APPLYING ERGONOMICS TO DENTAL SCALERS

by

STACEY AHERN

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Approved by:

Major Professor
Dr. Malgorzata Rys

Abstract

The current state of the dental industry shows an increasing number of dentists and dental hygienists who are reducing hours and retiring early due to the injuries sustained while working. These injuries, or cumulative trauma disorders, can be reduced by applying ergonomics in dental tool design. The goal of ergonomics is to reduce current injuries but also prevent future ones. In addition, population demographics have shown an increasing trend in female dentists. With a shift from the male dominated field, design for different anthropometric measurements needs to be investigated.

In order to pinpoint sources of pain, a survey was designed and distributed to dentists in Kansas, Missouri, and Texas. Even with a small sample size (n=24), results confirmed past studies in the dental industry of pain originating in the neck, shoulder, lower back, and wrist/hand region. The reasons stemmed from the repetitive motions and forces applied during dental procedures. Responses also found that ergonomic principles need to be applied to the handle and grip portion of dental scaler design. Dental scaling is the procedure to remove deposits on teeth, such as plaque and calculus, most commonly performed by dental hygienists.

First, the history of dental tools, angulation, tool weight, and materials currently utilized were researched before looking into specific design factors for modification. Currently, the handle grip area on all dental tools range in size, but a 10 mm grip has been proven to be optimal. The optimal tool weight has yet to be determined as 15 grams is the lowest weight to be tested. Most tools are made of stainless steel and resins, which are not compressible.

An experiment was designed to test a new dental scaler (A) made of a titanium rod with added compressibility in the precision grip area. The aim was to help reduce pressure on the fingers and hand muscles and increase comfort during scaling. The experiment utilized a Hu-Friedy sickle scaler (B) and a Practicon Montana Jack scaler (C) as controls to show two design spectrums, weight and material. The subjects (n=23) were taught the basics of scaling and required to scale using a typodont. The change in grip strength (Δ GS), pinch strength (Δ PS), and steadiness of the subjects hand were tested. An absolute and relative rating technique was utilized pinpointing that the new dental scaler was preferred with the eigenvector (A=0.8615, B=0.1279, C=0.0106). Statistical analysis confirmed this tool preference while also finding the interaction of gender and tool and Δ GS Tool A versus Tool B for males to be significant.

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CHAPTER 1 - Introduction

In the United States, approximately nine million people work in the health-care industry. This nine million includes 179,594 professionally active dentists and 140,750 licensed dental hygienists in the United States as of 2006 (ADA, 2006).

The dental industry helps diagnose and treat problems with the teeth and mouth cavity tissues (US BLS, 2009). The work environment is safe in terms of sterilization, yet the repetitive nature of tasks and design limitations in the industry creates a strong need for advancement in the current ergonomics. Ergonomics can be defined as the "body of knowledge about human abilities, human limitations, and other human characteristics that are relevant to design" (Konz et al., 2008).

The motions and high degree of manual dexterity required by dentists and dental hygienists are the main cause of cumulative trauma disorders (CTD) in the dental industry, an issue that needs to be addressed. CTDs are synonymous with many other names, such as, musculoskeletal disorders or even occupational overuse syndrome and are injuries that occur due to repetitive motions that gradually wear away at the body (Konz et al., 2008). Many people in the dental industry have undergone surgery to correct injuries created from years of precision work. The most common reported injuries have resulted from awkward working positions and the poor design of hand-held tooling. The main goal of ergonomics is to design an environment that will reduce and, ultimately, eliminate these injuries.

A step towards reducing injury comes in evaluating current tool design. Dental tools require meticulousness work, a steady hand, and use of small muscles in the hand. In addition, practitioners require diagnostic ability, good visual memory, and excellent judgment in detecting different shapes and colors in the mouth (US BLS, 2009).

There are many considerations that need to be addressed while redesigning dental tools. The first is assessing gender shifts in the industry and looking into the diverse anthropometric dimensions related to females versus males. Another consideration is the tool durability along with the ability to sterilize the materials utilized in design. Sterilization is an important factor because diseases can be carried from one patient to the next with reusable dental tools.

As new ergonomically friendly designs are tested, it is important that the people in the industry who will be utilizing the tools on a daily basis have input in the process. Students will become the first generation of dentists to use them in practice. If more students are aware of the current issues, the urgency for change will become more apparent for the future generations in the dental industry.

Also, as technology increases and new materials are created, the need for new tools and an ergonomic intervention remains essential. Especially since many individuals in the dental industry are concerned with their ability to do the same job until retirement (Jamjoom, 2008).

1.1 Dentistry Background

Dentistry as a profession saw its origin in the beginning of the sixteenth century although references to tooth ache remedies have been noted to date back to ancient Egyptian times. Rapid progress in the dental industry was not prevalent until the 19^{th} and 20^{th} centuries with the opening of the first dental school, Baltimore College of Dental Surgery, in 1840 (Taylor, 1922).

The 1960's marked another important time in the dental industry. In this year, the dentist switched from standing up to sitting down while performing procedures (Dougherty, 2001). Even with this major adjustment in positioning during dental work, tooling design has not evolved. The angles of insertion and line of sight have changed, yet the tasks remain the same.

The switch from completing dental procedures standing versus sitting is a positive ergonomic factor in the industry. Standing has been shown to cause lower leg and foot discomfort. Sitting, on the other hand, increases cardiac output by 125% meaning your heart pumps more liters per minute. In addition, it has been shown to reduce the mean arterial pressure and heart rate (Konz et al., 2008). Sitting also reduces energy expenditure, increases practitioner stability, and decreases static muscle activity and strain on the legs (Osuna, 2003). Also, since tasks in the dental industry do not require movements between multiple workstations sitting is the recommended positioning.

Another positive reduction of cumulative trauma disorders also came in the 1960's from the University of Alabama School of Dentistry. The need for this shift started in the 1940's when the number of Americans was forecasted to increase while the number of dentists would be on the decline. Subsequently, U.S. Congress acted to increase the number of dental schools and class sizes. One of the benefits of this increase came from the introduction of four-handed dentistry in the 1960's. This new practice in the dental office not only became prominent in the United States but also internationally (Smith, 1999).

Four-handed dentistry uses strategic positioning of the dentist, dental assistant, and the patient. A bird's eye view of the dentist, denoted by the red circle, and the assistant, denoted by the green circle, can be seen in Figure 1-1 below. In order to be effective, the dentist must utilize the dental assistant while treating the patient. The last and most important principle is the placement of dental tools prior to the appointment. Dental tooling should be arranged from left to right in the sequence utilized during the procedure. The dentist should not be required to move his or her finger rests and eyes focused on the patients during the transfer (Smith, 1999).

