction attributes

6.3.1 Correlation between Experimental Measures

According to the results of correlation analysis, following significant relationships between measures were identified.

Within Maximum Torque Experimental Measures

- Positive correlation between average efficiency (FDS and BB) and efficiency of BB (r = 1, P < 0.001).
- Negative correlation between subjective ratings on slipperiness and efficiency of BB (r = -0.9, P < 0.05), and between subjective ratings on slipperiness and average efficiency (FDS and BB) (r = -0.9, P < 0.05), respectively.

These results indicated that efficiency measure (ratio of Torque/EMG) was closely related to the muscular activity of BB (powerful supinator) in heavy screwdriving task (maximum torque experiment). In addition, it was revealed that subjective feelings of slipperiness increased as the muscular activity decreased.

Within Constant Torque Experimental Measures

- Positive correlation between average efficiency (FDS and BB) and efficiency of BB (r = 0.97, P < 0.01).

This result also showed an agreement with the result of maximum torque experiment in that efficiency measure was closely related to the muscular activity of BB rather than that of flexor muscle (FDS) even in light screwdriving task (constant torque experiment).

Between Experimental Measures

- Positive correlation between efficiency of FDS (maximum torque experiment) and average efficiency (FDS and BB, constant torque experiment) (***r*** = 1, P < 0.001), and between efficiency of FDS (maximum torque experiment) and efficiency of BB (constant torque experiment) (***r*** = 0.97, P < 0.01).
- Positive correlation between subjective discomfort ratings of both experiments (***r*** = 0.9, P < 0.05).

These results may indicate that the muscular activity of flexor muscle (FDS) in heavy screwdriving task was closely related to the muscular activity of supinator (BB) in light screwdriving task. In addition, it was revealed that subjective discomfort ratings on each of five different screwdriver designs were consistent regardless of workloads (heavy or light). Consequently, it can be claimed that subjective rating on overall discomfort is a reliable measure for the ergonomic evaluation of screwdriver design. Though there was no statistical significant evidence, torque production capability positively correlated with the muscular activity and discomfort ratings regardless of workload. However, as torque production increased, it seemed that the subjective feelings on slipperiness decreased in both experimental tasks.

6.3.2 Correlation between Subjective Evaluation Measures

According to the results of correlation analysis, it was revealed that there were negative relationships (***r*** = -0.4 ~ -0.9) between performance-related evaluation measures and affective image/impression related evaluation measures though there was lack of statistical significance. In addition, relatively low correlation coefficients (***r*** = -0.1 ~ 0.4) indicated that overall score of subjective evaluation was not dominated by any single dimension. Regarding the integrated priority measure embedding four objective measures, there was no statistically significant evidence that any of subjective evaluation measures was closely related with the integrated measure ($\boldsymbol{r}$ = -0.6 ~ 0.4).

6.3.3 Correlation between Experiments and Subjective Evaluation

According to the results of correlation analysis, following significant correlations between objective experimental measures and subjective evaluation score were identified.

- Positive correlation between subjective ratings on slipperiness in constant torque experiment and overall subjective evaluation score ($\boldsymbol{r} = 1$, $P < 0.001$).
- Positive correlation between subjective ratings on slipperiness in constant torque experiment and functionality related evaluation score with 12 significant user satisfaction attributes ($\boldsymbol{r} = 1$, $P < 0.001$).
- Negative correlation between subjective ratings on slipperiness in constant torque experiment and affective image/impression related evaluation score with 12 significant user satisfaction attributes ($\boldsymbol{r} = -0.9$, $P < 0.05$).
- Positive correlation between wrist posture of maximum torque experiment and overall subjective evaluation score ($\boldsymbol{r} = 0.9$, $P < 0.05$), and between wrist posture of maximum torque experiment and overall subjective evaluation score with 12 significant user satisfaction attributes ($\boldsymbol{r} = 1$, $P < 0.001$).

In addition, except wrist angle of maximum torque experiment, relatively low correlation coefficients ($\boldsymbol{r}$ = -0.5 ~ 0.5) between objective experimental measures and overall subjective evaluation score indicated that there was no strong association between objective measurements and subjective evaluation.

Finally, regarding an integrated design priority measure, the results of rank correlation analysis revealed that there were significant positive relationships with torque production ($\boldsymbol{r}$ = 0.9, $P < 0.05$) and subjective ratings on overall discomfort in constant torque experiment ($\boldsymbol{r}$ = 0.9, $P < 0.05$). According to the published literature, torque production capability and subjective ratings on discomfort have been generally accepted as established measures in the ergonomic evaluation of hand tools. In addition, 9 out of 11 objective measures were positively correlated to the integrated design priority measure with relatively higher correlation coefficients ($\boldsymbol{r}$ = 0.3 ~ 0.9). This result may support the applicability of the integrated design priority measure, which incorporates objective measurements into subjective evaluation criteria, as a comprehensive evaluation method from a holistic perspective.

Chapter 7

DISCUSSION AND CONCLUSION

7.1 DISCUSSION

This section is organized in a topical manner by discussing the limitations and research findings of this study successively.

7.1.1 Ergonomic Design of Hand Tools

New Ergonomic Design Perspective: Pleasurability

In the area of ergonomic design of hand tools, traditional design approaches have mainly focused on the functionality of hand tools. However, from the last decade product usability or pleasurability has become a crucial issue in the ergonomic design and evaluation of hand tools. According to the literature from a recently evolved ergonomics perspective, in order to capture the usability, a product must be designed by adapting some or all of the ergonomic design principles related to a given product (Jordan, 1999). Wichansky (2000) also claimed that product usability is a function of both the user's performance and the user's subjective satisfaction. In addition, a number of studies in the literature asserted that pleasurability should be greatly emphasized in the consumer product design (Nielsen, 1996; den Buurman, 1997; Han et al, 2000; Han and Hong, 2003). In general, pleasurability is regarded as an expanded concept beyond the traditional concept of usability as well as a new challenge in the area of ergonomics (Jordan, 1999; Green and Jordan, 2002). A recently published literature aiming at investigating which attributes of hand tools correspond to pleasurability addressed that functionally well-designed product did not guarantee users' satisfaction or pleasure (Hauge-Nilsen and Flyte, 2002). In order to capture the product pleasurability, there is an agreement among studies in the literature in that users' subjective aspects such as taste, preference, and satisfaction are thoroughly investigated and systematically considered in the product design process. From quality technology perspective, it might be accepted that attractive user needs are closely related to product pleasurability. However, attractive user needs are extremely difficult to identify since they might be beyond the customer's current knowledge or expectations. Hence, product design engineers or ergonomists are fully responsible for identifying attractive user needs and incorporating them to product design attributes.

In the proposed design methodology of this study, there exist twofold promising methodological benefits to enhance the possibility for capturing the product pleasurability as followings. First, regarding the identification of product design attributes, the use of hierarchical structures of human variables and product variables and relationship matrix analysis between the two variables might enable one to thoroughly investigate and systematically consider various aspects of user characteristics as well as product design attributes in the product design process. Relationship matrix analysis adapted from the High touch design methodology could help focus group (ergonomists and product design engineer) find potential ergonomic design area. Second, regarding the identification of user satisfaction attributes, the modified HoQ method of this study utilized the ergonomics knowledge while existing QFD method is mostly based on customer survey. As mentioned earlier, a number of studies in the literature addressed that existing QFD method may fall short of identifying attractive user needs since users sometimes are not conscious of their high-level attractive needs (beyond the user's current knowledge). In order to mitigate the limitation or drawbacks of existing QFD method, this study utilized a systematic way of questionnaire formulation to elicit users' functional and affective needs related to user satisfaction using extensive ergonomics literature survey and statistical analysis. Apparently, this is a clear distinction between existing QFD method and the proposed design methodology of this study. The result of a case study revealed that ergonomics knowledge of design recommendations/checklists/guidelines related to a target product could help collect comprehensive list of user needs or requirements in terms of user satisfaction. A number of studies in the literature also supported that ergonomics knowledge can help reveal potential user needs or requirements (Nagamachi, 1995; Lee et al., 1997; Han and Hong, 2003).

However, according to the result of this study, it seemed that there were few attributes closely related to product pleasurability. This lack of product pleasurability may be partly explained by the following two reasons. First, the design target of the case study (screwdriver) is relatively simple compared to consumer electronics such as video/audio products. Accordingly, its inherent characteristics may limit or reduce usability or pleasurability issues (users' experience of enjoyment or pleasure to use) related to high-level user expectation or attractive user needs. Second, from quality perspective, Kano model (three types of user requirements) is dynamic over time or individuals. For example, a pleasurable (attractive) product attribute or function may not satisfy experienced individuals if they are well aware of it while a basic (must-be) product attribute or function can satisfy or surprise inexperienced individuals who have no idea about it. Regarding the result of this study, the magnetic tip of screwdriver can be a functionality-related attribute to experienced individuals while it can be a pleasurability-related attributes to inexperienced individuals. According to the recent studies of hand tools such as pepper grinders, nut crackers, and bottle openers (Hauge-Nilsen and Flyte, 2002), the product attributes/features identified to be closely associated with pleasurability were aesthetics, effectiveness, grip, easy of use, and easy control of the product. In fact, those attributes can be regarded as either functionality or usability between individuals. Their findings also supported that the concept of pleasurability mainly depends on user's current knowledge or level of experience in using hand tools.

Identification of Product Design Attributes

First of all, small number of expert focus group (2 ergonomists and 1 engineering professional) might be a potential limitation of this study. Even if product design attributes and user satisfaction attributes were systematically identified using their expert knowledge, and then they reached consensus within the focus group, this may not guarantee that their decision would satisfy all requirements and attributes since the decision of selecting and weighting product design attributes can be biased by subjective judgment of their practical experience and expert knowledge. One possible remedy of minimizing this concern would be to increase the number of focus group.

Identification of User Satisfaction Attributes

In general, user needs or expectation to a product is really important in the QFD methodology (Hauser and Clausing, 1988). In this study, the fact that samples from student population were used for identification of user needs can be a potential limitation since they are suspected of a representative sample of the general population of hand tools users. In fact, their experience in screwdriving task mostly amounted just one or two times in a month (mean: 3.6, s.d.: 4.87) so that they were not well aware of their needs or preference in using a screwdriver. A previous study commented that lack of user knowledge may restrict the usability of QFD (Haapalainen et al., 2000). For the same reason, their relative ratings of user satisfaction attributes associated with user satisfaction might be unreliable. In this case, the proposed ergonomic design methodology and subjective evaluation technique, which were based on the ratings of user, might be limited. In order to avoid or at least alleviate this limitation, experienced users (industrial professionals) were employed in this study. However, the number of experienced users ($n = 7$) was relatively too small to resolve the above mentioned limitation.

Interestingly, it should be emphasized that there exist a great difference of user expectations between novice group and expert group. According to the result of Mann-Whitney test for importance ratings on user satisfaction attributes, 11 out of 30 attributes were significantly differently rated between two groups. In addition, average rating score of novice group with regard to the third user satisfaction dimension (affective image/impression) was 3.06 while that of expert group (industrial professionals) was 1.92. This relatively large difference of ratings between novice and expert group may be partly explained by the following three reasons.

First, regarding the level of experience, inexperienced users may focus primarily on the holistic impression and the styling of a product since they may not be able to comment on functionality (Haapalainen et al., 2000; Khalid and Helander, 2004).

However, in this study, functionality-related score of novice group (3.85) was also higher than that of expert group (3.28). In addition, according to the result of Spearman rank correlation analysis, the ranks of two groups were significantly correlated ($\boldsymbol{r} = 0.911$, $P < 0.001$). One may argue why results of Mann-Whitney test and Spearman rank correlation analysis were inconsistent between two groups. As described in section 4.4.2 and shown in Figure 4.3, the resulting design priorities of two groups may explain this inconsistency. The result of design priority analysis revealed that industrial professionals may be well aware of their needs or expectations in using a screwdriver. On the other hand, inexperienced users may have no idea about their needs or preference to the screwdriver. As a result, for each of user satisfaction attribute, there could be a large difference in terms of average importance rating with same rank order. Accordingly, even if two groups differently rated the importance of user satisfaction attributes, the resulting ranks of user satisfaction attributes may show close agreement between two groups.

Second, cultural difference might be another explanation. In reality, origins of the majority of novice participants (student population) were Asian countries such as South Korea, China, and India while origin of expert group was the United State of America. Due to the cultural difference, their subjective expectations or preference related to the user satisfaction attributes, specifically in the third "affective image/impression" dimension, might be different from those of Americans (Khalid and Helander, 2004). Interestingly, though it was not expected, this study may suggest a possibility to compare the effects of cultural difference on users' subjective needs or expectation in a systematic way because the proposed methodology was designed to be applied regardless of the cultural background.

Third, occupational characteristics might be a possible explanation. In fact, the expert group consists of industrial professionals employed in the same company/business. Accordingly, it is assumed that their experience of screwdriving task in daily practice may not be quite different among them. Consequently, it may result in that they showed similar expectation or needs in using a screwdriver. This explanation was also supported by the resulting design priority score (described in section 4.4.2). Design priority of expert group was distinctly divided while that of novice group scattered across the product design attributes.

Questionnaire Formulation

One possible limitation of identification of user needs or requirements is related to the questionnaire formulation. In general, questionnaire survey has been widely used as a reliable technique to capture the voice of customer in QFD methodology (Bossert, 1991). However, questionnaire methodology has its inherent limitations. According to the literature, users usually don’t know what they really want (Kano et al., 1984; ReVelle et al., 1997) so that it is not sufficient to collect only the customer's explicit requirement (Griffin and Hauser, 1992). In addition, comprehensive customer surveys may result in excessive cost while small group of customers may not guarantee meeting customer needs thoroughly.

In order to mitigate the above mentioned drawbacks, pre-screened question item (user satisfaction attributes) were identified from the extensive ergonomics literature survey, and then utilized in this study. However, one may still suspect whether the final lists of user satisfaction attributes (user needs) utilized in this study were comprehensive and meaningful enough to resolve this limitation. In fact, it is difficult to obtain a comprehensive list of user needs. However, it is expected that this concern might be mitigated by comparing the result of this study with that of other studies in the literature. A previous study (Haapalainen et al., 2000), which used the QFD method for the ergonomic design of pruning shear, utilized 26 user requirements and employed 20 participants for preliminary test. Another study (Kuijt-Evers et al., 2004), which aimed to identify comprehensive comfort factors in using hand tools, selected 40 descriptors for the final list (58 initial descriptors) and utilized 22 participants. Khalid and Helander (2004) also employed 15 attributes and 80 participants to collect customer needs in product design. Hence, the question related to the user needs might be alleviated when comparing this study (60 initial and 26 final attributes, 57 participants) with the above published studies from a theoretical perspective. However, without a reliable user needs, the result from the proposed method would conclude with a poor performance. Hence, for enhancing the applicability in practice, it is believed that additional research is required to validate the user satisfaction questionnaire on different strata of population.

Regarding the reliability of questionnaire itself, this study examined the reliability of questionnaire using the established techniques such as factor analysis, item-total correlation, and Cronbach coefficient alpha. However, the selection of cutoff threshold could have great effect on the following questionnaire screening procedure and the final list of questionnaire. Especially, its effect on this study might increase compared to other studies since the final list of questionnaire was also utilized as input of the subjective evaluation method in the ergonomic evaluation of hand tools. Though there is no accepted standard of cutoff threshold, this might be a potential limitation of this study.

User Satisfaction Dimension

According to the published literature, user satisfaction is multi-dimensional and it could be defined and classified into several distinct dimensions (Han and Hong, 2003; Han et al., 2004). For the basis of this approach, a conceptual model of user satisfaction dimensions in using hand tools was adapted from the published literature (Han and Hong, 2003; Khalid and Helander, 2004; Kuijt-Evers et al., 2004). In general, the user satisfaction dimensions may differ with respect to the product. For instance, Han and Hong (2003) defined 25 dimensions for consumer electronics such as audio/video products. Khalid and Helander (2004) extracted three generic factors (dimensions), which consisted of holistic impression, styling, and functionality, related to affective customer needs for electronic devices such as navigation map and personal digital assistant. In addition, with respect to the concept of comfort in using hand tools, Kuijt-Evers et al. (2004) identified 3 meaningful groups including functionality, physical interaction and appearance. In fact, their functional definition of "comfort" was quite similar to that of user satisfaction in that their underlying descriptors of "comfort" included the concept of functionality, physical interaction, aesthetics, and quality. A common of above mentioned research findings was that the concept of user satisfaction is to embrace both functionality and subjective or affective aspects corresponding to consumer taste and preference.