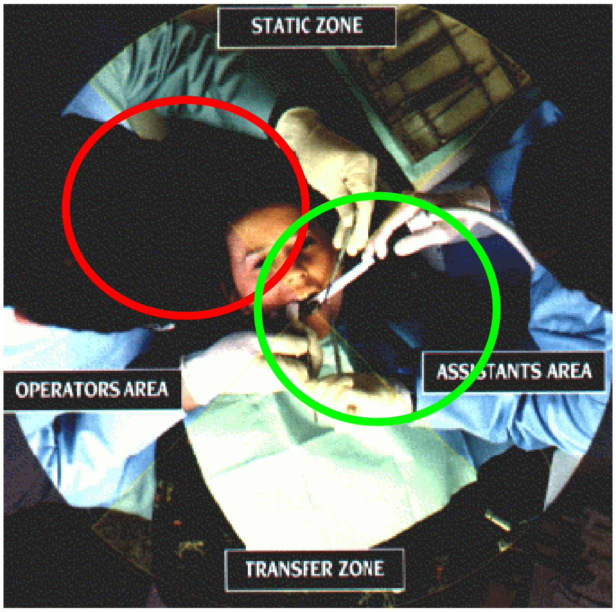


Figure 1-1. Aerial View of Four-Handed Dentistry (Smith, 1999)

The concept of four-handed dentistry helps to minimize fatigue without sacrificing productivity and quality of patient care. Research has shown that efficiency is increased along with a decrease in muscular stresses. This is through the 50% to 70% conservation of muscle activity (Smith, 1999).

1.2 Current Situation in the Dental Industry

At this time, there are no industry standards involving dental tools and ergonomic requirements in the industry except for tool sterilization. In 1992, the Occupational Safety and

Health Administration (OSHA) issued a proposal to teach ergonomic standards to the entire American workforce (Bramson et al., 1998). This was intended to help educate Americans in terms of workstation design and risk factors they should be aware of while at work. Unfortunately, this proposal did not get accepted.

An additional problem specifically in the current dental industry is that there are many companies who market their tools as being "ergonomic" in design. These tools have created a misconception with people working in the dental industry, whether in schools or private practices. Frequently, individuals have overpaid for the dental tools but not received an ergonomic benefit. Often, it is too late after purchasing that the dentist realizes the design does not help them yet only continues to hinder their injuries.

Dental tools used today do have some design qualities that follow ergonomic principles related to tool design. First, dental tools are a special purpose tool. This means that no one tool is used to do another task outside of its scope. For example, there is a suction hose that is used to keep the mouth area dry, a dental scalar used to remove tartar and plaque, and a dental mirror used to reflect images that the human eye cannot see directly. Having special purpose tools is important in design because the user does not have to alter his or her positioning to do jobs outside of the design capabilities of the tool.

Another guideline for handtool design is that the tools should be able to be used by either hand (Konz et al., 2008). As of now, dental tools are designed for both hands. Most dentists and hygienists use their dominate hand to clean the teeth while holding the mirror in their non-dominate hand. This ambidextrous tool design allows for multiple users although does not take into account important anthropometric differences between people, such as, hand size.

Anthropometry is of Greek origin meaning "to measure man" (Konz et al., 2008). These measurements help explain how people vary. This data also helps quantitatively explain how everyone is not the same, whether it is height, weight, or even hand size. This is one of the main reasons that the dental workstation and tools have not been standardized.

Finally, the dental industry has seen a shift in gender. In the last twenty years, there has been an increase in the number of female dentists entering the industry. In 2007, the American Dental Association (ADA) reported 44.5% female enrollment in dental schools versus only 33% in 1987 (ADA, 2007). In addition, 97.7% of dental hygienists are female (US BLS, 2010) although more hygiene schools are looking for ways to increase the male enrollment rates. Since dentists and hygienists are performing tasks that require precision, it is important that the tools fit a variety of anthropometric dimensions especially with the differences between genders.

1.3 Explanation of Chapters

This thesis addresses the past, present, and future trends in the dental industry in five chapters. In the next chapter is a literature review. Past research was analyzed looking for more information on current dental tool materials, the sterilization process, and tool classification methods. Other topics researched were the gender shift from predominately male dentists to more females entering the industry and injuries associated with the industry. This was accomplished by discussing the prevalence of cumulative trauma disorders, such as Carpal Tunnel Syndrome, because it is important to reduce these while utilizing ergonomic principles.

Chapter 3 contains the results and analysis of a survey with 24 responses. This survey was distributed to collect feedback from dentists in regards to their background information, work-related activities, and sources of pain and injury resulting from specific tasks performed in their daily work environment. The results of the survey were then compared to a similar survey completed at the University of Kentucky with female dental hygienists in 1999. Based on survey results the dental scaler was identified as the most frequent source of pain and injury.

Chapter 4 then utilizes the analysis from the survey to isolate dental scalers as a predominant source of pain. Dental scaling pinch force and angulation is first discussed and employed as research to aid in redesigning a dental scaler. The last part of Chapter 4 analyzes the results of an experiment conducted with 23 subjects to test new tool design versus current tools in the industry. The new dental scaler was found to be statistically significant in terms of subject preference over the two control tools. Interaction was also evident between gender and tool preference as females chose the new scaler the most on average.

Chapter 5 contains recommendations and conclusions. It is recommended that more research is completed in terms of grip compressibility added to dental scalers and finding the optimal weight to reduce fatigue and force required.

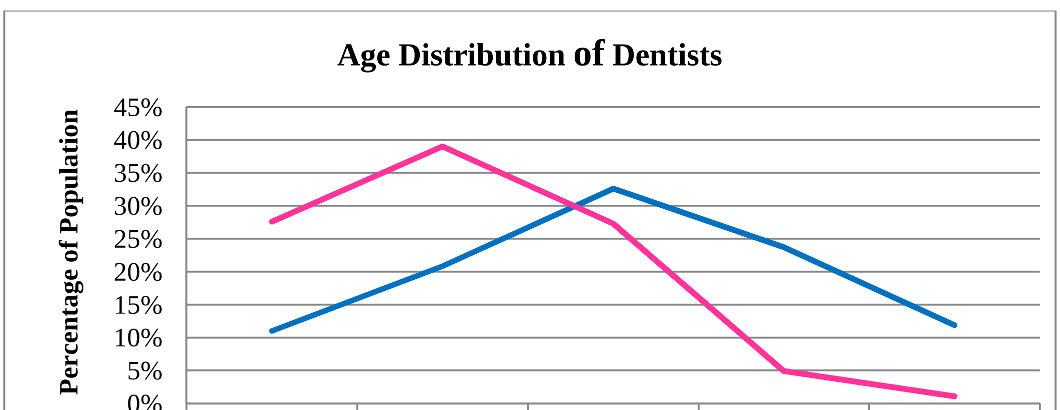
CHAPTER 2 - Literature Review

2.1 Gender Distribution

2.1.1 Increase in Female Dentists

Before the 1970's dentists in the United States were almost exclusively males (Carlisle, 2004). There are two main reasons linked to the shift towards more females in dentistry. The first was the 1960-1970's women's liberation and civil rights movement. This directly led to the increase in federal grants to help enroll more females and minorities in health related fields. The second was the impact of birth control. The introduction of birth control in the United States allowed women more freedom on when to start a family. This decision provided more females the ability to pursue health related degrees including dentistry (Carlisle, 2004).

Based on 2003 data from the American Dental Association (ADA) the percentage of male versus female dentists based on age range can be seen in line chart in Figure 2-1 below. This chart shows an increasing trend of younger female dentists while the percentage of males falls below the percentage of females in age groups up to 44 years old. Also, based on the 2003 data it has been estimated that by 2015 the total percentage of male dentists to female dentists will be closer to 60% and 40%, respectively (ADA, 2003). This is due to the retirement of dentists from the male dominant "Silent" and "Baby Boom" generations (Carlisle, 2004).



	< 35	35 - 44	45 - 54	55 - 64	≥ 65
Male	11.0%	20.8%	32.6%	23.7%	11.9%
Female	27.6%	39.0%	27.3%	4.9%	1.1%

Figure 2-1. Age Distribution of Dentists (ADA, 2003)

In 2008 a census was completed to evaluate the distribution of dentists in the United States by region and state. This survey found that there were approximately 237,851 dentists in the United States. Overall, 24.2% are female. The study also found that 79.1% were in general practice with the remaining 20.9% in a specialty area (ADA Survey Center, 2010).

Another increasing trend in the dental industry is the number of females enrolling in dental schools in the United States while the number of males enrolling is decreasing. In the 1970 to 1971 school year females only represented 1.4% of dental school enrollment (Sinkford et al., 2003). Then by the 2004 to 2005 school year, male enrollment had dropped from 98.6% to 56.2% while female enrollment increased from 1.4% to 43.8% (ADA, 2005).

2.1.2 Dental Hygienists

In 2008 there were 174,100 dental hygienists in the United States. A dental hygienist is a licensed oral health professional who works on preventing and treating oral diseases in order to protect the oral cavity (ADHA, 2010). The gender spread for hygienists is even worse than dentists yet on the other end of the spectrum. The US Census Bureau reported that 97.7% of hygienists are female (US BLS, 2010). Men in the dental hygiene profession have been compared to males entering the nursing field, another occupation traditionally reserved for the opposite gender (Faust, 1999). The trend has not changed either because recently accredited schools around the United States only see a 3% rate of male enrollment and 13.4% minority enrollment (ADHA, 2010).

The main reason for this gender gap can be linked back to 1915 when the first documented dental hygiene position was formed in Connecticut. This position called for, “any registered or licensed dentist may employ <u>women</u> assistants who shall be known as dental hygienists” (Faust, 1999). Since the beginning of this profession until the 1960s recruitment has been predominantly focused on women.

The American Dental Hygienists’ Association (ADHA) has noticed this trend and is hoping to not only increase the number of males enrolled in dental hygiene schools but also minorities. Recent steps have been taken to remove gender specific lingo in textbooks while publishing more brochures with a mixture of male and female hygienists (Faust, 1999). This is aimed at changing the social latitude and help men break into the already established network.

Being a dental hygienist has also been linked to a part time job due to the fact that 51% of current hygienists work less than 35 hours per week. Yet, with this in mind employment is expected to grow by 36% through the year 2018. This is considered above average growth in industry because the average lies between 7% and 31% (US BLS, 2010).

2.2 Positioning

2.2.1 Posture

In school, dentists and hygienists are taught the importance of an ergonomic work environment in textbooks, yet only 47% of American schools employ an ergonomics educator on staff (Maillet et al., 2008). Posture is taught using Figure 2-2 below since the switch from standing to sitting occurred in the mid-1960s.

Training starts with the neck in a neutral position with a maximum tilt of 0° to 15°. Moving down from the head and neck, the shoulders need to be balanced with a horizontal line keeping the weight even between the left and right side of the torso. Next, the back should remain upright with trunk flexion of 0° to 20° maximum. Upper arms should be parallel to the long axis of the torso with elbows at waist level avoiding greater than 20° abduction. Next, forearm positioning needs to remain parallel to the floor with elbows being the pivot point to raise or lower the arm (Neild-Gehrig, 2008).

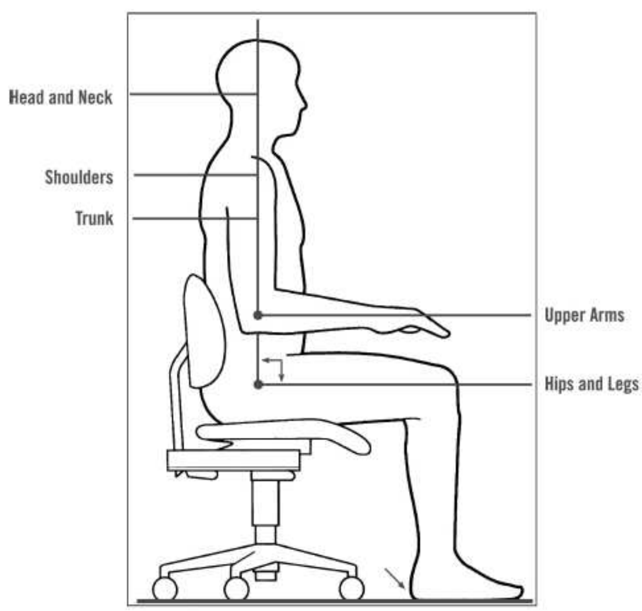


Figure 2-2. Dentist and Dental Hygienists Ideal Posture (Neild-Gehrig, 2008)

The second part of posture comes from the positioning of the patient. First, the patient should be supine. The clinician chair should be adjusted to establish a hip angle of 90°. Ultimately, the tip of the patient's nose should be below the clinician's waist while allowing the clinician's elbows to be at 90° (Neild-Gehrig, 2008). These recommendations can be seen in addition to the angles where possible injury can occur in Figure 2-3 below. The angles to avoid can be seen in the red and yellow zones.

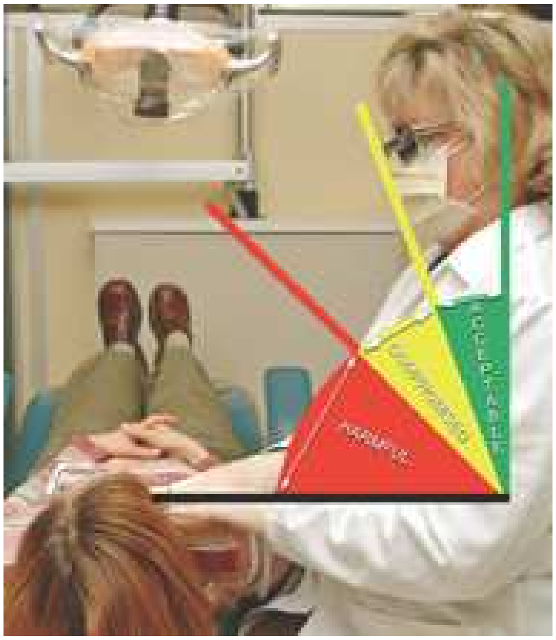


Figure 2-3. Clinician Posture Assessment (Simmer-Beck et al., 2005)

In addition to posture and positioning, textbooks also discuss the importance of these guidelines due to the percentage of practitioners suffering from a work related repetitive motion injury. One common injury for individuals working in dental offices is Carpal Tunnel Syndrome.

2.2.2 Carpal Tunnel Syndrome

Carpal tunnel Syndrome (CTS) is a condition resulting from compression of the median nerve at the wrist. Pinching of the median nerve can cause a numbness and tingling feeling in the thumb and index fingers (Konz et al., 2008). It is estimated to affect 8% of women and 0.6% of men. The most at risk individuals are those with occupations that involve repetitive hand movements. In addition, obesity and prior consultation for another musculoskeletal disorder were both found to directly correlate with an increase in percentage of women diagnosed with CTS versus men (Ferry et al., 2000).

CTS can occur due to nonoccupational and work-related risk factors. Additional nonoccupational risk factors other than obesity and gender are age, diabetes, pregnancy, rheumatoid arthritis, wrist fracture, and personal hobbies. Repetitive occupational risk factors occur due to pinching, gripping, and non-neutral wrist arrangement. A neutral wrist position is defined to be the handshake position (Konz et al., 2008). The use of vibrating tools can also lead to CTS (Dong et al., 2006).