In this study, 26 user satisfaction attributes were successfully classified into the three user satisfaction dimensions that consisted of performance, physical interaction, and affective image/impression. Consequently, the result of this study agreed with the findings of published literature. In particular, the functional definition of user satisfaction dimension defined in this study was quite similar to the functional definition of "comfort" in the previous study (Kuijt-Evers et al. 2004). However, there is a clear distinction between two studies in that their underlying comfort descriptors were not related or mapped to the product design attributes for the ergonomic design of a hand tool. Consequently, it is likely that this study validated their research findings related to ergonomic aspects of hand tools with regard to user satisfaction.

Validation of Design Methodology

Even though the case study of screwdriver did successfully demonstrate the applicability of the proposed ergonomic design methodology, there still exist methodological issues to be clarified. For example, the question may arise whether the proposed design methodology can be generalized to other products. Obviously, the next step in this stream of investigation is to validate the proposed design methodology of this study. Therefore, elaborated efforts for ensuring validity and reliability of the proposed methodologies needs to be considered for future study as followings.

First, the user satisfaction attributes, which were identified and prioritized in this study, need to be tested in terms of reliability. According to the results of this study, relative importance of user satisfaction attributes and resulting design priorities and critical ergonomic design areas varied with respect to the level of experience. Hence, in terms of test-retest reliability, it may be required to repeat questionnaire survey for examining whether the proposed method can give consistent results.

Second, an investigation for comparison of the proposed design technique (modified HoQ) and current QFD method regarding identification of users needs might be a future study. This study aims to examine whether the resulting user satisfaction attributes, which were derived by ergonomics literature survey instead of customer survey, can provide more comprehensive user needs and include potential (attractive) user requirements that may not be identified by simply asking users what they really want.

Third, as for another way to validate the proposed design methodology, a working prototype of screwdriver needs to be redesigned and manufactured as followed by the design process of this study. The resulting working prototype of screwdriver will be experimentally compared against the other screwdrivers which were employed and tested in this study. Once experimental results would indicate that the newly designed screwdriver would be superior to the other design alternatives, thereby it is expected that potential problem related to validation would be resolved.

Finally, more applications of the modified HoQ method to other products should be considered and evaluated analytically and experimentally. This work aims to demonstrate the capability of the proposed design methodology which can provide a unified environment for ergonomic product design.

7.1.2 Ergonomic Evaluation of Hand Tools

Maximum Torque Experiment

The maximum torque production has been a major criteria considered in the ergonomic evaluation of hand tools. Some important factors affecting the torque production capability are handle type, direction of rotation, posture, grip type, grip orientation, and temporal demands such as duration. In this study, handle type and direction of rotation were evaluated to prioritize screwdriver designs. According to the results from this study, the level of torque production significantly differed between subjects, handle types and directions of rotation. The result indicated that the cross-sectional handle shape could influence torque production. The findings of this study agreed with the previous study asserted that triangular shape handle generally produced more torque than cylindrical shape screwdrivers since the chances of slippage were reduced (Mital and Channaveeraiah, 1988). In fact, screwdriver type "B" and "C" have the tri-angular cross-sectional shape. Previous studies proved that a higher torque was obtained from the handle with larger diameter. However, the diameters of two screwdrivers evaluated in this study were not greatly different form each other (B: 3.7 cm, C: 3.3). Consequently, it was suspected that the smooth surface property of screwdriver type "B" reduced frictional resistance so as to lead to a poor performance. The significant effect of rotation direction revealed that supination torque was superior to pronation though there was no agreement between the published literatures.

Regarding the maximum torque production capability, the result of this study showed relatively low values (2.0 ~ 2.3 Nm). However, it may be difficult to directly compare the result of this study with previous research findings in the literature (described in Table 5.15). In general, the value of maximum torque strength might vary greatly with regard to various factors such as handle characteristics, experimental condition, and individual differences. Accordingly, relatively low value of maximum torque strength may be partly explained by the following three reasons. First, in terms of handle characteristics, the screwdrivers tested in this study have relatively small diameter (3.1 ~ 3.7 cm). Second, the working posture in terms of elbow angle employed in this study was 90° instead of 110°, which was expected to maximize the torque strength based on the previous research findings (Mital et al., 1994; O'Sullivan and Gallwey, 2002). Finally, participants' anthropometric characteristics employed in this study were below average in terms of height, weight, and hand size.

Regarding muscular activity (EMGs), it is difficult to claim that the lower is the better since this fact did not generally support the efficiency measure (ratio of Torque/EMG). In terms of efficiency measure, screwdriver type C was superior to other screwdriver types. It should be emphasized that muscular activity of BB was not an appropriate measure for pronation since bicep brachii (BB) acts on only supination while pronator quadratus and pronator teres are generally regarded as prime pronating muscles. Due to the channel limitation of data collection system, this study did not perform a detailed EMG study of upper extremity muscle activity during pronation. In future avenues of the study, more detailed EMG study of upper extremity muscles in screwdriving task should be considered. In terms of subjective ratings on overall discomfort and slipperiness, it can be claimed that handle type A was the most acceptable handle design. This result agreed with previous study suggested that longitudinal grooves could improve surface friction (Robinson and Lyon, 1994).

Constant Torque Experiment

Regarding the result of constant torque experiment, the results of Tukey's test revealed that muscular activity of BB of screwdriver type C was significantly lower. In terms of the efficiency measure (ratio of Torque/EMG), it can be claimed that the lower is the better in this case since a constant level (0.5 Nm) of torque exertion was utilized in this study. In terms of ulnar deviation angle, screwdriver type C was the worst design.

However this result was not meaningful since the mean difference was within 5 degrees that could result from measurement error. In terms of subjective ratings on overall discomfort and slipperiness, it is difficult to assert which one is the most desirable or acceptable design. Hence, it is likely that relatively low level of torque (0.5 Nm) used in this study was not sufficient to differentiate the five screwdriver designs. In reality, most of participants claimed that they had difficulty in rating on discomfort and slipperiness in the constant torque experiment.

Subjective Evaluation

The results of subjective evaluation revealed that screwdriver type A was the most favorable or acceptable design while type B was the worst design in terms of user satisfaction. Interestingly, screwdriver type E showed the best score in "performance" user satisfaction dimension. However its overall score deteriorated due to the worst score of "affective image/impression" dimension. In other words, screwdriver type E satisfied users' functional requirements while its appearance failed to appeal the users' subjective and affective feelings or preference. This result agreed with recent studies emphasizing the affective or emotional user needs. According to the results of objective measurements, torque production capabilities of 5 screwdriver designs did not differ considerably (2.02 ~ 2.3). Jordan (1999) asserted that *"once appropriate functionality is satisfied, the user has tendency to need something beyond the functionality."* In this respect, the proposed subjective evaluation technique in this study may have possibility to be utilized for ergonomic evaluation of product in terms of user satisfaction. However, it was difficult to find an agreement between the objective experimental measurements and subjective evaluation in terms of priority rank.

Finally, regarding the integrated priority measure proposed in this study, the design priority ranked by the integrated priority measure agreed with the result of subjective evaluation. The integrated priority measure also agreed with the results from major objective experimental measures such as torque production capability and discomfort rating. Moreover, 9 out of 11 objective measures were positively correlated to the integrated priority measure with relatively higher correlation coefficients ($\boldsymbol{r}$ = 0.3 ~ 0.9). This result may suggest that the integrated priority measure incorporating objective measurements into subjective evaluation method could be a comprehensive evaluation technique from a holistic perspective.

Comparison of Evaluation Methods

According to the results of correlation analysis, there was no strong evidence of significant association between evaluation methods. The research findings of this study may be partly explained by the following reasons. First, experimental condition of constant torque task may not be appropriate for evaluation method since relatively low torque level (0.5 Nm) utilized in the constant torque experimentation was not sufficient to differentiate the similar screwdriver design. Accordingly, most of participants complained of difficulties in subjective ratings of discomfort and slipperiness. Second, the results of subjective evaluation could be biased due to the inexperienced rater recruited from the student population. In addition, it might be difficult to subjectively evaluate the objective “performance” criteria such as torque output, precision, effectiveness, efficiency, and productivity.

7.2 CONCLUSION AND RESEARCH CONTRIBUTIONS

This thesis was motivated by recent studies which have suggested that the product attributes, closely associated with user satisfaction, were not only functionality but also users' subjective and affective feelings to a product.

Regarding the proposed ergonomic design methodology using a multidisciplinary approach, this study investigated the possibility of incorporating ergonomics knowledge into the established engineering design methodology (QFD) in order to enhance overall user satisfaction. It is hypothesized that comprehensive user needs can be systematically identified by utilizing ergonomics knowledge instead of existing customer survey techniques. This hypothesis was partly verified by successful demonstration of a case study of screwdriver. Accordingly, it can be asserted that a major contribution of this study is to suggest a systematic way of identifying the functional relationship between user satisfaction attributes and product design attributes. Once a reliable relationship is identified, it is likely to prioritize the product design attributes so as to identify the critical ergonomic design area for enhancing overall user satisfaction in using hand tools.

It is also hypothesized that user needs may vary between individuals with respect to their level of experience. This hypothesis was verified in accordance with the research findings of this study. According to the results of this study, relative importance of user needs related to user satisfaction varied over the level of experience (e.g., novice vs. expert) in using a hand tool. To satisfy each customer group, it is definitely required to identify design preference or priority to a specific product of each customer group. Hence, the proposed methodology in this study may provide valuable information for market segmentation (e.g., novice vs. expert).

As mentioned earlier, ergonomic knowledge related to hand tool design may be very extensive and scattered. In practice, engineering product designer or manufacturers might be overwhelmed by the amount of ergonomics data available. Once the proposed methodology in this study is validated in practice, it is expected that this multidisciplinary approach may enable the product designers to gain insights on critical design area to be seriously considered for enhancing overall user satisfaction.

The results of ergonomic design of screwdriver reached the following conclusions. A multidisciplinary approach incorporating ergonomics into the QFD method was appropriate for the ergonomic design of a hand tool. This thesis developed a systematic approach for identifying critical product design attributes of hand tools. The user satisfaction attributes identified from ergonomics perspective played a key role in both ergonomic design and subjective evaluation of a hand tool. The proposed approach was successfully demonstrated through a case study of screwdriver. The result of case study suggested that the critical design area of a screwdriver was closely related to the physical handle characteristics regardless of the level of user experience. User needs related to the supplementary functions of a screwdriver varied over the level of experience. Consequently, this thesis provided the information related to the critical product design attributes of a screwdriver, which could help engineering product designers identify what to seriously consider for enhancing overall user satisfaction.

The results of ergonomic evaluation of screwdriver reached the following conclusions. Five existing screwdriver were tested to evaluate the effects of screwdriver designs on objective measurement in terms of ergonomic effectiveness and subjective judgment with respect to user satisfaction. Although the results indicated that it was difficult to identify the design priority over the five different designs, subjective evaluation methodology using user satisfaction attributes showed a possibility to provide the basis for adequate and meaningful evaluation technique that considered all aspects relevant to the hand tools. In addition, it is likely that the integrated priority measure incorporating objective measurements into subjective evaluation method can be a comprehensive ergonomic evaluation technique from a holistic perspective. In the area of ergonomic design and evaluation of hand tools, ergonomic aspects of the human–hand tool interface including subjective aspects of users should be thoroughly considered. Finally, it is expected that the proposed ergonomic design and evaluation techniques could be applied to other hand tools.

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APPENDIX A: FUNCTIONAL ANATOMY OF UPPER EXTREMITY

A.1 Skeletal System of the Forearm

The skeleton of the hand is divided into three segments that consist of eight carpal bones, five metacarpal bones, and fourteen phalanges. The carpal bones are transversely arranged in two rows at the wrist. From the radial to the ulnar side, carpal bones of the proximal row are named scaphoid, lunate, triquetrum, and pisiform, respectively. Again, carpal bones in distal row are named trapezium, trapezoid, capitate, and hamate, respectively. The metacarpal bones consist of five cylindrical bones. The fourteen phalanges include three phalanges for each four finger and two phalanges for the thumb. The three phalanges of each finger are named proximal, middle, and distal, respectively while the thumb has no middle phalange. In the forearm, there are two parallel bones consisting of ulna and radius located from medial to lateral based on the anatomical position (Spence, 1990). Figure A.1 illustrates the skeleton of the hand and the forearm.

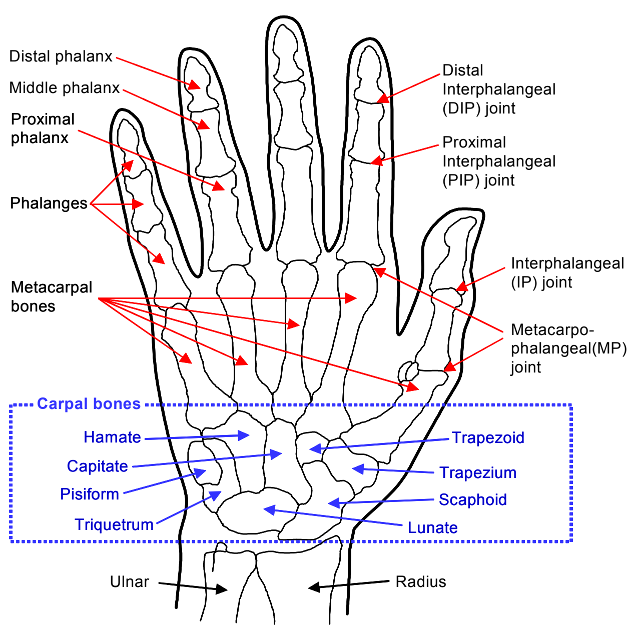

Figure A.1. Skeleton of the hand (Adapted from: Spence, 1990)

A.2 Muscular System of the Forearm

Based on the origin of the muscles, the muscle groups associated with movement of the forearm and the hand can be divided into extrinsic and intrinsic muscle groups. The extrinsic muscles originate in the forearm while the intrinsic muscles are entirely restricted in the hand. In this regard, extrinsic muscles are long and large so as to provide strength while intrinsic muscles are short and small so as to provide precise coordination of the fingers. In nature, the forearm movement is controlled by these two muscle groups. Although the function of each muscle group is quite different, coordination of the two muscles is essential for a variety of forearm movements such as flexion/extension, supination/pronation, and radial/ulnar deviation.

Extrinsic muscles of the forearm and hand can be divided into two groups, which are named as anterior muscles and posterior muscles based on the locations. Again, each muscle group can be separated further into superficial and deep muscle groups based on its location.

The anterior muscle groups serve as flexors. Most of anterior muscles originate from the medial epicondyle of the humerus and insert on the carpal bones, metacarpals or phalanges. Among the anterior superficial muscles, the flexor digitorum superficialis serves for flexion of the fingers. The flexor carpi ulnaris both flexes and adducts the wrist while the flexor carpi radialis flexes and abducts the wrist. The palmaris longus flexes the wrist and tenses the palm. Among the anterior deep muscles, the flexor pollicis longus flexes the thumb. The pronator teres performs the pronation of the forearm so that the palm turns downward. The brachioradialis performs the flexion of the forearm and it also serves as a synergist of the biceps brachii of the upper, which is strong supinator muscle.

The posterior group of forearm muscles serves as extensors. Most of posterior muscles originate from the lateral epicondyle of the humerus and insert on the carpus, metacarpals or phalanges. Among the posterior superficial muscles, the extensors carpi radialis longus and brevis perform the extension and abduction of the wrist while the extensor carpi ulnaris serves the extension and adduction of the wrist. The extensor digitorum plays important role of extension of the fingers. The extensor pollicis brevis and pollicis longus perform extension of the thumb, the extensor digiti minimi extends the little finger, and extensor indicis extends the index finger. The major extrinsic muscles are summarized and illustrated in Table A.1 and Figure A.2, respectively.