In 1998 the U.S. Bureau of Labor Statistics reported that dental hygiene ranked first among all occupations in the United States in occurrences of CTS cases per 1,000 employees. Physical, social, organizational, and personal factors account for the development of CTS symptom reports by 65% of dental hygienists. These factors can be seen in more detail in Figure 2-4 below.

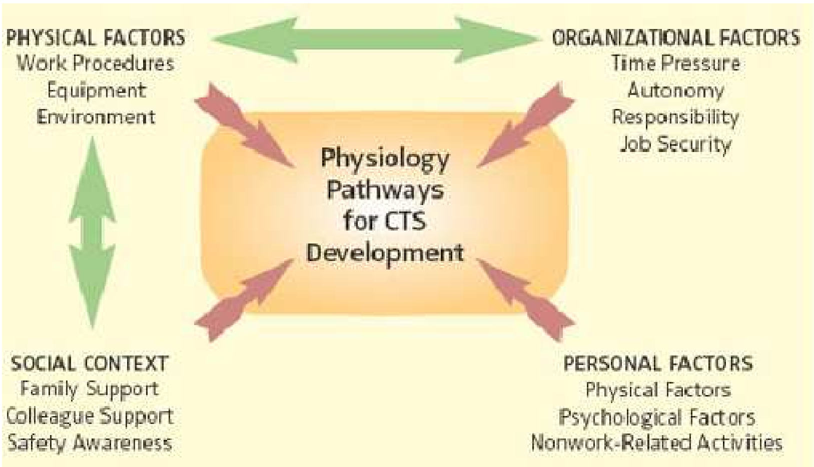


Figure 2-4. Physiology Pathways for CTS Development (Simmer-Beck et al., 2005)

Other repetitive motion disorders are increasing for both dentists and hygienist (Dong et al., 2005). In 1997 the American Dental Association reported that 9.2% of dentists had been diagnosed with some type of work related disorder. The study also found that among the 9.2%, approximately 19% required surgery and over 40% had to decrease their working hours per week. The prevalence of CTS and other repetitive motion disorders was most commonly seen in females and older respondents (Hamann et al., 2001). Also, around 79% of dental hygienists have reported days away from work due to repetitive trauma (Simmer-Beck et al., 2005).

Overall, any repetitive motion disorder can cause a loss of income, increased medical expenses, rising workers compensation claims, an increase in personal days off work, and ultimately, a career change (Simmer-Beck et al., 2005).

2.3 Dental Work Environment

2.3.1 Dental Tooling

One of the main causes of injury in the dental industry is tool design. In dentistry there are four categories of tooling utilized, examination, hand-cutting, restorative, and accessory. Examination tools include mirrors, probes, forceps, and retractors (Bird et al., 2002). Hand cutting instruments contain sharp edges that are utilized in operatory procedures. Examples of hand cutting instruments are excavators, chisels, hoes, and gingival margin trimmers (DON, 2010). Next, restorative instruments are used to place, condense, and carve the restorative dental materials back to the normal tooth anatomy. These include condensers, burnishers, carvers, plastic composite placement instruments, and amalgam carriers. The last group of dental instrumentation is accessory, which is comprised of spatulas, scissors, an amalgam well, and pliers (Bird et al., 2002).

Dental tooling is placed on a sterilized tray and color coded as a universal way of organizing different sets in an office for convenience and efficiency. There is also a common left to right pattern of instrumentation. The tools from left to right are examination, hand cutting, restorative, and accessory items (Bird et al., 2002). This helps increase productivity of the clinician while decreasing the patient's time waiting for a hygienist or dentist searching for a specific tool.

Each tool is divided into three sections: the handle, shank, and working end. The handle is the portion of the instrument where the operator grips the tool. The shank attaches to the working end of the handle, and the working end is the tip of the tool that is utilized for a specific task (Bird et al., 2002). This can be seen in Figure 2-5 below.

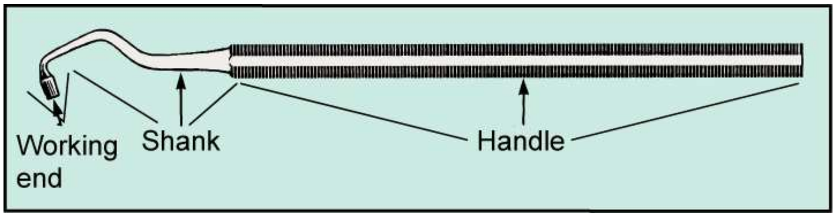


Figure 2-5. Dental Tool Sections (Bird et al., 2002)

Electromyography (EMG) measurements have shown that there is not enough variety in the most common tasks completed by dentists (Virtanen, 2001). The current design of dental tooling requires similar grips, precision, motions, and cycle times. An important factor in tool design is providing variability, giving the muscles a chance to recover (EDSAC, 2004).

It has been shown through research that the percentage of time spent probing was 10%, scaling – 50%, polishing – 25%, and flossing – 15% (Bramson et al.,1998). This is important background information to show how much time is spent doing different tasks. During scaling, flossing, and polishing, the hand and wrist movements occurred more than 30 times per minute. Repetitions of 30 movements per minute can lead to tendon disorders in the hands and wrist.

2.3.2 Magnification

In order to help improve accuracy for dentists performing fine restorative work magnification was introduced in the dental industry in 1876. As posture is an important factor in the reduction of work related injuries, the need for distribution of magnification loupes, pictured below in Figure 2-6, becomes more apparent. Studies have shown that magnification of at least 2.5 times strength show significant postural benefits for not only dentists but also hygienists (Osuna, 2003).

Figure 2-6. Magnification Loupes

2.4 Dental Tool Materials

Most dental tools are made of stainless steel although many instruments manufactured more than 10 years ago were not necessarily made of stainless steel. Early dental tool sets often featured unplated dental instruments with handles made of ebony, ivory, tortoise shell, and mother of pearl. The switch to all metal tooling came after the Civil War due to the inability of specific materials to be sterilized (Ring, 1985). Prior to the introduction of stainless steel tools, discoloration, corrosion, and the spread of disease were common problems (Hu-Friedy, 2007). More recently, some companies have experimented with making handles out of a resin or composite material.

Hand cutting instruments are typically manufactured from two materials, stainless steel and carbon steel. More durable cutting edges can be provided with carbide inserts in some of the tooling. There are many differences between carbon steel and stainless steel. First, stainless is softer than carbon yet remains brighter. A downfall to stainless steel is that it loses a sharp edge quicker during usage. Carbon steel when not protected is subject to corrosion. Even carbide inserts that are hard and wear resistant are not utilized in all conditions due to brittleness.

Instruments categorized in other dental tool groups such as examination, restorative, and accessory that are not for the cutting of tooth structures have been found to be manufactured from alloys of nickel, cobalt, and chromium in addition to stainless steel (Roberson et al., 2006).

2.5 Dental Instrument Sterilization

2.5.1 Sterilization Process

Sterilization is important in any healthcare field, especially dentistry, because infectious diseases can be spread through cross-infection due to reusable dental tools (Venkatasubramanian et al., 2010). Therefore, dental instruments are grouped into three categories of sterilization based on their risk of transmitting infection. The American Dental Association (ADA) abides by sterilization rules from the Center for Disease Control (ADA, 2009).