Table A.1. Extrinsic muscles of the forearm and the hand (Adapted From: Spence, 1990)

Group	Layer	Name	Function
Anterior	Superficial	Flexor carpi radialis	Flex and abduct the hand Support flexion of forearm
Anterior	Superficial	Palmaris longus	Flex hand
Anterior	Superficial	Flexor carpi ulnaris	Flex and adduct hand
Anterior	Middle	Flexor digitorum superficialis	Flex phalanges and the hand
Anterior	Deep	Flexor digitorum profundus	Flex phalanges and the hand
Anterior	Deep	Flexor pollicis longus	Flex the thumb Support flexion of the hand
Posterior	Superficial	Extensor carpi radialis longus	Extend and abduct hand
Posterior	Superficial	Extensor carpi radialis brevis	Extend hand
Posterior	Superficial	Extensor digitorum communis	Extend fingers and hand
Posterior	Superficial	Extensor digiti minimi	Extend little finger
Posterior	Superficial	Extensor carpi ulnaris	Extend and adduct hand
Posterior	Deep	Abductor pollicis longus	Extend thumb and abduct hand
Posterior	Deep	Extensor pollicis brevis	Extend thumb and abduct hand
Posterior	Deep	Extensor pollicis longus	Extend thumb and abduct hand
Posterior	Deep	Extensor indicis	Extend index finger

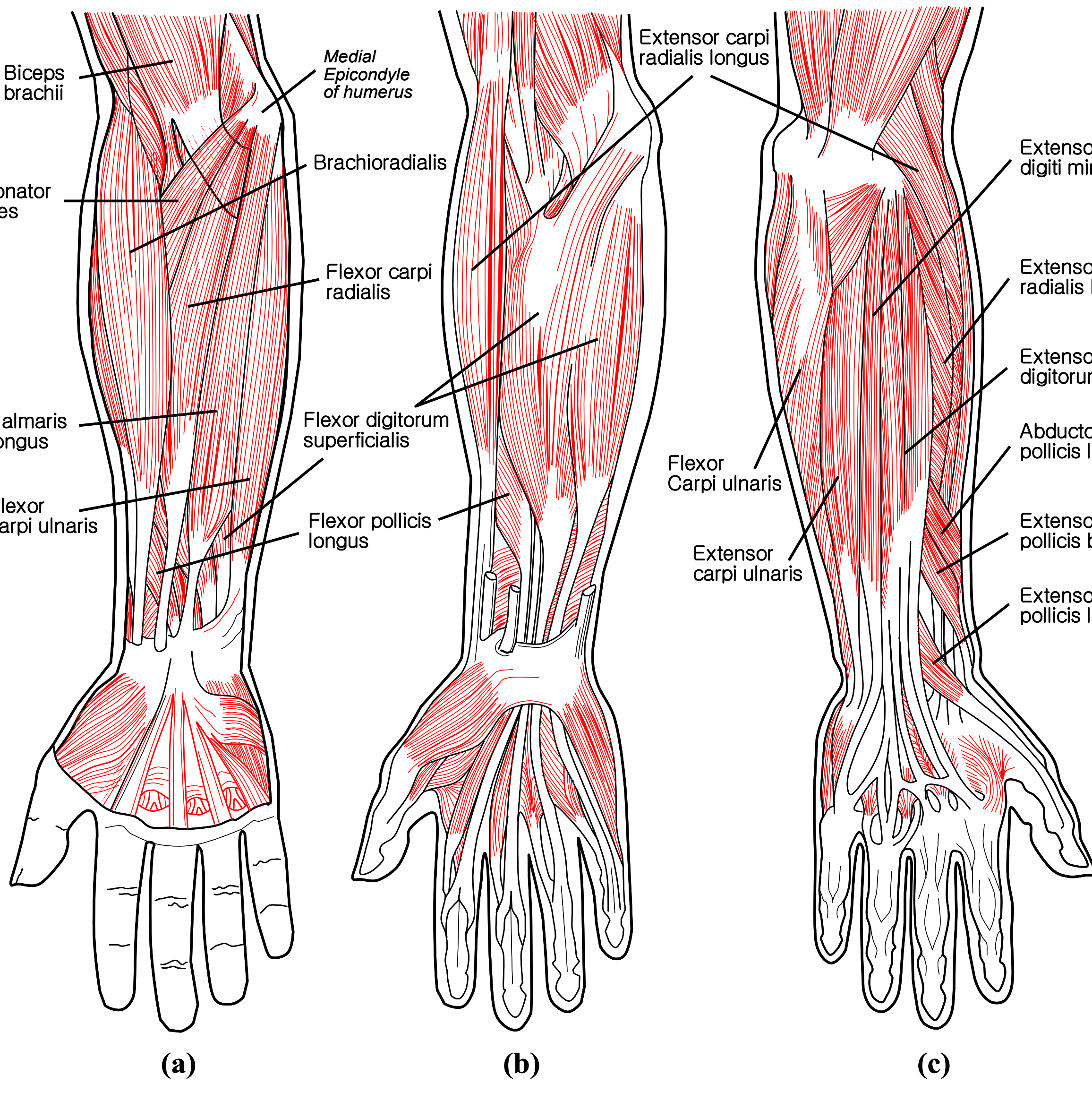

Figure A.2. Forearm muscles of the right hand (Adapted from: Spence, 1990)
: a) anterior superficial layer, b) anterior middle layer, c) posterior superficial layer

APPENDIX B: HAND GRIP CLASSIFICATIONS

There are infinite number of ways to grasp an object by changing the kinematics and kinetics of the human hand. A number of researchers have attempted to classify the variety of functional positions of the hand (Schlesinger, 1919; Napier, 1956; Cutkosky and Howe, 1990; MacKenzie and Iberall, 1994). Hand grip classifications have been developed to study the characteristics of the human hand in manipulating objects. Initially, the various hand grips were defined based on the static grasp of the hand holding the object. Some of these classifications are more anatomical, but most focus on functionality.

Schlesinger (1919) first categorized grasps as cylindrical, fingertip, hook, palmar, spherical, and lateral. Since the type of grasp employed tends to reflect the task to be performed, Napier (1956) suggested a categorization based on the distinction between power grasps and precision grasps. Cutkosky and Howe (1990) provided a grasp taxonomy that defines grasp attributes as dexterity, precision, sensitivity, stability, and security.

A simple taxonomy developed by Schlesinger (1919) represents one of many attempts that have been made to classify hand postures by researcher from different perspectives for medical, clinical, occupational, and industrial applications. His classification incorporated three critical notions: object shape (cylindrical, spherical), particular hand surface (tip, palmar, lateral), and hand shape (hook, close fist, open fist) (MacKenzie and Iberall, 1994).

Napier (1956) introduced his classification based on anatomy and physiology of the hand. Napier's classification for hand grip is more useful when it comes to the functional aspects of the hand. Napier classified handgrip into two different categories such as power grip and precision grip. Napier's hand grip classification is described as follows:

- Power grip: the thumb is in the plane of the palm. Thumb's metacarpophalangeal and carpometacarpal joints are adducted. Finger's are flexed, laterally rotated, and inclined towards the ulnar side of the hand. The fingers flex in opposition to the palm with the degree of flexion depending on object dimensions. The wrist is positioned with ulnar deviation, neural between extension and flexion.

- Precision grip: the thumb is abducted and medially rotated at the metacarpophangeal and the carpometacarpal joint. The fingers are flexed and abducted at the metacarpophalangeal joints producing a degree of axial rotation in the digits. The wrist is dorsiflexed, positioned between ulnar and radial deviation. The object is pinched between the finger and the opposing thumb, especially between the thumb and index finger which are used to hold a small object.

In particular, the thumb position mainly decides whether a grip is under the category of precision or power grip. When the thumb is more adducted, then the grip becomes close to precision and vice versa. The most important movement of hand is opposition. Opposition is a movement by which the pulp surface of the thumb is placed squarely in contact with or diametrically opposite to the terminal pads of one or all of the remaining digits.

Cutkosky and Howe (1990) developed taxonomy of grasp function based on Napier's definition of power grip and precision grip. Grasp functions are divided into power and precision orientation and classified further using attributes as dexterity, precision, sensitivity, stability, and security. Using the taxonomy, they developed a scheme for selecting a particular grip posture based on task requirements for controlling grip postures for robotic grippers. However, their classification scheme is comprehensive enough to describe the grasp tasks by humans (Yun, 1994).

APPENDIX C: SPECIFICATIONS OF APPARATUS

C.1 FlexComp Infiniti™ Encoder (SA7550, Thought Technology)

The sensors such as EMG and FSRs pass signals to the host computer via the microprocessor-controlled FlexComp Infiniti™ encoder unit. The encoder samples the incoming signals, digitizes, encodes, and transmits the sampled data to the TT-USB interface unit. A fiber optic cable is used for transmission, providing maximum freedom of movement, signal fidelity, and electrical isolation. Cable lengths up to 25 feet can be used without signal degradation. A unique feature of the system design allows inputs to accept any sensor, interchangeably. This allows a wide variety of configurations to be created by simply changing the sensor types.

The TT-USB interface unit is connected to one of the host computer's USB ports. It receives the data arriving from the encoder in optical form and converts it into the USB format to communicate with the software. The detailed specifications and features of FlexComp Infiniti™ encoder unit is summarized and illustrated in Table C.1 and Figure C.1, respectively.

Figure C.1. FlexComp Infiniti™ encoder (SA7550, Thought Technology)

Table C.1. Specifications and features of FlexComp Infiniti™ encoder

FlexComp Infiniti Encoder (SA7550)	
Size (approx.)	130mm x 95mm x 37mm (5.1” x 3.7” x 1.5”)
Weight (approx.)	200g (7oz)
Power Source	4AA batteries, single use alkaline or NiMh Rechargeable
Supply Voltage	3.6V – 6.5V (fiber optic), minimum 4.0V (Compact Flash)
Battery Life (Alkaline cells)	30h typical, 20h minimum
Low-battery warning	20 - 30 minutes of battery life remaining
Sensor supply voltage	7.260V ± 2mV
ADC output	14bits
Full-scale input range	2.8V±1.696V (DC)
LSB magnitude	207μV
Encoder channel bandwidth (3dB) and sample rate	DC – 512Hz @ 2048 samples/second DC – 64Hz @ 256 samples/second DC – 64Hz @ 200 samples/second DC – 8Hz @ 32 samples/second DC – 8Hz @ 20 samples/second
Anti-aliasing Filter	5th order Butterworth
Alias rejection	30dB typical
DC gain accuracy	±0.5% (initial, or after self-calibration)
DC offset	±3LSB (initial, or after self-calibration)
Overall system accuracy	5%
Offset drift	±5 LSB
Calibration temperature	±10C
Encoder noise	150μV RMS, 1mV p-p typical, offset removed

C.2 Electronic Torque Tester (ARM64-632, Armstrong Tools)

Electronic torque tester is designed to be a sturdy, compact, and cost efficient tester. It can be mounted on a wall or workbench allowing operators to test torque wrenches or power tools at their work stations. It also has unique neck design that allows easy viewing of the display screen even when the operator is testing long handled torque wrenches. Furthermore, it provides precise reading of torque tools (accuracy of +/- .5% of indicated value with 10-100% of full range). The detailed specifications and features of electronic torque tester is summarized and illustrated in Figure C.2 and Table C.2, respectively.

Figure C.2. Electronic Torque Tester (ARM64-632, Armstrong Tools)

Table C.2. Specifications of Electronic Torque Tester (Armstrong Tools)

Multifunction	Specifications
• First peak mode • Peak mode • Track mode • Power tool mode (non-impacting) • Dual scale (English/NM or English/dNM) • Auto/Manual reset • Reads in both clockwise/counter clockwise	• Drive Size: 3/8" • Primary Scale Range: 25-250 In/lb. • Secondary Scale Range: 28-280 dNm • Weight: 4.5 lbs.

C.3 FlexiForce™ Sensor (A201, Tekscan)

The detailed specifications and features of FlexiForce™ A201 sensor are shown in Figure C.3 and summarized in Table C.3.

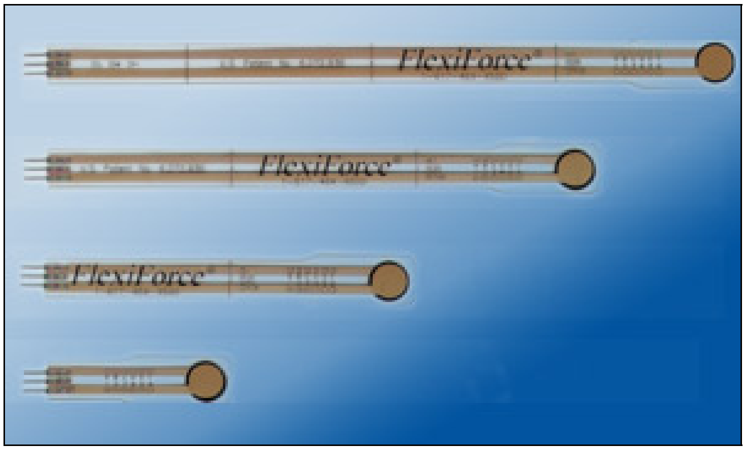

Figure C.3. FlexiForce™ sensors (A201, Tekscan)

Table C.3. Specifications of FlexiForce™ sensor (A201, Tekscan)

Features		Specifications
Physical Properties	Thickness	0.008" (0.127 mm)
	Length	8.000" (203 mm)
	Width	0.55" (14 mm)
	Active sensing area	0.375" (9.53 mm) Diameter
	Connector type	male square pin
Typical Performance	Linearity (Error)	< ±5%
	Repeatability	< ±2.5% of Full Scale *
	Hysteresis	< 4.5 % of Full Scale *
	Drift	< 3% / logarithmic time
	Rise Time **	< 5 µsec
	Operating Temperature	15°F - 140°F (-9°C - 60°C)

* Full Scale: 80% of full force applied to the conditioned sensor
** Rise Time: time required for the sensor to respond to an input force

Calibration of FlexiForce™ A201 Sensor

For the calibration of force measurement system, five known masses (89, 589, 1739, 4039, and 9239 g) as shown in Figure C.4 were placed on a FlexiForce™ sensor which was randomly chosen. Once good contact was established between the mass and the sensor surface, data sampling performed for 5 seconds using the FlexComp Infiniti™ data collection system (Thought Technology). Since the output value of FlexComp Infiniti™ system is represented by relative pressure unit (PU), a regression was performed to predict the actual force values based on measurement values, and presented in the Figure C.5.

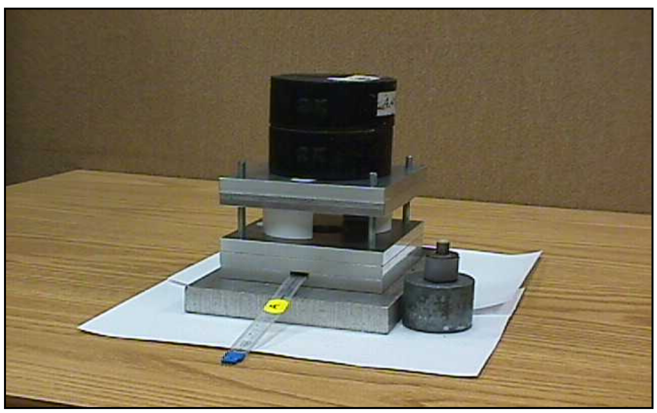

Figure C.4. A purpose built calibration device for FlexiForce™ sensor

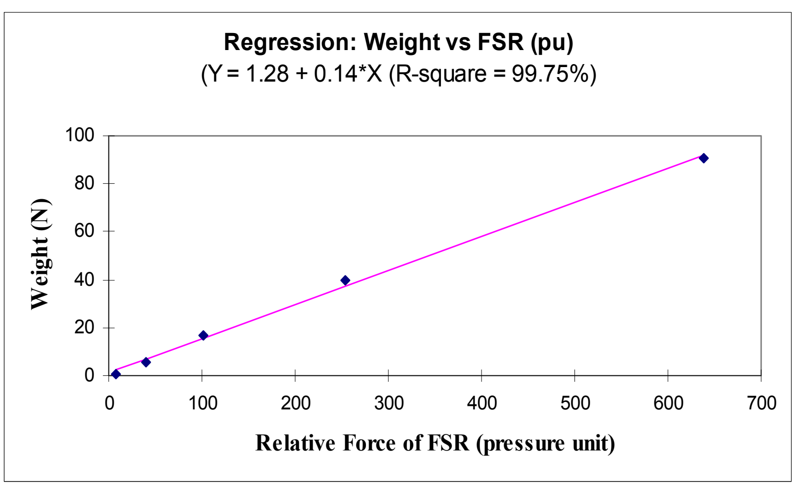

Figure C.5. Result of regression for calibration

C.4 Biaxial Electrogoniometer (XM110, Biometrics)

The biaxial electrogoniometer consists of two plastic end blocks which are separated by a flexible spring protecting a strain wire. The goniometer incorporates gauge elements which measure bending strain along or around a particular axis. The biaxial goniometer measures orthogonal rotational axes simultaneously (e.g. wrist flexion/extension and radial/ulnar deviations). Its width is 18 mm (0.7") and the length is 65 mm (2.6"). The measuring range of angles is ±150 degrees. The goniometer will be attached on a subject's right forearm and hand using two points, the third metacarpal and the dorsal center of the wrist. Figure C.6 shows a picture of biaxial electrogoniometer.

Figure C.6. Biaxial electrogoniometers (Biometrics)

C.5 MyoScan-Pro™ EMG Sensor (SA9401M, Thought Technology)

The MyoScan-Pro™ EMG sensor has built-in electronic circuitry to perform a root mean square (RMS) computation on the EMG signal, directly inside the sensor. The resulting RMS signal has a much slower rate of change and can be sampled at lower frequencies, including the 32 s/s available on the FlexComp Infiniti™ system. The MyoScan-Pro™ EMG sensor has a tiny switch, on its back that allows you to select a sensitivity scale of either 400 or 1600 micro-volts (μV). For most EMG applications, the 400 scale is preferable because it gives the best resolution. When you are defining EMG physical channels for specific large muscle groups, like thigh or buttock muscles, then you can ask the user of your channel set to switch to the 1600 μV scale.