The three classifications are critical, semi-critical, and non-critical. Critical instruments are those that penetrate the soft tissue or bone. Examples include forceps, scalpels, bone chisels, hand scalers, and surgical burs. Semi-critical instruments make contact with mucous membranes in the mouth, such as, mirrors and reusable impression trays. The last group, non-critical, only comes into contact with skin that is intact on a patient. In a dental work environment, an example of a non-critical classification is an x-ray head (ADA, 2009).

Tools classified as critical or semi-critical must be properly sterilized after each patient. There are three main types of dental tool sterilization, which includes: autoclaving (steam under pressure), dry heat, and heat/chemical vapor. The standard conditions for these sterilization methods can be seen below in Table 2-1 (Hu-Friedy, 1989).

Table 2-1. Comparison of Sterilization Method Conditions

Method	Standard Sterilization Condition
Autoclave	20 min at 250°F at 15 psi
Dry Heat	60 – 120 min at 320°F
Heat/Chemical Vapor	20 min at 270°F at 20 – 40 psi

The process of sterilization includes three phases. Phase one is the decontamination process where all debris and bodily fluids are removed. Next, rust inhibitors are applied to avoid corrosion of carbon steel, and the dental instruments are dried and packaged while waiting for sterilization. This can be accomplished by ultrasonic or automated cleaning. Both of these methods decrease the probability for operator injury and the spread of contamination if hand scrubbing is utilized in phase one. The second phase is sterilization, and the final stage is the storage and care of sterile instruments and materials (ADA, 2009).

2.5.2 Sterilization Effectiveness

A study was conducted in 2010 comparing the effectiveness of sterilizing endodontic files, a critical instrument classification, using four methods of sterilization, autoclaving, carbon dioxide laser, chemical vapor, and glass-bead. One hundred endodontic files were split into groups of 20 and subjected to one of the four methods with the fifth group the control. Each file was exposed to bacillus stearothermophillus, which is a common bacteria used in sterilization validation testing. This is because the growth of spores can be easily monitored to determine the findings of the sterilization process (Venkatasubramanian et al., 2010).

The results showed the files sterilized by autoclaving and laser methods were 100% sterile. Even though lasers proved to be an effective at sterilization, more research is suggested to look into cutting capability and other mechanical properties of the files after repeated exposure to the carbon dioxide laser. Glass bead, a method popular in Europe has not been approved by the U.S. Food and Drug Administration (FDA) and Centers for Disease Control and Prevention (CDC, 2009), was 90% effective. The last group, chemical sterilization, resulted in only up to 80% sterile endodontic files (Venkatasubramanian et al., 2010).

2.5.3 Appropriate Materials for Steam Sterilization

The main concern with utilizing materials other than stainless steel instruments is its ability to be sterilized using common sterilization techniques as previously described that are universally accepted by dentists in the United States. The main consideration with steam sterilization (autoclaving) is the material composition of the tool must be able to withstand temperatures of 250°F or greater (Thermo Scientific, 2007).

As referenced in a Thermo Scientific Sterilemax Table Top Sterilizer operating manual, there are multiple materials appropriate for steam sterilization. The list includes: carbon steel (with special preparation instructions), air powered instruments made to be autoclaved, heat resistant plastic items, and heat resistant rubber tubing (Thermo Scientific, 2007). Other considerations must be made to reduce the effects of corrosion. Corrosion becomes a risk when the tools spend more time in a wet, oxygen rich environment (Hu-Friedy, 2007).

Another concern with changing material composition is that all instruments with any metallic component must be sterilized with other tooling made up of the same metallic composition. If metals are mixed, unforeseen damages to the tools will possibly occur (Thermo Scientific, 2007). An example of this is how corrosion can spread from low quality stainless steels to high quality stainless steel tools (Hu-Friedy, 2007).

2.6 Dental Tool Classification

To identify hand tools they are commonly referred to by their common name (i.e. mouth mirror) or named after the doctor who designed them. For example, in the 1940s Dr. Clayton H. Gracey and Hugo Friedman from Hu-Friedy collaborated to design 18 scalers and 14 single ended area specific curettes. The naming scheme for the tools provides a design number that identifies the working end in addition to "Gracey" the name (Nield-Gehrig, 2008).

On the other hand, hand-cutting instruments are assigned a number using Dr. Black's instrument formula to describe the angulations and dimensions. Black's formula provides a uniform method of instrument classification using a three-unit formula. The first unit describes the blade width in tenths of millimeters, the second unit is the length of the unit in millimeters, while the third describes the angle the blade forms with the axis of the handle in centigrade. An example is 15-8-12. This correlates with a 1.5 mm blade with a length of 8 mm and an angle of 12 centigrade from the axis of the handle. A fourth unit can be added when the cutting edge of an instrument is not at a right angle to the length of the blade (Hadavi, 2006).

2.7 Literature Review Summary

In summary, past research has found gaps in testing weight, material, and grip compressibility of dental tooling. With an increasing trend in the number of females entering the dental profession and possible decrement of the gender gap in the dental hygienist profession, both gender's anthropometric dimensions need to be designed for. Material selection should look for the best feasible option, whether, metal, composite, or resin, in terms of hardness and durability. Additionally, this material must also be able to withstand strict sterilization requirements in the dental industry. Overall, weight and grip compressibility need to be tested to increase comfort during repetitive tasks while trying to reduce the number of cumulative trauma disorders originating from tool design.

CHAPTER 3 - Survey

In order to identify current tooling design concerns, a survey for dentists was designed and dispersed. The Redesign of Dental Tooling Survey looks into the prevalence of work related musculoskeletal disorders due to the repetitive nature of daily tasks in the dental industry. The goal of the survey was to help pinpoint the source and frequency of pain or injuries (neck, back, and upper and lower extremities) associated with daily dental procedures and tasks. A copy of the original survey can be referenced in Appendix A.

The respondents of the survey were provided with background information regarding the research intended. The survey was classified as exempt under the criteria set forth in the Federal Policy for the Protection of Human Subjects. The proposal number assigned by the Committee on Research Involving Human Subjects is 5453 at Kansas State University and can be seen in Appendix B.

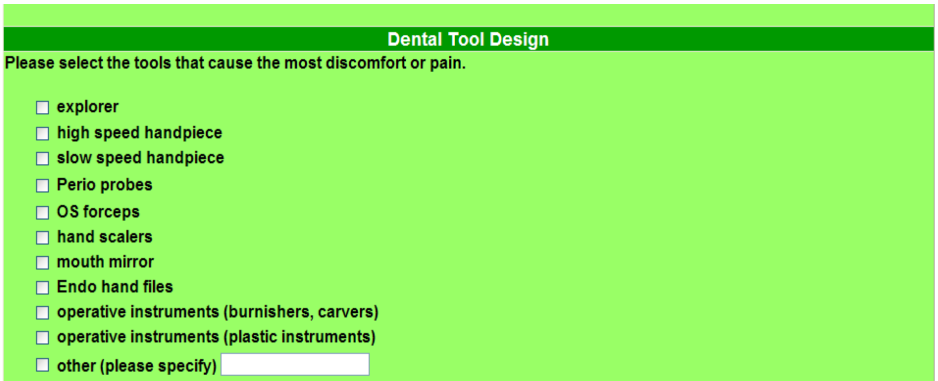
All participants were informed that responses to the survey would remain confidential and only be used in statistical and future design analysis as a group. Surveys were distributed through emails to dental schools and to local dental offices in person and by mail.

3.1 Survey Background

3.1.1 Survey Versions

The survey was designed to ensure that age groups were not eliminated based on design aspects. In order to construct a questionnaire that can be filled out quickly for multiple generations of dentists, two submission options were determined to be adequate in the distribution of the survey. The first was a hard copy of the survey, which could be mailed back while the second was an online form. Both had three main sections which included: background information, dental tool usage, and work related activities.

The online form was created using html language. This version of the survey was created to accommodate societies changing viewpoint of the internet. Multiple features were utilized on the form including: radio buttons, text boxes, check boxes, and select boxes. Then after the dentist answers the questions and pushes submit, the individual would be notified that their responses have been sent while emailing the responses to the resolver directly. This was accomplished using php coding. The format of the survey also does not disclose the identification of the dentist, which keeps the confidentiality of the respondent. A snapshot of the online form can be seen below in Figure 3-1.


Dental Tool Design

Please select the tools that cause the most discomfort or pain.

- ☐ explorer
- ☐ high speed handpiece
- ☐ slow speed handpiece
- ☐ Perio probes
- ☐ OS forceps
- ☐ hand scalers
- ☐ mouth mirror
- ☐ Endo hand files
- ☐ operative instruments (burnishers, carvers)
- ☐ operative instruments (plastic instruments)
- ☐ other (please specify)

Figure 3-1. Snapshot of Web-Based Form

3.1.2 Distribution

The survey was distributed by contacting over 30 private dental practices by phone in two Kansas cities, Kansas City and Manhattan. The survey was also emailed to over 15 dental schools in the United States. Due to stringent university policy, distribution was limited to only two schools, the University of Texas Dental Branch and professors at the University of Missouri-Kansas City School of Dentistry**.** There were 24 responses, 18 through the web-based form and six hard copies by mail.

3.2 Survey Design

The survey is split into three sections to gather information from the dentist. The three sections included: background information, dental tool design, and work related activities.

3.2.1 Background Information

Background information is the first section of the survey providing general data about the dentist. It will be used to compare the entire responding population in terms of gender, height, weight, and age. Each individuals body mass index (BMI) was also calculated using the height and weight information provided to see if there is any correlation between obesity and work related injuries to dentists. Other questions looked into the duration of the dentist’s workday along with an approximate number of patients seen on a daily basis. The last question asks about the particular dentist's specialties to look for any association with specific tool usage and pain regarding procedures utilizing that hand tool.

Out of the 24 responses, there were 18 male and 6 female dentists. This shows a 4:1 male to female ratio, which is similar to the ADA gender distribution based on active versus new active (10 years or less) private practicing dentists. The ADA has reported a range of female dentists from 17.2% to 34.6% based on diminishing years of service. This means the survey responses accurately represent the female population with a 25% response rate.

The next question looked into dominant tool hand, right versus left. Right was reported 22 times. This means that 91.7% of the dentists who responded are right handed. Research has shown that 90% of the population is right hand dominant with no difference based on gender (Konz et al., 2008). An important note is that all of the respondents who listed their left hand as their dominant tool hand were male. Although, based on the number of female versus male respondents, the sample can be taken as a population because out of six females less than one should be left handed while approximately two males should, which is represented by the results.

Height and weight were also included in the background information in order to calculate body mass index (BMI). The female's height ranged from 5' to 5'9" while weight ranged from 102 to 180 pounds. The male's height ranged from 5'7" to 6'3" with weight ranging from 140 to 250 pounds. Each individual's BMI was then calculated using the following formula (CDC, 2009):

$$BMI = 703 \times \frac{weight(lbs)}{(height(in))^2}$$

Based on the US Department of Health and Human Services, BMI is a measure of body fat based on height and weight for adult men and women. Higher BMI ratios tend to lead to more risk for certain complications, such as, heart disease, high blood pressure, type 2 diabetes, and breathing problems. Some limitations to only using height and weight are that it may overestimate people who have a more muscular build. It also may underestimate body fat in older individuals who have lost muscle (CDC, 2009).

Once calculated each individual is then categorized into one of four groups. The four categories are underweight, normal, overweight, and obese. The breakdown of the BMI's for the dentists surveyed can be seen below in Table 3-1.

Table 3-1. Survey Results of Body Mass Index

BMI Category	BMI	Male (n=18)	Male %	Female (n=6)	Female %
Underweight	Below 18.5	0	0.0%	0	0.0%
Normal	Between 18.5 to 24.9	4	22.2%	4	66.7%
Overweight	Between 25 to 29.9	11	61.1%	1	16.7%
Obese	30 or Above	3	16.7%	1	16.7%

A similar study was completed at the University of Kentucky (UK) on female dental hygienists (Szeluga, 2000). This survey found that the majority (57.6%) of the population of 245 dental hygienists were in the normal BMI category. The results from the female hygienists study were similar to this survey for female dentists where 66.7% had BMI's listed as normal. The UK study also listed 21.2% as overweight and 8.6% obese (Szeluga, 2000). Similar results were also seen in the dental survey with both overweight and obese accounting for 16.7% of the female population.

A study completed by the National Center for Health Statistics (NCHS) in 2005-2006 found that an estimated 32.7% of U.S. adults over 20 years old are overweight. The same study also stated that 34.3% of Americans are obese (BMI greater than or equal to 30), and 5.9% are extremely obese. From 1988 to 2006 the trends show an increasing percentage of obese and extremely obese individuals (NCHS, 2008). The sample size of 24 for the dental survey did not correlate directly with the NCHS percentages most likely due to the small sample size especially since the NCHS study contained over 4,000 people for each two year sampling time frame.

Other demographics such as age and years of experience were collected in the dental survey and can be seen below in Table 3-2 and Table 3-3. The breakdown of age ranges show that there are more older males than older females, which fits the overall distribution of dentists and the gender shift as previously described in Chapter 2. This also shows that the number of males that will be retiring in the next five to ten years will facilitate a realignment in the distribution of males and females.

Table 3-2. Age Distribution of Dentists

Age	Male	Female	Total %
< 35 years	2	0	8.3%
35 to 44 years	2	4	25.0%
45 to 54 years	6	2	33.3%
55 to 64 years	5	0	20.8%
> 65 years	3	0	12.5%

Years of experience, as seen in Table 3-3, also shows the same correlation between age and the number of males with more experience. The results show that 83.3% of males (15 out of 18) have more than 16 years of experience. Yet, from less than one year to 15 years, there is almost an equal number of male and females in practice.

Table 3-3. Years of Experience

Years of Experience	Male	Female	Total %
< 1 year	0	0	0.0%
1 to 5 years	0	1	4.2%
6 to 10 years	2	1	12.5%
11 to 15 years	1	2	12.5%
16 to 20 years	2	0	8.3%
> 20 years	13	2	62.5%

The next questions looked into averages per work week. The number of working days per week ranged from three to greater than five with a median of five days. The number of working hours per day ranged from six to greater than nine hours. The median number of hours per day was eight. This work environment is similar to research completed by the U.S. Bureau of Labor Statistics. On average dentists work four to five days a week with hours per day having a high variance. Although, most full time dentists have reported 35 to 40 hour work weeks, which may include evenings and weekends to accommodate patients' needs (US BLS, 2009). Each dentist was also asked to estimate the number of patients seen per day. The average number listed was 13.4 while responses ranged from five up to 40 patients/day.