The MyoScan-Pro™ EMG sensor's active range is from 20 to 500 Hz. It can record surface EMG signals of up to 1600 μV RMS. On the back of the sensor, there is a small switch with three positions: 400N, 1600W and 400W. In the 400W (wide bandwidth) position, the sensor will be sensitive to the full 20-500Hz bandwidth. When recording surface EMG from the upper body muscles, the sensor might pick up some electrical interference from the heart muscle, which is usually seen as a sharp spike occurring at every heartbeat. This noise can be filtered out by moving the switch to the 400N (narrow bandwidth) position. In this position, the sensor will only be sensitive to frequencies between 100 and 200 Hz. The third position, 1600W is for monitoring large muscle groups like thigh muscles. At the 400W or 400N positions, the sensor's amplitude scale is 400 µV, which allows for a good resolution for most of the body's muscles. The larger body muscles can produce microvolt readings of up-to 1600 µV. To properly monitor their activity, set the sensor to the 1600W position. The MyoScan-Pro™ EMG sensor's active range is from 10 to 500 Hz. It can record surface EMG signals from zero up to 2000 µV. The specifications of MyoScan Pro™ EMG Sensor are shown in Table C.4.

Table C.4. Specifications of MyoScan Pro™ EMG sensor

Specifications of MyoScan Pro™ EMG Sensor (SA9401M)	
Size (Approx.)	37mm x 37mm x 15mm (1.45" x 1.45" x 0.60")
Weight	25g (1 oz)
Input Impedance	10GΩ in parallel with 10pF
Input Range	0 – 400µ, 0 – 1600µ
Sensitivity	<0.1µ
Bandwidth	20Hz – 500Hz
Accuracy	±5%, ±0.3µ

APPENDIX D: INFORMED CONSENT FORM

INFORMED CONSENT FORM FOR BIOMEDICAL RESEARCH

The Pennsylvania State University

ORP USE ONLY:
The Pennsylvania State University
Office for Research Protections

Approval Date: 04/21/05 M. Becker

Expiration Date: 04/18/06 M. Becker

Biomedical Institutional Review Board

Title of Project: Ergonomic Evaluation of Manual Screwdrivers

Principal Investigator: Cheol Lee, Ph.D. Candidate
310 Leonhard Building, University Park, PA16802
(Email: CZL114@psu.edu, Phone 814-862-0168)

Advisor: Andris Freivalds, Ph.D., CPE, Professor
213 Leonhard Building, University Park, PA16802
(Email: axf@psu.edu, Phone 814-863-2361)

1. **Purpose of the study:** The purpose of this study is to evaluate five types of screwdrivers in order to investigate the effects of different handle designs of screwdrivers on both production capability and human's muscular effort and discomfort involved in screwdriving tasks; as well as user satisfaction in terms of subjective feelings about the design, simultaneously.

2. **Procedures to be followed:** This study consists of two types of questionnaire surveys and two sessions of experiment. You may choose to participate in the 1st questionnaire survey only (study 1). Otherwise, you would participate in all the questionnaire surveys and experimentations (study 2), respectively.

a. Study 1 (1st Questionnaire only)

For the study 1, you will be asked to answer the questions following the instruction in the 1st questionnaire form. The 1st questionnaire is intended to investigate your subjective taste or preference about user satisfaction related to the screwdriver design. The 1st questionnaire consists of 30 questions and it will take approximately 30 minutes.

b. Study 2 (1st Questionnaire, 1st experiment session, 2nd experiment session, and 2nd Questionnaire)

First, you will be asked to answer the questions following the instruction in the 1st questionnaire form. The 1st questionnaire is intended to investigate your subjective taste or preference about user satisfaction related to the screwdriver design.

Secondly, for the experiments, you will be asked to turn each screwdriver type clockwise and counterclockwise on the provided measuring device (torque tester) and build up your maximum muscular effort for the 1st experimental session. After the 1st experimental session, you will be also asked to maintain a predetermined level of your muscular effort for the 2nd experimental session. Each effort will be held for about three seconds. During this time your two forearm muscles will be connected to a device (EMG) which measures your muscular activity, for each muscle. After scrubbing the recording muscle sites with alcohol, a small sticky patch (electrode) will be attached. You will be also asked to attach six thin sensors on your fingers and palm area in order to measure the contact force between your hand and screwdriver. In addition, an angle-measuring device will be attached on your wrist area in order to monitor your wrist posture. There will be 3 trials for each handle type of 5 screwdrivers and 2 directions of rotation evaluated in each session in random order. Overall, the experiment consists of a total of 60 (3 trials×5 handle types×2 directions×2 sessions) trials. Between each trial you will be given a two minute resting break so you do not get tired. During the resting break between trials, you will be asked to verbally answer your subjective discomfort for each trial.

Finally, you will be asked to answer the questions following the instruction in the 2nd questionnaire form. The 2nd questionnaire is intended to evaluate the five types of screwdriver designs. The 2nd questionnaire consists of 30 questions and it will take approximately 30 minutes.

3. **Discomforts and risks:** There are no risks in participating in the questionnaire survey. However, if you would participate in the experiment, you may experience minimal discomforts such as fatigue or minor skin irritation from electrodes and muscle strain or soreness. However, there is no chance to develop a repetitive use injury or trauma due to the low exposure in terms of time. If you feel any significant discomfort, fatigue, and/or buzzing sensations on hand/finger area during participation, please stop and inform the investigator.

4. **Benefits:** You might learn more about different types of screwdrivers and their limitations. The benefits to society include that this study may help identify which type of screwdriver is more efficient in performing industrious tasks. Also, the findings of this study will help to develop an ergonomically designed screwdriver in efforts to reduce misusage and cumulative trauma disorders associated with current designs.

5. **Duration/time of the procedures and study:** Your participation in this study will take approximately 30 minutes (study 1) or a total of 210 minutes (study 2) including 30 minutes for each of two questionnaires, 30 minutes for experimental preparation, and 60 minutes for each of two experimental sessions.

6. **Alternative procedures that could be utilized:** No other alternative procedures will be utilized.

7. **Statement of confidentiality:** Your participation in this research is confidential. Only the investigator will have access to your identity and to information that can be associated with your identity. In the event of any publication or presentation resulting from the research, no personally identifiable information will be shared. The Office for Research Protections and the Biomedical Institutional Review Board (IRB) may review records related to this project.

8. **Right to ask questions:** You have been given an opportunity to ask any questions you may have, and all such questions or inquiries have been answered to your satisfaction. Questions regarding the nature of the research should be directed to Cheol Lee (University Park, PA, Email:CZL114@psu.edu, Phone: 814-862-0168). If you have questions about your rights as a research participant, you can contact The Pennsylvania State University's Office for Research Protections at 814-865-1775.

9. **Compensation**: You will be compensated either $5.00 (study 1) or $20.00 (study 2) or $5.00/hour for your participation in the study, respectively.

10. **Voluntary participation:** Your participation is voluntary. You can stop at any time. You do not have to answer any questions you do not want to answer. Your withdrawal from this study or your refusal to participate will in no way affect your care or access to medical services.

11. **Injury Clause:** In the unlikely event you become injured as a result of your participation in this study, medical care is available but neither financial compensation nor free medical treatment is provided. By signing this document, you are not waiving any rights that you have against The Pennsylvania State University for injury resulting from negligence of the University or its investigators**.**

You must be 18 years of age or older to take part in this research study. If you agree to take part in this research study and the information outlined above, please sign your name and indicate the date below.

You will be given a copy of this signed and dated consent for your records.

____ ____________________
Participant Signature **Date**

____ ____________________
Person Obtaining Consent (Principal Investigator) **Date**

APPENDIX E: QUESTIONNAIRE FOR USER SATISFACTION

QUESTIONNAIRE FOR USER SATISFACTION

Personal Information Form

ID#:	Age: ( ) yrs	Gender: Male ( ), Female ( )
Tool (screwdriver) Experience (sample answer: 3 per a week, 3 hours per a week)		
- Numbers of use per a day/week/month		
- Hours of use per a day/week/month		

Introduction

This questionnaire is intended to capture the "voice of customer" so as to identify critical design requirements related to user satisfaction for the ergonomic design of screwdriver. User satisfaction means that products should have the right function required to perform the intended tasks, correspond to users' subjective taste and preference, and provide pleasure in use of the product.

Assuming you are working for 8 hours a day with a screwdriver, how important to you is each of the following 30 user satisfaction factors considering your overall satisfaction in use of the screwdriver? Please pick a number from the scale and jot it in the bracket beside the question.

Rating Scale						
Extremely Unimportant	**1**	**2**	**3**	**4**	**5**	**Extremely Important**

Rating instruction*: if you feel the requirement is extremely important, pick a number from the far right side of the scale (e.g., 5). If you feel it is extremely unimportant, pick a number from the far left (e.g., 1), and if you feel the importance is between these extremes, pick a number from someplace in the middle of the scale to show your opinion.*

1. **Force/torque output** [scale: ________]
: The tool provides the force/torque output required to perform the intended task

*If you have any specific requirement/needs with regard to the **force/torque output**, please write down your needs. If not, you may skip this question.*

____

2. **Precision** [scale: ________]
: The tool provides the precision required to perform the intended task

*If you have any specific requirement/needs with regard to the **precision**, please write down your needs. If not, you may skip this question.*

____

3. **Effectiveness** [scale: ________]
: The tool provides the right function required to perform the intended task

*If you have any specific requirement/needs with regard to the **effectiveness**, please write down your needs. If not, you may skip this question.*

____

4. **Efficiency** [scale: ________]
: The tool performs the intended task with minimum user effort

*If you have any specific requirement/needs with regard to the **efficiency**, please write down your needs. If not, you may skip this question.*

____

5. **Productivity** [scale: ________]
: The tool maximizes the work output during a work day

*If you have any specific requirement/needs with regard to the **productivity**, please write down your needs. If not, you may skip this question.*

____

6. **Durability** [scale: ________]
: The tool maximizes the duration of product/part life; avoid damage to the working object and product itself with adequate handle/tip hardness

*If you have any specific requirement/needs with regard to the **durability**, please write down your needs. If not, you may skip this question.*

____

7. **Multi-function** [scale: ________]
: The tool provides different functions for a variety of tasks

If you have any specific requirement/needs with regard to the ***multi-function****, please write down your needs. If not, you may skip this question.*

____

8. **Handle shape** [scale: ________]
: The tool provides an adequate grip for different users (gender/age) and/or grip type (power/precision)

If you have any specific requirement/needs with regard to the ***handle shape****, please write down your needs. If not, you may skip this question.*

____

9. **Handle size** [scale: ________]
: The tool provides an adequate handle size to fit various hand sizes and/or grip type (power/precision)

If you have any specific requirement/needs with regard to the ***handle size****, please write down your needs. If not, you may skip this question.*

____

10. **Tool weight** [scale: ________]
: The tool is as light as the function requires

If you have any specific requirement/needs with regard to the ***tool weight****, please write down your needs. If not, you may skip this question.*

____

11. **Manipulation** [scale: ________]
: The tool is easy to understand the intended use of the product, so as to be able to manipulate the product for performing the required task

If you have any specific requirement/needs with regard to the ***manipulation****, please write down your needs. If not, you may skip this question.*

____

12. **Convenience/Portability** [scale: ________]
: The tool is easy to carry/store/pick up & put down the product, the shape and size of the product is adequate for its function

If you have any specific requirement/needs with regard to the ***convenience/portability****, please write down your needs. If not, you may skip this question.*

____

13. **Identification** [scale: ________]
: The tool is easy to discriminate this product from other similar products

*If you have any specific requirement/needs with regard to the **identification**, please write down your needs. If not, you may skip this question.*

____

14. **Maintenance** [scale: ________]
: The tool is easy to maintain/clean/repair the product

*If you have any specific requirement/needs with regard to the **maintenance**, please write down your needs. If not, you may skip this question.*

____

15. **All-weather proof** [scale: ________]
: The tool provides the right function regardless of weather conditions

*If you have any specific requirement/needs with regard to the **all-weather proof**, please write down your needs. If not, you may skip this question.*

____

16. **Safety** [scale: ________]
: The tool is safe to use; the product does not harm the user

*If you have any specific requirement/needs with regard to the **safety**, please write down your needs. If not, you may skip this question.*

____

17. **Feedback** [scale: ________]
: The tool provides adequate feedback of task completion

*If you have any specific requirement/needs with regard to the **feedback**, please write down your needs. If not, you may skip this question.*

____

18. **Grip comfort** [scale: ________]
: The tool provides a good fit in hand/fingers without pain/peak pressures on hand/fingers, irritation of tissue/blisters, numbness/lack of tactile feeling, muscle cramping/soreness, and interference from protective equipment such as gloves

*If you have any specific requirement/needs with regard to the **grip comfort**, please write down your needs. If not, you may skip this question.*

____

19. **Grip friction** [scale: ________]
: The tool provides adequate grip friction between hand and handle; no slippery handle/ no sweaty handle

*If you have any specific requirement/needs with regard to the **grip friction**, please write down your needs. If not, you may skip this question.*

___

The following questions are closely related to your subjective feelings /preference (perceived image/impression) to the product appearance

20. **Luxurious** [scale: ________]
: The product looks flashy, splendid, or extravagant

*If you have any specific requirement/needs with regard to the **luxurious**, please write down your needs. If not, you may skip this question.*

___

21. **Harmony** [scale: ________]
: The components of the product are well-matched, balanced, and in harmony

*If you have any specific requirement/needs with regard to the **harmony**, please write down your needs. If not, you may skip this question.*

___

22. **Neatness** [scale: ________]
: The product looks clean, tidy, and well-arranged

*If you have any specific requirement/needs with regard to the **neatness**, please write down your needs. If not, you may skip this question.*

___

23. **Rigidity** [scale: ________]
: The product looks solid, stable, and secure

*If you have any specific requirement/needs with regard to the **rigidity**, please write down your needs. If not, you may skip this question.*

___

24. **Attractiveness** [scale: ________]
: The product looks pleasing/charming and arouses interest/fun

*If you have any specific requirement/needs with regard to the **attractiveness**, please write down your needs. If not, you may skip this question.*

___

25. **Craftsmanship** [scale: ________]
: The product is produced with great care and in fine detail

*If you have any specific requirement/needs with regard to the **craftsmanship**, please write down your needs. If not, you may skip this question.*

____

26. **Prominence/Uniqueness** [scale: ________]
: The product is outstanding, prominent, unique, and eye-catching

*If you have any specific requirement/needs with regard to the **prominence/uniqueness**, please write down your needs. If not, you may skip this question.*

____

27. **Shape** [scale: ________]
: The shape of the tool integrates its components characteristics (ratio, length, area, etc.) well

*If you have any specific requirement/needs with regard to the **shape**, please write down your needs. If not, you may skip this question.*

____

28. **Color** [scale: ________]
: The conceptual image of the product is identified by its color/color combination

***How many** color combination do you like? (e.g., 1, 2, 3, etc.):* ____________________

*What is your **favorite color** or color combination to be applied to the design of screwdriver in accordance with the above answer? (e.g., if you answer '2', you should pick two colors)*

____

*If you have any specific requirement/needs with regard to the **color**, please write down your needs. If not, you may skip this question.*

____

29. **Texture** [scale: ________]
: The image/impression of the product is developed by its texture (e.g., soft, coarse, etc.)

*If you have any specific requirement/needs with regard to the **texture**, please write down your needs. If not, you may skip this question.*

____

30. **Design/Styling** [scale: ________]

: The conceptual image of the product is identified by its design (e.g., conventional or innovative, traditional or modern, common or unique)

Several image/impressions related to the ***design/styling*** *are listed below. Please indicate your degree of preference by circling a number*

			Scale			
Conventional	**1**	**2**	**3**	**4**	**5**	**Innovative**
Traditional	**1**	**2**	**3**	**4**	**5**	**Modern**
Common	**1**	**2**	**3**	**4**	**5**	**Unique**
Simple	**1**	**2**	**3**	**4**	**5**	**Tangled**

If you have any specific requirement/needs with regard to the ***design/styling****, please write down your needs. If not, you may skip this question.*

____

If you have any specific requirement/needs that are not related to the above user satisfaction factors, please write down your needs. If not, you may skip this question.

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APPENDIX F: QUESTIONNAIRE FOR DESIGN EVALUATION

QUESTIONNAIRE FOR DESIGN EVALUATION

Personal Information Form

ID#:	Age: ( ) yrs	Gender: Male ( ), Female ( )
Tool (screwdriver) Experience (sample answer: 3 per a week, 3 hours per a week)		
- Numbers of use per a day/week/month		
- Hours of use per a day/week/month		

Introduction

This questionnaire is intended to evaluate different design of screwdriver in terms of user satisfaction. User satisfaction means that products should have the right function required to perform the intended tasks, correspond to users' subjective taste and preference, and provide pleasure in use of the product.