The last question in the background information section of the survey was to see the breakdown of dental backgrounds included. Of the 24 responses there were 15 General, 4 Pediatrics, 2 Endodontics, 2 Prosthodontics, and 1 Periodontic Dentist. This distribution of general (62.5%) versus specialty (37.5%) dentists is very close to ADA survey where 20.9% of dentists reported a specialty practice (ADA Survey Center, 2010). The deviation can be attributed to the small sample size of this dental survey.

3.2.2 Dental Tool Design

The next section of the survey looks into specific tools that may cause pain or discomfort for an individual dentist. The purpose of this section is to look for the tool most recurrent in causing discomfort to redesign. Each dentist was prompted to select all tools that cause any source of pain during their daily practice. This section also provides the dentist with an open-ended question that allows the individual to provide any suggestions on the redesigning process.

The tool inquiry resulted in a tie between the high speed handpiece and hand scalers. Overall, hand scalers caused the most pain for males with Endo hand files being the second most common. Yet for females, the most significant source of pain was linked to the high speed handpiece followed by hand scalers. The comments listed for tool redesign revolved around making the tool handle diameters thicker with friction grip grooves. Comments for the high speed handpiece were to make it lighter and less noisy.

Another question regarding endodontic procedures was added to determine the use of a rotary instrument versus hand files. Endodontics is a specialty branch of dentistry that deals with diseases of the tooth root, dental pulp, and surrounding tissue. This specialty practice was adopted by the Council on Dental Education and Licensure of the ADA in December of 1983.The most familiar endodontic procedures are root canals (ADA, 1995-2010).

The rotary file instrumentation technology has been utilized the last couple of decades, yet there remains the need for hand files due to more difficult anatomical cases. In the survey results, 10 responded saying “yes” they use rotary, yet they frequently have to use hand files while only one of the 10 responded saying hand files were only needed minimally.

3.2.3 Work Related Activities

The last survey section addresses discomfort, pain, or soreness in different areas of the human body ranging from the neck and back to the upper and lower extremities. The dentist was asked to select the body part(s) he or she currently feels or has felt discomfort while noting the frequency of pain (daily or weekly). The last part of this question looked into how many work days of the year the dentist has missed due to this pain. It also attempts to pinpoint any tool or procedure related to the specific body part ache.

The responses for this question showed a wide range of body parts as the source of discomfort, soreness, or pain. The self-reported prevalence of pain regarding a tool or procedure as the source stemmed around the repetition due to similar work positioning, the forces required in scaling and other procedures, and the actual design of the workstation, including chair discomfort and improper patient positioning. The maximum estimated number of missed days per year came from the neck region at five, while the shoulders, lower back, wrist/hand, and upper back were also sources of missed days ranging from one to two per year. The remaining results can be seen below in Table 3-4.

Table 3-4. Self-Reported Prevalence of Pain

Body Part	Male	Male %	Female	Female %
Neck	10	55.5%	3	50.0%
Shoulder(s)	6	33.3%	5	83.3%
Upper Back	4	22.2%	3	50.0%
Lower Back	8	44.4%	2	33.3%
Elbow	1	5.6%	0	0.0%
Forearm	2	11.1%	0	0.0%
Hip	0	0.0%	0	0.0%
Wrist/hand	6	33.3%	2	33.3%
Upper Leg	2	11.1%	0	0.0%
Knee	1	5.6%	0	0.0%
Lower Leg	1	5.6%	0	0.0%
Ankle	0	0.0%	0	0.0%

The University of Kentucky Survey of Work-Related Musculoskeletal Complaints among Dental Hygienists also saw comparable results. The most prominent body parts selected in this 1999 survey were the neck, shoulder, lower back, and wrist/hand. These body parts were selected by the dental hygienists over 75% of the time (Szeluga, 2000). In the dentist survey the only difference in prominent body regions was the addition of the upper back.

Along with the body part discomfort question, each respondent was asked if they have sought medical help for injuries/pain related to work. Out of the 24 total replies, five responded with “yes”. The medical suggestions for a reduction in pain ranged from: exercises, yoga prescribed to increase flexibility, and chiropractic work sought to help lower back pain. In the most extreme case, one dentist required surgery to remove a bone spur, which resulted from years of pressure and stress applied to this individual’s neck.

The next question allowed the dentist to estimate the amount of time sitting versus standing while doing dental procedures to look for any correlation between tooling, procedure, and positioning research in ergonomics. A majority of hygiene checks, restorative dentistry, crown/bridge work, endodontic procedures, and orthodontics were completed while sitting. Sitting is the most common position of the dentist while performing procedures due to the research completed in the 1960’s at the University of Alabama (Smith, 1999). Removable work and oral surgery were both found to be split equally on sitting versus standing. The results appear to show no correlation between age and posture during specific procedures.

The last question looked into if the dentist completed any preventative measures (stretching, medication, etc) in order to reduce pain or future injuries. The results can be seen below in Table 3-5. Overall, the most popular common preventative measures were stretching, improved posture, over-the-counter medication, personal relaxation, and exercise. The UK study also had common responses with the addition of proper fitting gloves being significant.

Table 3-5. Summary of Preventative Measures

Preventative Measure	n	%
Stretching	15	62.5%
Reduced work hours	3	12.5%
Bandage or brace	1	4.2%
Chiropractor	3	12.5%
Improved posture	14	58.3%
Ergonomic instruments	6	25.0%
Lumber/chair supports	6	25.0%
Personal relaxation	9	37.5.%
Prescription medication	2	8.3%
Workstation adjustment	6	25.0%
Over-the-counter medication	10	41.7%
More frequent breaks	4	16.7%
Exercise	8	33.3%
Magnification	1	4.2%
Massage	1	4.2%

3.2.4 Survey Summary

Overall, the results of the dental survey show analogous findings with previous studies completed in the dental industry in terms of work-related activities. There were 24 total responses, 18 males and 6 females. The female's ages ranged from 35 to 54 while the males had representation in all age groups with a majority being between 45 to 64 years old. The neck, shoulders, lower back, and wrist/hand were the most selected self-reported body parts associated with pain and missed work. The results of the survey also pinpoint dental scalers as a cause of pain and therefore a primary candidate for redesign. The next chapter will look into the current design of hand scalers along with the pinch forces required during use in order to make design improvements that benefit both dentists and dental hygienists.

CHAPTER 4 - Dental Tool Design

Ergonomics and biomechanics principles were applied to the design of hand scalers to reduce discomfort while being used by dentists. Hand scaling technique will first be analyzed along with a study on the pinch force required prior to the analysis of the experiment testing new tool design.

4.1 Scaling

Scaling is a procedure used to remove deposits of plaque and calculus from teeth. The tool is usually made of stainless steel with additional materials available for the handle. Diameters range approximately between 5 mm to 12 mm, and at both ends there are stainless steel blades set perpendicular to the long axis of the handle that are 4 mm to 5 mm in length. The dentist or hygienist uses a modified pen or chuck pinch to grip the tooling. This type of pinch grip consists of the pad of the thumb being opposite to the pads of the middle and index fingers. The handle of the tool then rests on the radial side of the dentist's metacarpophalangeal joint (Nield-Gehrig, 2008). The desired grip for a right-handed person can be seen below in Figure 4-1.