Assuming you are working for 8 hours a day with a screwdriver, please rate your level of satisfaction or preference with respect to the each user satisfaction factor, which is defined/described. Please pick a number from the scale for each screwdriver design, which will be presented and tested by you, based on your subjective evaluation and jot it in the space below the each design type, respectively.

Rating Scale						
Not at all	**1**	**2**	**3**	**4**	**5**	**Perfectly satisfied or preferred**

Rating instruction*: if you feel the given design is perfectly satisfied or preferred, pick a number from the far right side of the scale (e.g., 5). If you feel it is extremely unsatisfied, pick a number from the far left (e.g., 1), and if your level of preference or satisfaction is between these extremes, pick a number from someplace in the middle of the scale to show your opinion.*

1. **Force/torque output**

: The tool provides the force/torque output required to perform the intended task

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

2. **Precision**

: The tool provides the precision required to perform the intended task

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

3. **Effectiveness**

: The tool provides the right function required to perform the intended task

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

4. **Efficiency**

: The tool performs the intended task with minimum user effort

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

5. **Productivity**

: The tool maximizes the work output during a work day

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

6. **Durability**

: The tool maximizes the duration of product/part life; avoid damage to the working object and product itself with adequate handle/tip hardness

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

7. **Multi-function**

: The tool provides different functions for a variety of tasks

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

8. **Handle shape**
: The tool provides an adequate grip for different users (gender/age) and/or grip type (power/precision)

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

9. **Handle size**
: The tool provides an adequate handle size to fit various hand sizes and/or grip type (power/precision)

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

10. **Tool weight**
: The tool is as light as the function requires

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

11. **Manipulation**
: The tool is easy to understand the intended use of the product, so as to be able to manipulate the product for performing the required task

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

12. **Convenience/Portability**
: The tool is easy to carry/store/pick up & put down the product, the shape and size of the product is adequate for its function

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

13. **Identification**
: The tool is easy to discriminate this product from other similar products

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

14. **Maintenance**
: The tool is easy to maintain/clean/repair the product

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

15. **All-weather proof**
: The tool provides the right function regardless of weather conditions

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

16. **Safety**
: The tool is safe to use; the product does not harm the user

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

17. **Feedback**
: The tool provides adequate feedback of task completion

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

18. **Grip comfort**
: The tool provides a good fit in hand/fingers without pain/peak pressures on hand/fingers, irritation of tissue/blisters, numbness/lack of tactile feeling, muscle cramping/soreness, and interference from protective equipment such as gloves

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

19. **Grip friction**
: The tool provides adequate grip friction between hand and handle; no slippery handle/ no sweaty handle

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

The following questions are closely related to your subjective feelings /preference (perceived image/impression) to the product appearance

20. **Luxurious**
: The product looks flashy, splendid, or extravagant

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

21. **Harmony**
: The components of the product are well-matched, balanced, and in harmony

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

22. **Neatness**
: The product looks clean, tidy, and well-arranged

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

23. **Rigidity**
: The product looks solid, stable, and secure

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

24. **Attractiveness**
: The product looks pleasing/charming and arouses interest/fun

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

25. **Craftsmanship**
: The product is produced with great care and in fine detail

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

26. **Prominence/Uniqueness**
: The product is outstanding, prominent, unique, and eye-catching

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

27. **Shape**
: The shape of the tool integrates its components characteristics (ratio, length, area, etc.) well

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

28. **Color**
: The conceptual image of the product is identified by its color/color combination

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

29. **Texture**
: The image/impression of the product is developed by its texture (e.g., soft, coarse, etc.)

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

30. **Design/Styling**
: The conceptual image of the product is identified by its design (e.g., conventional or innovative, traditional or modern, common or unique)

	Screwdriver design type				
	A	B	C	D	E
Rating scale					

APPENDIX G: QUESTIONNAIRE FOR SCREENING PARTICIPANT

QUESTIONNAIRE FOR SCREENING PARTICIPANT

Participant Information

ID#:	Participant Code (PI use only):
Age: _______ yrs	Gender: Male ( ), Female ( )

Screening Questions

1) Have you had any incidents of hand or wrist pain?

YES NO

If yes, please explain ____

____

2) If your answer to question 1) was "yes", have these incidents limited your physical activities?

YES NO

If yes, please explain ____

____

3) Have you had any hand surgery?

YES NO

If yes, please explain ____

____

4) If your answer to question 3 was "yes", has this surgery limited your physical activities?

YES NO

If yes, please explain ____

____

5) Are you suffering from any chronic disease (e.g. diabetes, epilepsy, etc.)?

YES NO

If yes, please explain ____

____

________________________________ ____________________

Participant Signature **Date**

APPENDIX H: QUESTIONNAIRE FOR DISCOMFORT RATING

QUESTIONNAIRE FOR DISCOMFORT RATING

Participant Information: Participant Code (   )

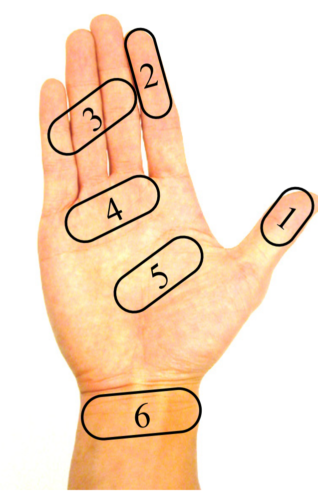
ID#:	Age: _______ yrs
Hand Laterality: Left ( ) Right ( )	Gender: Male ( ) Female ( )

Experimental conditions

Screwdriver type	A ( ) B ( ) C ( ) D ( ) E ( )
Rotation direction	Clockwise ( ), Counterclockwise ( )

Rating Instruction

Please give a rating of the perceived discomfort on the hand/fingers/wrist area and slipperiness in use of a given screwdriver; pick a number form the scale based on your subjective evaluation and jot it in the space beside each of area codes and slipperiness, respectively.

Area code (1-6)	Rating	Rating scale (Borg's CR-10)	Hand map
1 Thumb		0. No discomfort 0.5 Barely noticeable discomfort 1. Very mild discomfort 2. Mild discomfort 3. Moderate discomfort 4. 5. Strong discomfort 6. 7. Very strong discomfort 8. 9. 10. Unbearable discomfort	
2 Index finger			
3 Middle phalange			
4 Metacarpal			
5 Thenar			
6 Wrist			
Slipperiness			
Overall discomfort			

APPENDIX I: RESULTS OF STATISTICAL ANALYSIS

I.1 Pilot Experiment

I.1.1 Analysis of Variance (ANOVA): General Linear Model

Factor	Type	Levels	Values
Type	fixed	5	1 2 3 4 5
Subject	random	4	1 2 3 4
Trial	fixed	2	1 2

Response Variable: Maximum Torque (Torque)

Analysis of Variance for Torque, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type	4	3.15194	3.15194	0.78799	10.01	**0.000****
Subject	3	0.32584	0.32584	0.10861	1.38	0.267
Trial	1	0.21609	0.21609	0.21609	2.74	0.108
Error	31	2.44077	2.44077	0.07873		
Total	39	6.13464				

Least Squares Means for Torque

Type	Mean
1	2.264
2	2.284
3	1.648
4	1.814
5	1.676

Response Variable: Normalized EMG of FDS (EMG_FDS)

Analysis of Variance for EMG_FDS, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type	4	0.118150	0.118150	0.029537	4.45	**0.006****
Subject	3	0.244980	0.244980	0.081660	12.31	**0.000****
Trial	1	0.000360	0.000360	0.000360	0.05	0.817
Error	31	0.205710	0.205710	0.006636		
Total	39	0.569200				

Least Squares Means for EMG_FDS

Type	Mean
1	0.8138
2	0.7563
3	0.8888
4	0.7950
5	0.8963

Response Variable: Normalized EMG of Biceps Brachii (EMG_BB)

Analysis of Variance for EMG_BB, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type	4	0.17974	0.17974	0.04493	2.19	0.093
Subject	3	0.12614	0.12614	0.04205	2.05	0.127
Trial	1	0.03136	0.03136	0.03136	1.53	0.226
Error	31	0.63593	0.63593	0.02051		
Total	39	0.97316				

Least Squares Means for EMG_BB

Type	Mean
1	0.7613
2	0.8225
3	0.6663
4	0.6650
5	0.8050

Response Variable: Normalized Subjective Ratings on Overall Discomfort (Dis_All)

Analysis of Variance for Dis_All, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type	4	1.67462	1.67462	0.41866	16.15	**0.000****
Subject	3	0.13869	0.13869	0.04623	1.78	0.171
Trial	1	0.06806	0.06806	0.06806	2.63	0.115
Error	31	0.80356	0.80356	0.02592		
Total	39	2.68494				

Least Squares Means for Dis_All

Type	Mean
1	0.3125
2	0.2438
3	0.7250
4	0.6687
5	0.6812

Response Variable: Normalized Subjective Ratings on Slipperiness (Slip)

Analysis of Variance for Slip, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type	4	3.53663	3.53662	0.88416	39.92	**0.000****
Subject	3	0.15319	0.15319	0.05106	2.31	0.096
Trial	1	0.03306	0.03306	0.03306	1.49	0.231
Error	31	0.68656	0.68656	0.02215		
Total	39	4.40944				

Least Squares Means for Slip

Type	Mean
1	0.43750
2	0.05000

3	0.71875
4	0.79375
5	0.85625

Response Variable: Normalized Grip Force at Middle Finger Area (FSR1)

Analysis of Variance for FSR1, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type	4	0.10292	0.10292	0.02573	3.69	**0.014***
Subject	3	1.51817	1.51817	0.50606	72.62	**0.000****
Trial	1	0.00048	0.00048	0.00048	0.07	0.795
Error	31	0.21603	0.21603	0.00697		
Total	39	1.83760				

Least Squares Means for FSR1

Type	Mean
1	0.3778
2	0.3895
3	0.4309
4	0.3287
5	0.2845

Response Variable: Normalized Grip Force at Ring Finger Area (FSR2)

Analysis of Variance for FSR2, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type	4	0.047003	0.047003	0.011751	1.49	0.229
Subject	3	0.751934	0.751934	0.250645	31.77	**0.000****
Trial	1	0.000781	0.000781	0.000781	0.10	0.755
Error	31	0.244606	0.244606	0.007891		
Total	39	1.044324				

Least Squares Means for FSR2

Type	Mean
1	0.3640
2	0.3598
3	0.3992
4	0.3039
5	0.3177

Response Variable: Normalized Grip Force at Metacarpal Area (FSR3)

Analysis of Variance for FSR3, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type	4	0.26228	0.26228	0.06557	1.77	0.160
Subject	3	0.10632	0.10632	0.03544	0.96	0.425
Trial	1	0.05813	0.05813	0.05813	1.57	0.219
Error	31	1.14716	1.14716	0.03701		
Total	39	1.57390				

Least Squares Means for FSR3

Type	Mean
1	0.5829
2	0.3999
3	0.5477
4	0.4655
5	0.3743

Response Variable: Normalized Grip Force at Thenar Area (FSR4)

Analysis of Variance for FSR4, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type	4	0.28522	0.28522	0.07131	5.86	**0.001****
Subject	3	1.16222	1.16222	0.38741	31.83	**0.000****
Trial	1	0.02310	0.02310	0.02310	1.90	0.178
Error	31	0.37732	0.37732	0.01217		
Total	39	1.84787				

Least Squares Means for FSR4

Type	Mean
1	0.1892
2	0.1298
3	0.1001
4	0.3384
5	0.1402

Response Variable: Wrist Ulnar Deviation Angle (Wrist)

Analysis of Variance for Wrist, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type	4	96.30	96.30	24.07	2.24	0.088
Subject	3	479.75	479.75	159.92	14.87	**0.000****
Trial	1	0.11	0.11	0.11	0.01	0.918
Error	31	333.44	333.44	10.76		
Total	39	909.61				

Least Squares Means for Wrist

Type	Mean
1	29.63
2	28.84
3	26.97
4	26.06
5	25.67

I.1.2 Post-hoc Analysis: Tukey's Test

Response Variable: Maximum Torque (Torque)

All Pairwise Comparisons among Levels of Type

Type = 1 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.0200	0.1403	0.143	0.9999
3	-0.6163	0.1403	-4.392	**0.0011****
4	-0.4500	0.1403	-3.207	**0.0240***
5	-0.5875	0.1403	-4.188	**0.0019****

Type = 2 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	-0.6362	0.1403	-4.535	**0.0007****
4	-0.4700	0.1403	-3.350	**0.0169***
5	-0.6075	0.1403	-4.330	**0.0013****

Type = 3 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	0.16625	0.1403	1.1850	0.7597
5	0.02875	0.1403	0.2049	0.9996

Type = 4 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
5	-0.1375	0.1403	-0.9801	0.8622

Response Variable: Normalized EMG of FDS (EMG_FDS)

All Pairwise Comparisons among Levels of Type

Type = 1 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-0.05750	0.04073	-1.412	0.6250
3	0.07500	0.04073	1.841	0.3692
4	-0.01875	0.04073	-0.460	0.9903
5	0.08250	0.04073	2.026	0.2780

Type = 2 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	0.13250	0.04073	3.2531	**0.0215***
4	0.03875	0.04073	0.9514	0.8743
5	0.14000	0.04073	3.4373	0.0136

Type = 3 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	-0.09375	0.04073	-2.302	0.1715
5	0.00750	0.04073	0.184	0.9997

Type = 4 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
5	0.1012	0.04073	2.486	0.1200

Response Variable: Normalized Subjective Ratings on Overall Discomfort (Dis_All)

All Pairwise Comparisons among Levels of Type

Type = 1 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-0.06875	0.08050	-0.8540	0.9112
3	0.41250	0.08050	5.1242	**0.0001****
4	0.35625	0.08050	4.4254	**0.0010****
5	0.36875	0.08050	4.5807	**0.0006****

Type = 2 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	0.4812	0.08050	5.978	**0.0000****
4	0.4250	0.08050	5.279	**0.0001****
5	0.4375	0.08050	5.435	**0.0001****

Type = 3 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	-0.05625	0.08050	-0.6988	0.9552
5	-0.04375	0.08050	-0.5435	0.9819

Type = 4 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
5	0.01250	0.08050	0.1553	0.9999

Response Variable: Normalized Subjective Ratings on Slipperiness (Slip)

All Pairwise Comparisons among Levels of Type

Type = 1 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-0.3875	0.07441	-5.208	**0.0001****
3	0.2813	0.07441	3.780	**0.0056****

4	0.3562	0.07441	4.788	**0.0004****
5	0.4188	0.07441	5.628	**0.0000****

Type = 2 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	0.6687	0.07441	8.987	**0.0000****
4	0.7437	0.07441	9.995	**0.0000****
5	0.8062	0.07441	10.835	**0.0000****

Type = 3 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	0.07500	0.07441	1.008	0.8498
5	0.13750	0.07441	1.848	0.3657

Type = 4 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
5	0.06250	0.07441	0.8399	0.9160

I.1.3 Correlation Analysis: Pearson Correlation Coefficient

Correlations: Torque, Dis_All, Slip, EMG_FDS, EMG_BB, Wrist

	Torque	Dis_All	Slip	EMG_FDS	EMG_BB
Dis_All	-0.502				
	0.001**				
Slip	-0.499	0.750			
	0.001**	**0.000****			
EMG_FDS	-0.423	0.191	0.244		
	0.006**	0.237	0.129		
EMG_BB	0.167	-0.321	-0.211	0.064	
	0.302	0.043	0.191	0.695	
Wrist	0.330	-0.194	-0.164	-0.664	0.041
	0.037*	0.230	0.312	**0.000****	0.801

Cell Contents: Pearson correlation
P-Value (*: P <0.05, **: P < 0.01)

I.2 Maximum Torque Experiment

I.2.1 Analysis of Variance (ANOVA): General Linear Model

Factor	Type	Levels	Values
Direction	fixed	2	1 2
Type	fixed	5	1 2 3 4 5
Subject	random	15	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Trial	fixed	3	1 2 3

Response Variable: Maximum Torque (Torque)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	554.00	554.00	554.00	46.92	**0.000****
Type	4	264.23	264.23	66.06	5.59	**0.000****
Subject	14	4505.60	4505.60	321.83	27.25	**0.000****
Trial	2	13.25	13.25	6.62	0.56	0.571
Direction*Type	4	35.79	35.79	8.95	0.76	0.553
Error	424	5006.75	5006.75	11.81		
Total	449	10379.62				

Response Variable: Normalized EMG of FDS (EMG_FDS)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.25016	0.25016	0.25016	18.62	**0.000****
Type	4	0.10987	0.10987	0.02747	2.04	0.087
Subject	14	1.10889	1.10889	0.07921	5.90	**0.000****
Trial	2	0.02209	0.02209	0.01104	0.82	0.440
Direction*Type	4	0.00923	0.00923	0.00231	0.17	0.953
Error	424	5.69639	5.69639	0.01343		
Total	449	7.19663				

Response Variable: Normalized EMG of FDS (EMG_BB)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	46.5162	46.5162	46.5162	3878.87	**0.000****
Type	4	0.2143	0.2143	0.0536	4.47	**0.002****
Subject	14	1.7166	1.7166	0.1226	10.22	**0.000****
Trial	2	0.0369	0.0369	0.0184	1.54	0.216
Direction*Type	4	0.2283	0.2283	0.0571	4.76	**0.001****
Error	424	5.0847	5.0847	0.0120		
Total	449	53.7970				

Response Variable: Wrist Ulnar Deviation Angle (Wrist)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	7527.64	7527.64	7527.64	416.48	**0.000****
Type	4	40.91	40.91	10.23	0.57	0.688
Subject	14	3568.30	3568.30	254.88	14.10	**0.000****
Trial	2	2.92	2.92	1.46	0.08	0.922
Direction*Type	4	176.02	176.02	44.00	2.43	**0.047***
Error	424	7663.56	7663.56	18.07		
Total	449	18979.35				

Response Variable: Normalized Grip Force at Thumb Area (FSR1)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.00811	0.00811	0.00811	0.27	0.601
Type	4	0.82910	0.82910	0.20728	7.00	**0.000****
Subject	14	5.93623	5.93623	0.42402	14.32	**0.000****
Trial	2	0.09480	0.09480	0.04740	1.60	0.203
Direction*Type	4	0.26635	0.26635	0.06659	2.25	0.063
Error	424	12.55055	12.55055	0.02960		
Total	449	19.68514				

Response Variable: Normalized Grip Force at Index Finger Area (FSR2)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	1.57472	1.57472	1.57472	71.11	**0.000****
Type	4	0.06098	0.06098	0.01525	0.69	0.600
Subject	14	4.51675	4.51675	0.32263	14.57	**0.000****
Trial	2	0.05911	0.05911	0.02955	1.33	0.264
Direction*Type	4	0.17969	0.17969	0.04492	2.03	0.090
Error	424	9.38897	9.38897	0.02214		
Total	449	15.78023				

Response Variable: Normalized Grip Force at Middle Finger Area (FSR3)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	3.40779	3.40779	3.40779	121.53	**0.000****
Type	4	0.88468	0.88468	0.22117	7.89	**0.000****
Subject	14	11.48274	11.48274	0.82020	29.25	**0.000****
Trial	2	0.10107	0.10107	0.05053	1.80	0.166
Direction*Type	4	0.54032	0.54032	0.13508	4.82	**0.001****
Error	424	11.88960	11.88960	0.02804		
Total	449	28.30620				

Response Variable: Normalized Grip Force at Ring Finger Area (FSR4)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.64147	0.64147	0.64147	28.84	**0.000****
Type	4	2.58682	2.58682	0.64671	29.08	**0.000****
Subject	14	5.72283	5.72283	0.40877	18.38	**0.000****
Trial	2	0.20784	0.20784	0.10392	4.67	**0.010***
Direction*Type	4	0.45531	0.45531	0.11383	5.12	**0.000****
Error	424	9.42964	9.42964	0.02224		
Total	449	19.04392				

Response Variable: Normalized Grip Force at Metacarpal Area (FSR5)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.51681	0.51681	0.51681	49.32	**0.000****
Type	4	0.53819	0.53819	0.13455	12.84	**0.000****
Subject	14	5.12284	5.12284	0.36592	34.92	**0.000****
Trial	2	0.00449	0.00449	0.00225	0.21	0.807
Direction*Type	4	0.11957	0.11957	0.02989	2.85	**0.024***
Error	424	4.44295	4.44295	0.01048		
Total	449	10.74485				

Response Variable: Normalized Grip Force at Thenar Area (FSR6)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	5.96506	5.96506	5.96506	249.36	**0.000****
Type	4	1.00208	1.00208	0.25052	10.47	**0.000****
Subject	14	8.37566	8.37566	0.59826	25.01	**0.000****
Trial	2	0.00114	0.00114	0.00057	0.02	0.976
Direction*Type	4	0.49920	0.49920	0.12480	5.22	**0.000****
Error	424	10.14268	10.14268	0.02392		
Total	449	25.98582				

Response Variable: Normalized Subjective Discomfort Ratings on Thumb Area (DR1)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.08053	0.08053	0.08053	6.77	**0.010***
Type	4	0.57020	0.57020	0.14255	11.99	**0.000****
Subject	14	6.04433	6.04433	0.43174	36.30	**0.000****
Trial	2	0.01943	0.01943	0.00971	0.82	0.443
Direction*Type	4	0.07344	0.07344	0.01836	1.54	0.189
Error	424	5.04276	5.04276	0.01189		
Total	449	11.83069				

Response Variable: Normalized Subjective Discomfort Ratings on Index Finger Area (DR2)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.03957	0.03957	0.03957	3.81	0.052
Type	4	0.97840	0.97840	0.24460	23.52	**0.000****
Subject	14	4.30444	4.30444	0.30746	29.57	**0.000****
Trial	2	0.01923	0.01923	0.00962	0.92	0.397
Direction*Type	4	0.05791	0.05791	0.01448	1.39	0.236
Error	424	4.40860	4.40860	0.01040		
Total	449	9.80816				

Response Variable: Normalized Subjective Discomfort Ratings on Middle Phalange Area (DR3)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.00231	0.00231	0.00231	0.14	0.712
Type	4	0.40048	0.40048	0.10012	5.89	**0.000****
Subject	14	3.36886	3.36886	0.24063	14.16	**0.000****
Trial	2	0.00670	0.00670	0.00335	0.20	0.821
Direction*Type	4	0.12152	0.12152	0.03038	1.79	0.130
Error	424	7.20532	7.20532	0.01699		
Total	449	11.10518				

Response Variable: Normalized Subjective Discomfort Ratings on Metacarpal Area (DR4)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.00657	0.00657	0.00657	0.50	0.478
Type	4	0.48949	0.48949	0.12237	9.39	**0.000****
Subject	14	3.70750	3.70750	0.26482	20.32	**0.000****
Trial	2	0.00325	0.00325	0.00162	0.12	0.883
Direction*Type	4	0.20852	0.20852	0.05213	4.00	**0.003****
Error	424	5.52621	5.52621	0.01303		
Total	449	9.94154				

Response Variable: Normalized Subjective Discomfort Ratings on Thenar Area (DR5)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.00493	0.00493	0.00493	0.29	0.587
Type	4	0.86648	0.86648	0.21662	12.95	**0.000****
Subject	14	5.26420	5.26420	0.37601	22.47	**0.000****
Trial	2	0.00840	0.00840	0.00420	0.25	0.778
Direction*Type	4	0.16875	0.16875	0.04219	2.52	**0.041***
Error	424	7.09489	7.09489	0.01673		
Total	449	13.40765				

Response Variable: Normalized Subjective Discomfort Ratings on Wrist Area (DR6)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.41770	0.41770	0.41770	23.78	**0.000****
Type	4	0.62628	0.62628	0.15657	8.91	**0.000****
Subject	14	4.98688	4.98688	0.35621	20.28	**0.000****
Trial	2	0.01992	0.01992	0.00996	0.57	0.568
Direction*Type	4	0.12007	0.12007	0.03002	1.71	0.147
Error	424	7.44692	7.44692	0.01756		
Total	449	13.61776				

Response Variable: Normalized Subjective Ratings on Slipperiness (Slip)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.00062	0.00062	0.00062	0.03	0.860
Type	4	1.82218	1.82218	0.45555	22.83	**0.000****
Subject	14	5.36787	5.36787	0.38342	19.21	**0.000****
Trial	2	0.08152	0.08152	0.04076	2.04	0.131
Direction*Type	4	0.06671	0.06671	0.01668	0.84	0.503
Error	424	8.46206	8.46206	0.01996		
Total	449	15.80096				

Response Variable: Normalized Subjective Ratings on Overall Discomfort (Dis_All)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.10734	0.10734	0.10734	7.41	**0.007****
Type	4	1.22394	1.22394	0.30599	21.12	**0.000****
Subject	14	4.11875	4.11875	0.29420	20.31	**0.000****
Trial	2	0.00955	0.00955	0.00477	0.33	0.719
Direction*Type	4	0.07509	0.07509	0.01877	1.30	0.271
Error	424	6.14283	6.14283	0.01449		
Total	449	11.67749				

Least Squares Means for All Response Variables

	Torque	**EMG_FDS**	**EMG_BB**
Type	Mean	Mean	Mean
1	22.6000	0.7354	0.4458
2	22.3756	0.6999	0.3954
3	23.5489	0.7407	0.4251
4	21.1456	0.7102	0.3923
5	22.4778	0.7306	0.4380
Direction			
1	23.5391	0.7469	0.7408
2	21.3200	0.6998	0.0978

	Wrist	FSR1	FSR2
Type	Mean	Mean	Mean
1	29.2311	0.4706	0.3673
2	29.5856	0.3963	0.3689
3	29.4400	0.3810	0.3558
4	29.0356	0.4380	0.3751
5	29.9156	0.4944	0.3422
Direction			
1	25.3516	0.4403	0.4210
2	33.5316	0.4318	0.3027

	FSR3	FSR4	FSR5
Type	Mean	Mean	Mean
1	0.4234	0.4521	0.2796
2	0.4656	0.4798	0.1916
3	0.5148	0.4838	0.1803
4	0.3936	0.3048	0.2107
5	0.4060	0.3352	0.2229
Direction			
1	0.5277	0.3734	0.2509
2	0.3536	0.4489	0.1831

	FSR6	DR1	DR2
Type	Mean	Mean	Mean
1	0.4088	0.4553	0.4802
2	0.3550	0.4662	0.4972
3	0.4558	0.4547	0.5059
4	0.3903	0.5384	0.5891
5	0.4880	0.5218	0.5871
Direction			
1	0.5347	0.4739	0.5225
2	0.3044	0.5007	0.5413

	DR3	DR4	DR5
Type	Mean	Mean	Mean
1	0.5810	0.6332	0.6640
2	0.6502	0.6583	0.6864
3	0.6376	0.7088	0.6960
4	0.6707	0.7236	0.7896
5	0.6294	0.6723	0.6857
Direction			
1	0.6315	0.6754	0.7076
2	0.6360	0.6831	0.7010

	DR6	Slip	Dis_All
Type	Mean	Mean	Mean
1	0.6340	0.5557	0.6362
2	0.6541	0.7136	0.6990
3	0.6781	0.7391	0.7330
4	0.7442	0.6942	0.7969
5	0.6868	0.6684	0.7043
Direction			
1	0.6490	0.6730	0.6984
2	0.7099	0.6754	0.7293

I.2.2 Post-hoc Analysis: Tukey's Test

Response Variable: Maximum Torque (Torque)

All Pairwise Comparisons among Levels of Type

Type = 1 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-0.224	0.5123	-0.438	0.9924
3	0.949	0.5123	1.852	0.3435
4	-1.454	0.5123	-2.839	**0.0365***
5	-0.122	0.5123	-0.239	0.9993

Type = 2 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	1.173	0.5123	2.291	0.1479
4	-1.230	0.5123	-2.401	0.1149
5	0.102	0.5123	0.200	0.9996

Type = 3 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	-2.403	0.5123	-4.692	**0.0000****
5	-1.071	0.5123	-2.091	0.2239

Type = 4 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
5	1.332	0.5123	2.601	0.0702

Response Variable: Normalized EMG of BB (EMG_BB)

All Pairwise Comparisons among Levels of Type

Type = 1 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-0.05033	0.01632	-3.083	**0.0175***
3	-0.02067	0.01632	-1.266	0.7122
4	-0.05344	0.01632	-3.274	**0.0094****
5	-0.00778	0.01632	-0.476	0.9895

Type = 2 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	0.029667	0.01632	1.8173	0.3634
4	-0.003111	0.01632	-0.1906	0.9997

5	0.042556	0.01632	2.6068	0.0691

Type = 3 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	-0.03278	0.01632	-2.008	0.2621
5	0.01289	0.01632	0.790	0.9337

Type = 4 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
5	0.04567	0.01632	2.797	**0.0412***

Response Variable: Normalized Subjective Rating on Slipperiness (Slip)

All Pairwise Comparisons among Levels of Type

Type = 1 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.1579	0.02106	7.497	**0.0000****
3	0.1834	0.02106	8.711	**0.0000****
4	0.1386	0.02106	6.579	**0.0000****
5	0.1128	0.02106	5.355	**0.0000****

Type = 2 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	0.02556	0.02106	1.213	0.7436
4	-0.01933	0.02106	-0.918	0.8901
5	-0.04511	0.02106	-2.142	0.2023

Type = 3 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	-0.04489	0.02106	-2.132	0.2066
5	-0.07067	0.02106	-3.356	**0.0071****

Type = 4 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
5	-0.02578	0.02106	-1.224	0.7373

Response Variable: Normalized Subjective Ratings on Overall Discomfort (Dis_All)

All Pairwise Comparisons among Levels of Type

Type = 1 subtracted from:

Level   Difference   SE of   Adjusted

Type	of Means	Difference	T-Value	P-Value
2	0.06278	0.01794	3.499	**0.0043****
3	0.09678	0.01794	5.394	**0.0000****
4	0.16067	0.01794	8.954	**0.0000****
5	0.06811	0.01794	3.796	**0.0014****

Type = 2 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	0.034000	0.01794	1.8949	0.3200
4	0.097889	0.01794	5.4555	**0.0000****
5	0.005333	0.01794	0.2972	0.9983

Type = 3 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	0.06389	0.01794	3.561	**0.0034****
5	-0.02867	0.01794	-1.598	0.4988

Type = 4 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
5	-0.09256	0.01794	-5.158	**0.0000****

All Pairwise Comparisons among Levels of Direction

Direction = 1 subtracted from:

Level Direction	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.03089	0.01135	2.722	**0.0065****

I.3 Constant Torque Experiment

I.3.1 Analysis of Variance (ANOVA): General Linear Model

Factor	Type	Levels	Values
Direction	fixed	2	1 2
Type	fixed	5	1 2 3 4 5
Subject	random	15	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Trial	fixed	3	1 2 3

Response Variable: Normalized EMG of FDS (EMG_FDS)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.04560	0.04560	0.04560	15.36	**0.000****
Type	4	0.02225	0.02225	0.00556	1.87	0.114
Subject	14	4.17443	4.17443	0.29817	100.46	**0.000****
Trial	2	0.01941	0.01941	0.00970	3.27	**0.039***
Direction*Type	4	0.02071	0.02071	0.00518	1.74	0.139
Error	424	1.25847	1.25847	0.00297		
Total	449	5.54087				

Response Variable: Normalized EMG of BB (EMG_BB)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.301088	0.301088	0.301088	401.67	**0.000****
Type	4	0.037896	0.037896	0.009474	12.64	**0.000****
Subject	14	0.197696	0.197696	0.014121	18.84	**0.000****
Trial	2	0.000723	0.000723	0.000362	0.48	0.618
Direction*Type	4	0.010368	0.010368	0.002592	3.46	**0.009****
Error	424	0.317825	0.317825	0.000750		
Total	449	0.865596				

Response Variable: Wrist Ulnar Deviation Angle (Wrist)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	848.72	848.72	848.72	37.38	**0.000****
Type	4	548.34	548.34	137.08	6.04	**0.000****
Subject	14	6091.95	6091.95	435.14	19.16	**0.000****
Trial	2	45.30	45.30	22.65	1.00	0.370
Direction*Type	4	191.88	191.88	47.97	2.11	0.078
Error	424	9627.32	9627.32	22.71		
Total	449	17353.51				

Response Variable: Normalized Subjective Discomfort Ratings on Thumb Area (DR1)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.00907	0.00907	0.00907	0.79	0.374
Type	4	0.71684	0.71684	0.17921	15.66	**0.000****
Subject	14	7.91207	7.91207	0.56515	49.39	**0.000****
Trial	2	0.03091	0.03091	0.01545	1.35	0.260
Direction*Type	4	0.03908	0.03908	0.00977	0.85	0.492
Error	424	4.85183	4.85183	0.01144		
Total	449	13.55980				

Response Variable: Normalized Subjective Discomfort Ratings on Index Finger Area (DR2)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.00043	0.00043	0.00043	0.03	0.856
Type	4	0.57223	0.57223	0.14306	10.91	**0.000****
Subject	14	7.89197	7.89197	0.56371	43.00	**0.000****
Trial	2	0.02493	0.02493	0.01246	0.95	0.387
Direction*Type	4	0.05307	0.05307	0.01327	1.01	0.401
Error	424	5.55828	5.55828	0.01311		
Total	449	14.10091				

Response Variable: Normalized Subjective Discomfort Ratings on Middle Phalange Area (DR3)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.10611	0.10611	0.10611	7.16	**0.008****
Type	4	0.33488	0.33488	0.08372	5.65	**0.000****
Subject	14	8.18859	8.18859	0.58490	39.46	**0.000****
Trial	2	0.08684	0.08684	0.04342	2.93	0.055
Direction*Type	4	0.01405	0.01405	0.00351	0.24	0.917
Error	424	6.28539	6.28539	0.01482		
Total	449	15.01586				

Response Variable: Normalized Subjective Discomfort Ratings on Metacarpal Area (DR4)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.05467	0.05467	0.05467	3.30	0.070
Type	4	1.06113	1.06113	0.26528	16.00	**0.000****
Subject	14	9.21499	9.21499	0.65821	39.71	**0.000****
Trial	2	0.10663	0.10663	0.05332	3.22	**0.041***
Direction*Type	4	0.22635	0.22635	0.05659	3.41	**0.009****
Error	424	7.02863	7.02863	0.01658		
Total	449	17.69241				

Response Variable: Normalized Subjective Discomfort Ratings on Thenar Area (DR5)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.00157	0.00157	0.00157	0.09	0.767
Type	4	0.88087	0.88087	0.22022	12.38	**0.000****
Subject	14	10.25138	10.25138	0.73224	41.16	**0.000****
Trial	2	0.08048	0.08048	0.04024	2.26	0.105
Direction*Type	4	0.07367	0.07367	0.01842	1.04	0.389
Error	424	7.54280	7.54280	0.01779		
Total	449	18.83077				

Response Variable: Normalized Subjective Discomfort Ratings on Wrist Area (DR6)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.12836	0.12836	0.12836	8.30	**0.004****
Type	4	0.99810	0.99810	0.24952	16.13	**0.000****
Subject	14	9.46317	9.46317	0.67594	43.69	**0.000****
Trial	2	0.01158	0.01158	0.00579	0.37	0.688
Direction*Type	4	0.23103	0.23103	0.05776	3.73	**0.005****
Error	424	6.55934	6.55934	0.01547		
Total	449	17.39157				

Response Variable: Normalized Subjective Ratings on Slipperiness (Slip)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.09159	0.09159	0.09159	6.60	**0.011****
Type	4	0.55634	0.55634	0.13909	10.02	**0.000****
Subject	14	8.54572	8.54572	0.61041	43.97	**0.000****
Trial	2	0.09516	0.09516	0.04758	3.43	**0.033***
Direction*Type	4	0.24610	0.24610	0.06153	4.43	**0.002****
Error	424	5.88561	5.88561	0.01388		
Total	449	15.42053				

Response Variable: Normalized Subjective Ratings on Overall Discomfort (Dis_All)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Direction	1	0.02785	0.02785	0.02785	1.67	0.197
Type	4	1.68983	1.68983	0.42246	25.36	**0.000****
Subject	14	6.25877	6.25877	0.44706	26.84	**0.000****
Trial	2	0.06380	0.06380	0.03190	1.92	0.149
Direction*Type	4	0.07300	0.07300	0.01825	1.10	0.358
Error	424	7.06243	7.06243	0.01666		
Total	449	15.17569				

Least Squares Means for All Response Variables

	EMG_FDS	**EMG_BB**	**Wrist.**
Type	Mean	Mean	Mean
1	0.2748	0.0799	27.5633
2	0.2641	0.0707	27.9322
3	0.2598	0.0554	30.6322
4	0.2744	0.0807	28.0678
5	0.2781	0.0749	29.0089
Direction			
1	0.2803	0.0982	27.2676
2	0.2602	0.0464	30.0142

	DR1	**DR2**	**DR3**
Type	Mean	Mean	Mean
1	0.4352	0.4819	0.5141
2	0.4154	0.4504	0.5568
3	0.4317	0.4856	0.5634
4	0.4996	0.5554	0.5999
5	0.5148	0.5176	0.5621
Direction			
1	0.4548	0.4992	0.5439
2	0.4638	0.4972	0.5746

	DR4	**DR5**	**DR6**
Type	Mean	Mean	Mean
1	0.5498	0.5710	0.5613
2	0.5867	0.6188	0.5711
3	0.5683	0.6229	0.6094
4	0.6893	0.7082	0.6866
5	0.6106	0.6340	0.6487
Direction			
1	0.5899	0.6291	0.5985
2	0.6120	0.6328	0.6323

	Slip	**Dis_All**
Type	Mean	Mean
1	0.5408	0.5954
2	0.6163	0.6090
3	0.5778	0.6154
4	0.5584	0.7631
5	0.5118	0.6617
Direction		
1	0.5468	0.6411
2	0.5753	0.6568

I.3.2 Post-hoc Analysis: Tukey's Test

Response Variable: Normalized EMG of BB (EMG_BB)

All Pairwise Comparisons among Levels of Type

Type = 1 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-0.00922	0.004081	-2.260	0.1582
3	-0.02444	0.004081	-5.989	**0.0000****
4	0.00078	0.004081	0.191	0.9997
5	-0.00500	0.004081	-1.225	0.7367

Type = 2 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	-0.01522	0.004081	-3.730	**0.0018****
4	0.01000	0.004081	2.450	0.1023
5	0.00422	0.004081	1.035	0.8394

Type = 3 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	0.02522	0.004081	6.180	**0.0000****
5	0.01944	0.004081	4.764	**0.0000****

Type = 4 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
5	-0.005778	0.004081	-1.416	0.6175

All Pairwise Comparisons among Levels of Direction

Direction = 1 subtracted from:

Level Direction	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-0.05173	0.002581	-20.04	**-0.0000****

Response Variable: Wrist Ulnar Deviation Angle (Wrist)

All Pairwise Comparisons among Levels of Type

Type = 1 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.3689	0.7103	0.5193	0.9855
3	3.0689	0.7103	4.3203	**0.0001****
4	0.5044	0.7103	0.7101	0.9543
5	1.4456	0.7103	2.0350	0.2492

Type = 2 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	2.7000	0.7103	3.8010	**0.0014****
4	0.1356	0.7103	0.1908	0.9997
5	1.0767	0.7103	1.5157	0.5522

Type = 3 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	-2.564	0.7103	-3.610	**0.0028****
5	-1.623	0.7103	-2.285	0.1495

Type = 4 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
5	0.9411	0.7103	1.325	0.6757

All Pairwise Comparisons among Levels of Direction

Direction = 1 subtracted from:

Level Direction	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	2.747	0.4493	6.114	**0.0000****

Response Variable: Normalized Subjective Ratings on Slipperiness (Silp)

All Pairwise Comparisons among Levels of Type

Type = 1 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.07556	0.01756	4.302	**0.0002****
3	0.03700	0.01756	2.107	0.2171
4	0.01767	0.01756	1.006	0.8528
5	-0.02900	0.01756	-1.651	0.4646

Type = 2 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	-0.0386	0.01756	-2.195	0.1814
4	-0.0579	0.01756	-3.296	**0.0087****
5	-0.1046	0.01756	-5.953	**0.0000****

Type = 3 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	-0.01933	0.01756	-1.101	0.8062
5	-0.06600	0.01756	-3.758	**0.0016****

Type = 4 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
5	-0.04667	0.01756	-2.657	0.0605

All Pairwise Comparisons among Levels of Direction

Direction = 1 subtracted from:

Level Direction	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.02853	0.01111	2.569	**0.0102***

Response Variable: Normalized Subjective Ratings on Overall Discomfort (Dis_All)

All Pairwise Comparisons among Levels of Type

Type = 1 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.01356	0.01924	0.7046	0.9555
3	0.02000	0.01924	1.0395	0.8370
4	0.16767	0.01924	8.7148	**0.0000****
5	0.06622	0.01924	3.4420	**0.0052****

Type = 2 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	0.006444	0.01924	0.3350	0.9973
4	0.154111	0.01924	8.0103	**0.0000****
5	0.052667	0.01924	2.7375	0.0487

Type = 3 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	0.14767	0.01924	7.675	**0.0000****
5	0.04622	0.01924	2.402	0.1146

Type = 4 subtracted from:

Level Type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
5	-0.1014	0.01924	-5.273	**0.0000****

I.4 Mann-Whitney U Test

Comparison of Ratings on User Satisfaction Attributes between Novice and Expert

User Satisfaction Attributes 1: Force/Torque Output

```
NOVICE_1      N = 50      Median = 5.0000
EXPERT_1      N =  7      Median = 4.0000
Point estimate for ETA1-ETA2 is      0.0000
95.2 Percent CI for ETA1-ETA2 is (-0.0002,1.0002)
W = 1483.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.4294
The test is significant at 0.3782 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 2: Precision

```
NOVICE_2      N = 50     Median = 4.000
EXPERT_2      N =  7     Median = 4.000
Point estimate for ETA1-ETA2 is       0.000
95.2 Percent CI for ETA1-ETA2 is (-1.000,1.000)
W = 1445.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.9129
The test is significant at 0.9049 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 3: Effectiveness

```
NOVICE_3      N = 50     Median = 5.000
EXPERT_3      N =  7     Median = 4.000
Point estimate for ETA1-ETA2 is      -0.000
95.2 Percent CI for ETA1-ETA2 is (-0.000,1.000)
W = 1476.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.5353
The test is significant at 0.4955 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 4: Efficiency

```
NOVICE_4      N = 50     Median = 5.000
EXPERT_4      N =  7     Median = 4.000
Point estimate for ETA1-ETA2 is       0.000
95.2 Percent CI for ETA1-ETA2 is (-0.000,1.000)
W = 1482.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.4438
The test is significant at 0.3948 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 5: Productivity

```
NOVICE_5      N = 50     Median = 4.000
EXPERT_5      N =  7     Median = 3.000
```

```
Point estimate for ETA1-ETA2 is       1.000
95.2 Percent CI for ETA1-ETA2 is (0.000,2.000)
W = 1505.5
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.1811
The test is significant at 0.1594 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 6: Durability

```
NOVICE_6      N = 50     Median = 4.000
EXPERT_6      N =  7     Median = 3.000
Point estimate for ETA1-ETA2 is       1.000
95.2 Percent CI for ETA1-ETA2 is (0.000,2.000)
W = 1519.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0958
The test is significant at 0.0765 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 7: Multi-function

```
NOVICE_7      N = 50     Median = 3.000
EXPERT_7      N =  7     Median = 2.000
Point estimate for ETA1-ETA2 is       1.000
95.2 Percent CI for ETA1-ETA2 is (-0.000,2.001)
W = 1530.5
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0518
```

The test is significant at 0.0427* (adjusted for ties)

User Satisfaction Attributes 8: Handle Shape

```
NOVICE_8      N = 50     Median = 4.000
EXPERT_8      N =  7     Median = 3.000
Point estimate for ETA1-ETA2 is       1.000
95.2 Percent CI for ETA1-ETA2 is (-0.000,2.000)
W = 1512.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.1348
The test is significant at 0.1187 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 9: Handle Size

```
NOVICE_9      N = 50     Median = 4.0000
EXPERT_9      N =  7     Median = 4.0000
Point estimate for ETA1-ETA2 is     -0.0000
95.2 Percent CI for ETA1-ETA2 is (-1.0003,-0.0004)
W = 1419.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.4584
The test is significant at 0.4378 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 10: Tool Weight

```
NOVICE_10      N = 50     Median = 3.500
EXPERT_10      N =  7     Median = 3.000
Point estimate for ETA1-ETA2 is      -0.000
95.2 Percent CI for ETA1-ETA2 is (-1.000,1.000)
W = 1472.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.6012
The test is significant at 0.5875 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 11: Manipulation

```
NOVICE_11     N = 50     Median = 4.000
EXPERT_11     N =  7     Median = 4.000
Point estimate for ETA1-ETA2 is       0.000
95.2 Percent CI for ETA1-ETA2 is (-0.999,1.999)
W = 1485.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.4016
The test is significant at 0.3774 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 12: Convenience/Portability

```
NOVICE_12     N = 50     Median = 4.000
EXPERT_12     N =  7     Median = 3.000
Point estimate for ETA1-ETA2 is       1.000
95.2 Percent CI for ETA1-ETA2 is (0.000,2.001)
W = 1513.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.1286
The test is significant at 0.1100 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 13: Identification

```
NOVICE_13     N = 50     Median = 3.000
EXPERT_13     N =  7     Median = 2.000
Point estimate for ETA1-ETA2 is       1.000
95.2 Percent CI for ETA1-ETA2 is (-0.001,2.001)
W = 1525.5
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0682
The test is significant at 0.0583 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 14: Maintenance

```
NOVICE_14     N = 50     Median = 3.000
EXPERT_14     N =  7     Median = 4.000
Point estimate for ETA1-ETA2 is      -0.000
95.2 Percent CI for ETA1-ETA2 is (-1.000,1.000)
W = 1459.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.8363
```

```
The test is significant at 0.8309 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 15: All-weather Proof

```
NOVICE_15     N = 50     Median = 3.000
EXPERT_15     N =  7     Median = 1.000
Point estimate for ETA1-ETA2 is       2.000
95.2 Percent CI for ETA1-ETA2 is (1.000,3.000)
W = 1555.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0111
```

The test is significant at 0.0093 (adjusted for ties)**

User Satisfaction Attributes 16: Safety

```
NOVICE_16     N = 50     Median = 5.000
EXPERT_16     N =  7     Median = 4.000
Point estimate for ETA1-ETA2 is       0.000
95.2 Percent CI for ETA1-ETA2 is (0.000,1.000)
W = 1486.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.3881
The test is significant at 0.3192 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 17: Feedback

```
NOVICE_17     N = 50     Median =  3.000
EXPERT_17     N =  7     Median =  1.000
Point estimate for ETA1-ETA2 is       2.000
95.2 Percent CI for ETA1-ETA2 is (0.000,3.000)
W = 1557.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0096
```

The test is significant at 0.0077 (adjusted for ties)**

User Satisfaction Attributes 18: Grip Comfort

```
NOVICE_18     N = 50     Median = 5.000
EXPERT_18     N =  7     Median = 4.000
Point estimate for ETA1-ETA2 is       1.000
95.2 Percent CI for ETA1-ETA2 is (0.001,2.000)
W = 1544.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0230
```

The test is significant at 0.0126* (adjusted for ties)

User Satisfaction Attributes 19: Grip Friction

```
NOVICE_19     N = 50     Median = 4.000
EXPERT_19     N =  7     Median = 4.000
Point estimate for ETA1-ETA2 is       1.000
95.2 Percent CI for ETA1-ETA2 is (0.000,1.000)
W = 1525.5
```

```
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0682
```

The test is significant at 0.0500* (adjusted for ties)

User Satisfaction Attributes 20: Luxurious

```
NOVICE_20     N = 50     Median = 2.000
EXPERT_20     N =  7     Median = 1.000
Point estimate for ETA1-ETA2 is       0.000
95.2 Percent CI for ETA1-ETA2 is (0.000,2.000)
W = 1504.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.1933
The test is significant at 0.1599 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 21: Harmony

```
NOVICE_21     N = 50     Median = 3.000
EXPERT_21     N =  7     Median = 2.000
Point estimate for ETA1-ETA2 is       1.000
95.2 Percent CI for ETA1-ETA2 is (1.000,2.000)
W = 1564.5
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0056
```

The test is significant at 0.0041 (adjusted for ties)**

User Satisfaction Attributes 22: Neatness

```
NOVICE_22     N = 50     Median = 3.000
EXPERT_22     N =  7     Median = 2.000
Point estimate for ETA1-ETA2 is       1.000
95.2 Percent CI for ETA1-ETA2 is (-0.000,2.000)
W = 1523.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0779
The test is significant at 0.0699 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 23: Rigidity

```
NOVICE_23     N = 50     Median = 4.000
EXPERT_23     N =  7     Median = 3.000
Point estimate for ETA1-ETA2 is       1.000
95.2 Percent CI for ETA1-ETA2 is (-0.000,2.000)
W = 1495.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.2793
The test is significant at 0.2625 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 24: Attractiveness

```
NOVICE_24     N = 50     Median = 3.000
EXPERT_24     N =  7     Median = 1.000
Point estimate for ETA1-ETA2 is       1.000
```

```
95.2 Percent CI for ETA1-ETA2 is (-0.000,2.000)
W = 1525.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0701
The test is significant at 0.0630 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 25: Craftsmanship

```
NOVICE_25     N = 50     Median = 4.000
EXPERT_25     N =  7     Median = 2.000
Point estimate for ETA1-ETA2 is       2.000
95.2 Percent CI for ETA1-ETA2 is (-0.001,2.999)
W = 1537.5
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0344
```

The test is significant at 0.0281* (adjusted for ties)

User Satisfaction Attributes 26: Prominence/Uniqueness

```
NOVICE_26     N = 50     Median = 3.000
EXPERT_26     N =  7     Median = 1.000
Point estimate for ETA1-ETA2 is       1.000
95.2 Percent CI for ETA1-ETA2 is (-0.000,2.000)
W = 1543.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0245
```

The test is significant at 0.0207* (adjusted for ties)

User Satisfaction Attributes 27: Shape

```
NOVICE_27     N = 50     Median = 4.000
EXPERT_27     N =  7     Median = 2.000
Point estimate for ETA1-ETA2 is       1.000
95.2 Percent CI for ETA1-ETA2 is (0.000,2.000)
W = 1524.5
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0720
The test is significant at 0.0592 (adjusted for ties)

Cannot reject at alpha = 0.05
```

User Satisfaction Attributes 28: Color

```
NOVICE_28     N = 50     Median = 3.000
EXPERT_28     N =  7     Median = 1.000
Point estimate for ETA1-ETA2 is       1.000
95.2 Percent CI for ETA1-ETA2 is (0.000,2.000)
W = 1553.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0127
```

The test is significant at 0.0105* (adjusted for ties)

User Satisfaction Attributes 29: Texture

```
NOVICE_29     N = 50     Median = 3.000
EXPERT_29     N =  7     Median = 1.000
```

```
Point estimate for ETA1-ETA2 is       2.000
95.2 Percent CI for ETA1-ETA2 is (1.000,2.000)
W = 1560.0
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0078
```

The test is significant at 0.0049 (adjusted for ties)**

User Satisfaction Attributes 30: Design/Styling

```
NOVICE_30     N = 50     Median = 4.000
EXPERT_30     N =  7     Median = 1.000
Point estimate for ETA1-ETA2 is       2.000
95.2 Percent CI for ETA1-ETA2 is (1.000,2.999)
W = 1576.5
Test of ETA1 = ETA2  vs  ETA1 not = ETA2 is significant at 0.0022
```

The test is significant at 0.0014 (adjusted for ties)**

I.5 Kruskal-Wallis Test

Comparison of Subjective Evaluation between Screwdriver Types

User Satisfaction Attributes 1: Force/Torque Output

Type	N	Median	Ave Rank	Z
1	15	4.000	42.3	0.85
2	15	3.000	27.0	-2.19
3	15	3.000	29.5	-1.70
4	15	4.000	33.6	-0.87
5	15	5.000	57.6	3.90
Overall	75		38.0	

H = 19.47 DF = 4 P = 0.001
H = 21.41 DF = 4 P = 0.000 (adjusted for ties)

User Satisfaction Attributes 2: Precision

Type	N	Median	Ave Rank	Z
1	15	4.000	46.0	1.58
2	15	3.000	26.4	-2.31
3	15	4.000	37.4	-0.12
4	15	3.000	35.1	-0.58
5	15	4.000	45.2	1.42
Overall	75		38.0	

H = 8.18 DF = 4 P = 0.085
H = 9.89 DF = 4 P = 0.042* (adjusted for ties)

User Satisfaction Attributes 3: Effectiveness

Type	N	Median	Ave Rank	Z
1	15	4.000	44.3	1.25
2	15	3.000	27.8	-2.03
3	15	3.000	35.5	-0.50
4	15	3.000	36.3	-0.34
5	15	4.000	46.2	1.63
Overall	75		38.0	

H = 6.96 DF = 4 P = 0.138
H = 8.50 DF = 4 P = 0.075 (adjusted for ties)

User Satisfaction Attributes 4: Efficiency

Type	N	Median	Ave Rank	Z
1	15	3.000	40.8	0.56
2	15	3.000	29.1	-1.76
3	15	3.000	27.5	-2.09
4	15	3.000	36.4	-0.32
5	15	4.000	56.2	3.62
Overall	75		38.0	

H = 16.78 DF = 4 P = 0.002
H = 18.43 DF = 4 P = 0.001 (adjusted for ties)**

User Satisfaction Attributes 5: Productivity

Type	N	Median	Ave Rank	Z
1	15	4.000	45.0	1.38
2	15	3.000	30.0	-1.58
3	15	3.000	29.4	-1.71
4	15	3.000	37.3	-0.13
5	15	4.000	48.3	2.04
Overall	75		38.0	

H = 9.22 DF = 4 P = 0.056
H = 10.52 DF = 4 P = 0.032* (adjusted for ties)

User Satisfaction Attributes 6: Durability

Type	N	Median	Ave Rank	Z
1	15	3.000	33.9	-0.81
2	15	3.000	33.9	-0.81
3	15	3.000	36.3	-0.34
4	15	4.000	48.1	2.01
5	15	3.000	37.7	-0.06
Overall	75		38.0	

H = 4.38 DF = 4 P = 0.357
H = 5.58 DF = 4 P = 0.233 (adjusted for ties)

User Satisfaction Attributes 7: Multi-function

Type	N	Median	Ave Rank	Z
1	15	3.000	39.0	0.21
2	15	3.000	34.9	-0.62
3	15	3.000	34.9	-0.62
4	15	3.000	40.4	0.47
5	15	3.000	40.9	0.57
Overall	75		38.0	

H = 1.09 DF = 4 P = 0.896
H = 1.28 DF = 4 P = 0.865 (adjusted for ties)

User Satisfaction Attributes 8: Handle Shape

Type	N	Median	Ave Rank	Z
1	15	3.000	38.6	0.12
2	15	3.000	33.1	-0.97
3	15	3.000	36.8	-0.25
4	15	4.000	37.8	-0.04
5	15	4.000	43.7	1.13
Overall	75		38.0	

```
H = 1.83  DF = 4  P = 0.766
H = 2.01  DF = 4  P = 0.734 (adjusted for ties)
```

User Satisfaction Attributes 9: Handle Size

Type	N	Median	Ave Rank	Z
1	15	4.000	42.9	0.98
2	15	3.000	28.3	-1.93
3	15	3.000	32.4	-1.11
4	15	4.000	46.4	1.67
5	15	4.000	40.0	0.40
Overall	75		38.0	

```
H = 7.11  DF = 4  P = 0.130
H = 8.36  DF = 4  P = 0.079 (adjusted for ties)
```

User Satisfaction Attributes 10: Tool Weight

Type	N	Median	Ave Rank	Z
1	15	4.000	38.2	0.04
2	15	4.000	40.3	0.46
3	15	4.000	36.9	-0.22
4	15	3.000	38.5	0.10
5	15	3.000	36.1	-0.38
Overall	75		38.0	

```
H = 0.33  DF = 4  P = 0.988
H = 0.40  DF = 4  P = 0.983 (adjusted for ties)
```

User Satisfaction Attributes 11: Manipulation

Type	N	Median	Ave Rank	Z
1	15	4.000	39.0	0.21
2	15	4.000	34.5	-0.70
3	15	4.000	37.6	-0.09
4	15	3.000	32.8	-1.03
5	15	4.000	46.1	1.61
Overall	75		38.0	

```
H = 3.35  DF = 4  P = 0.501
H = 3.93  DF = 4  P = 0.415 (adjusted for ties)
```

User Satisfaction Attributes 12: Convenience/Portability

Type	N	Median	Ave Rank	Z
1	15	4.000	45.1	1.42
2	15	3.000	31.5	-1.28
3	15	3.000	30.9	-1.40
4	15	4.000	39.8	0.36
5	15	4.000	42.6	0.91
Overall	75		38.0	

```
H = 5.27  DF = 4  P = 0.260
H = 5.92  DF = 4  P = 0.206 (adjusted for ties)
```

User Satisfaction Attributes 13: Identification

Type	N	Median	Ave Rank	Z
1	15	3.000	29.7	-1.66
2	15	4.000	40.8	0.56
3	15	4.000	43.0	0.99
4	15	4.000	44.7	1.33
5	15	3.000	31.8	-1.23
Overall	75		38.0	

```
H = 5.85  DF = 4  P = 0.211
H = 7.07  DF = 4  P = 0.132 (adjusted for ties)
```

User Satisfaction Attributes 14: Maintenance

Type	N	Median	Ave Rank	Z
1	15	4.000	42.6	0.91
2	15	4.000	46.9	1.76
3	15	4.000	43.2	1.03
4	15	3.000	27.3	-2.13
5	15	3.000	30.1	-1.58
Overall	75		38.0	

H = 9.60 DF = 4 P = 0.048
H = 11.69 DF = 4 P = 0.020* (adjusted for ties)

User Satisfaction Attributes 15: All-weather Proof

Type	N	Median	Ave Rank	Z
1	15	4.000	40.8	0.56
2	15	3.000	32.7	-1.05
3	15	4.000	33.3	-0.94
4	15	4.000	47.9	1.97
5	15	4.000	35.3	-0.54
Overall	75		38.0	

```
H = 5.17  DF = 4  P = 0.270
H = 6.05  DF = 4  P = 0.196 (adjusted for ties)
```

User Satisfaction Attributes 16: Safety

Type	N	Median	Ave Rank	Z
1	15	4.000	48.7	2.13
2	15	4.000	33.5	-0.89
3	15	4.000	35.2	-0.55
4	15	4.000	37.3	-0.13
5	15	3.000	35.2	-0.56
Overall	75		38.0	

H = 4.75 DF = 4 P = 0.314
H = 5.29 DF = 4 P = 0.259 (adjusted for ties)

User Satisfaction Attributes 17: Feedback

Type	N	Median	Ave Rank	Z
1	15	3.000	34.0	-0.79
2	15	3.000	34.0	-0.79
3	15	3.000	34.0	-0.79
4	15	4.000	43.5	1.09
5	15	4.000	44.5	1.30
Overall	75		38.0	

H = 3.81 DF = 4 P = 0.433
H = 4.38 DF = 4 P = 0.357 (adjusted for ties)

User Satisfaction Attributes 18: Grip Comfort

Type	N	Median	Ave Rank	Z
1	15	3.000	40.3	0.45
2	15	3.000	27.9	-2.00
3	15	3.000	35.5	-0.49
4	15	3.000	39.1	0.21
5	15	4.000	47.2	1.83
Overall	75		38.0	

H = 6.26 DF = 4 P = 0.180
H = 6.72 DF = 4 P = 0.151 (adjusted for ties)

User Satisfaction Attributes 19: Grip Friction

Type	N	Median	Ave Rank	Z
1	15	4.000	47.5	1.88
2	15	3.000	24.0	-2.78
3	15	3.000	28.8	-1.83
4	15	4.000	46.3	1.64
5	15	4.000	43.5	1.09
Overall	75		38.0	

H = 14.79 DF = 4 P = 0.005
H = 15.99 DF = 4 P = 0.003 (adjusted for ties)**

User Satisfaction Attributes 20: Luxurious

Type	N	Median	Ave Rank	Z
1	15	4.000	39.6	0.32
2	15	4.000	47.5	1.89
3	15	4.000	44.9	1.36
4	15	4.000	47.5	1.88
5	15	1.000	10.6	-5.45
Overall	75		38.0	

```
H = 31.02  DF = 4  P = 0.000
```
H = 34.58 DF = 4 P = 0.000 (adjusted for ties)**

User Satisfaction Attributes 21: Harmony

Type	N	Median	Ave Rank	Z
1	15	4.000	44.7	1.33
2	15	4.000	38.1	0.02
3	15	4.000	41.6	0.72
4	15	4.000	40.0	0.40
5	15	3.000	25.5	-2.48
Overall	75		38.0	

```
H = 6.87  DF = 4  P = 0.143
H = 8.36  DF = 4  P = 0.079  (adjusted for ties)
```

User Satisfaction Attributes 22: Neatness

Type	N	Median	Ave Rank	Z
1	15	3.000	36.2	-0.36
2	15	4.000	52.9	2.95
3	15	4.000	48.1	2.00
4	15	4.000	39.7	0.33
5	15	2.000	13.2	-4.93
Overall	75		38.0	

```
H = 29.79  DF = 4  P = 0.000
```
H = 33.08 DF = 4 P = 0.000 (adjusted for ties)**

User Satisfaction Attributes 23: Rigidity

Type	N	Median	Ave Rank	Z
1	15	4.000	41.4	0.68
2	15	3.000	30.2	-1.54
3	15	4.000	34.1	-0.77
4	15	4.000	48.0	1.99
5	15	4.000	36.2	-0.35
Overall	75		38.0	

```
H = 6.03  DF = 4  P = 0.197
H = 6.97  DF = 4  P = 0.138  (adjusted for ties)
```

User Satisfaction Attributes 24: Attractiveness

Type	N	Median	Ave Rank	Z
1	15	4.000	40.8	0.56
2	15	4.000	52.1	2.80
3	15	4.000	43.0	0.99
4	15	4.000	43.2	1.04
5	15	2.000	10.9	-5.38
Overall	75		38.0	

```
H = 31.36  DF = 4  P = 0.000
```
H = 34.31 DF = 4 P = 0.000 (adjusted for ties)**

User Satisfaction Attributes 25: Craftsmanship

Type	N	Median	Ave Rank	Z
1	15	4.000	40.3	0.45
2	15	3.000	34.2	-0.75
3	15	4.000	37.9	-0.03
4	15	4.000	45.9	1.56
5	15	3.000	31.8	-1.23
Overall	75		38.0	

H = 3.79 DF = 4 P = 0.436
H = 4.22 DF = 4 P = 0.377 (adjusted for ties)

User Satisfaction Attributes 26: Prominence/Uniqueness

Type	N	Median	Ave Rank	Z
1	15	3.000	31.9	-1.21
2	15	4.000	44.3	1.25
3	15	4.000	41.4	0.67
4	15	4.000	57.6	3.90
5	15	2.000	14.8	-4.61
Overall	75		38.0	

H = 31.93 DF = 4 P = 0.000
H = 34.73 DF = 4 P = 0.000 (adjusted for ties)**

User Satisfaction Attributes 27: Shape

Type	N	Median	Ave Rank	Z
1	15	4.000	44.8	1.36
2	15	3.000	37.0	-0.19
3	15	4.000	38.8	0.16
4	15	4.000	39.1	0.21
5	15	3.000	30.3	-1.54
Overall	75		38.0	

H = 3.45 DF = 4 P = 0.486
H = 3.81 DF = 4 P = 0.432 (adjusted for ties)

User Satisfaction Attributes 28: Color

Type	N	Median	Ave Rank	Z
1	15	4.000	50.0	2.38
2	15	4.000	41.7	0.73
3	15	3.000	38.0	-0.01
4	15	4.000	43.4	1.07
5	15	2.000	17.0	-4.17
Overall	75		38.0	

```
H = 19.81  DF = 4  P = 0.001
```
H = 21.49 DF = 4 P = 0.000 (adjusted for ties)**

User Satisfaction Attributes 29: Texture

Type	N	Median	Ave Rank	Z
1	15	3.000	39.5	0.30
2	15	4.000	44.2	1.23
3	15	3.000	41.9	0.77
4	15	4.000	43.8	1.16
5	15	3.000	20.6	-3.46
Overall	75		38.0	

```
H = 12.39  DF = 4  P = 0.015
```
H = 13.80 DF = 4 P = 0.008 (adjusted for ties)**

User Satisfaction Attributes 30: Design/Styling

Type	N	Median	Ave Rank	Z
1	15	4.000	43.2	1.04
2	15	4.000	43.4	1.08
3	15	4.000	42.1	0.81
4	15	4.000	46.9	1.77
5	15	2.000	14.3	-4.71
Overall	75		38.0	

```
H = 22.59  DF = 4  P = 0.000
```
H = 24.08 DF = 4 P = 0.000 (adjusted for ties)**

VITA

Cheol Lee was born in Naju, Korea on April 12, 1969. He earned his B.S. and M.S. in Industrial Engineering from Seoul National University, Seoul, Korea in 1993 and 1995, respectively. Before starting his Ph.D. program at the Pennsylvania State University, he held 5-year professional experience at the corporate technical planning team of Samsung Electronics Inc., Seoul, Korea as an associate, at the R&D department of Somansa Inc., Seoul, Korea as a technical director, and at the Strategic Planning Team of Cybermed Inc as a chief manager. As a lecturer, he taught the course of Human Factors Engineering at the Seoul National Polytechnic University, Seoul, Korea and the Soongsil University, Seoul, Korea, respectively. At Penn State, he worked as a graduate research assistant at the Penn State Ergonomics Laboratory and the Center for Cumulative Trauma Disorders. His area of interests includes industrial ergonomics, biomechanics, Kansei engineering, ergonomic design and evaluation methodology, and usability. He was a Rotary Scholar of the Rotary International. He is a member of the Human Factors and Ergonomics Society.