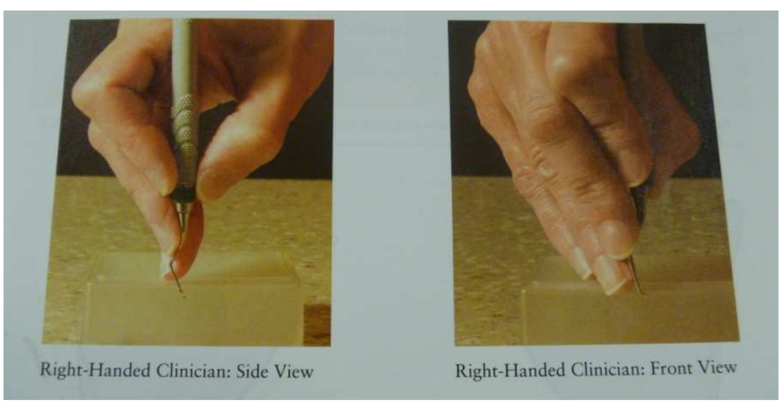


Figure 4-1. Side and Front View of Grip (Nield-Gehrig, 2008)

The scaling process is performed by pulling the tool along the long axis of the tool handle while the working end of the tool is used to scrape plaque and calculus deposits on the tooth surface. The tool blade should remain parallel to the surface of the tooth. If another tooth surface needs to be reached, the dentist or dental hygienist will change his or her wrist or torso posture (Villanueva et al., 2007). Different sections of the oral cavity are scaled using a clock methodology. For example, a right-handed operator needs to be able to move between 8 o'clock to 1 o'clock. The 8 o'clock positioning would be utilized for the lower right quadrant of the patient (Nield-Gehrig, 2008). Another scaling method involves changing the tool to a different tip design to clean every crevice in the patient's oral cavity (Villanueva et al., 2007).

With the precision necessary for the dental scaling task, the effect of finger rest positioning on the hand muscle load and pinch forces have been studied. Most experimentation has been completed utilizing a typodont, which is an artificial jaw. Typodonts are often used in clinical situations to help simulate scenarios prior to a real patient. In order to generate life-like plaque and calculus deposits, nail polish was used on the teeth. The study found using one or two finger rest(s) reduces the thumb pinch force and muscle activity. The different hand positions can be seen below in Figure 4-2 with no, one, or two finger rests from left to right, respectively.

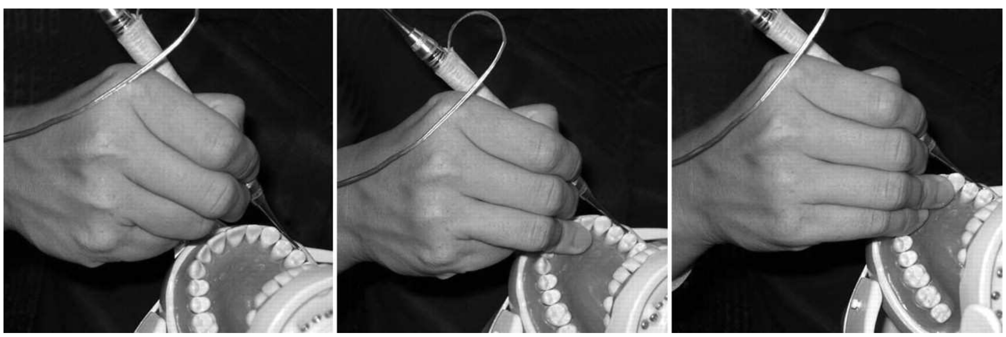


Figure 4-2. Dental Finger Rests (Dong et al., 2005)

The future of scaling techniques has started to look more advanced with the introduction of ultrasonic and sonic dental scalers. Ultrasonic scalers help reduce the pinch force, yet more research needs to be completed surrounding patient safety. With the development stages of this new technology, new risks arise in the industry. Therefore, risks associated with ultrasonic and sonic dental scalers need to also be researched further. One of the major risks to be analyzed is the effect of vibration (Dong et al., 2006).

Vibration starts to cause problems in work environments when a tool vibrates in the range of 20 to 80 cycles per second (EDSAC, 2004). Ultrasonic scaling devices vibrate at a frequency of 20,000 to 30,000 cycles per second (Neild-Gehrig, 2008). Thus, vibration from alternative scaling techniques creates a tightening of muscles, which could lead to more injuries. Consequently, the repetitive motion disorders trying to be reduced with ultrasonic and sonic dental scalers will remain present in the industry if the effect of vibration is not evaluated further.

4.2 Instrument Handle Pinch Force

The average pinch force exerted during dental scaling is 11% to 20% of the maximum pinch strength (Dong et al., 2006). In a 2006 study published in the Journal of the American Dental Association (JADA), the hand muscle load and pinch force were tested using 10 custom designed dental scaling instruments. The manufactured tools ranged in both diameter and weight. The diameter of the tools was 7 mm to 11.5 mm. The materials utilized were stainless steel and aluminum in order to ensure weight ranged from 15 grams to 24 grams.

The study consisted of 24 dentists and dental hygienists with muscle activity being recorded in the two extensors and flexors in the forearm with electromyography. In addition, thumb pinch force was measured using pressure sensors. Dong et al., 2006, found that the 10 mm diameter and 15 gram tool required the least amount of muscle load and pinch force. While diameters greater than 10 mm, showed no additional benefits in reduction of load or force required. The study did not test tools less than 15 grams. Thus, there is a need for research to look for a reduced pinch force effect directly resulting from reducing the weight of the tool.

A biomechanical analysis of applied pinch force was also completed in 2007 to develop a linear model capable of predicting the necessary pinch forces for experienced dentists based on applied tip forces. The study found that inexperienced dentists did not fit the model due to consistently more force being applied in similar experimental procedures. This can be seen in the R^2 value of 0.59 for the experienced dentists versus 0.01 for the inexperienced students (Villanueva et al., 2007).

The equation, as seen below, uses tool weight, tip forces, and tool-finger friction to predict pinch force. The trend modeled suggests that this force may be reduced with lighter tools, sharper blades, and tool surface textures of higher friction (Villanueva et al., 2007).

$$F_{pinch} = \left(\frac{w}{2\mu} + \frac{F_z}{2\mu} + 2F_t \right) S$$

Where,

w = tool mass

F_t and F_z = forces used to counteract gravity

μ = coefficient of friction between the gloved fingers and the tool

S = safety factor

4.3 Personal Protective Equipment – Gloves

OSHA mandates that dental health care workers wear surgical masks, protective eyewear, protective clothing, and gloves (CDC, 2010). Gloves are worn by dentists and dental hygienists as a safety precaution just as a doctor would wear gloves while performing surgery. The purpose of wearing gloves is to protect the hand and fingers from infections resulting from the transfer of saliva, blood, and infectious materials in the oral cavity during dental procedures.

For patient examination gloves are a medical device that is regulated by the Food and Drug Administration (FDA) and should be single-use only. Common glove materials include: natural rubber latex, nitrile, Polyethylene (plastic), and Polyvinyl chloride (vinyl) and other synthetics (CDC, 2010). A problem with the use of certain materials is the risk of an allergic reaction to the patient or dental clinician. Another concern is the effect of powdered gloves causing irritation to the users hand dermatitis (Field, 1997).

Gloves have been found to decrease grip and grasp capabilities while also reducing finger dexterity and manipulability (Bishu et al., 1999). Research has shown that there is no known affect of gloves on pinch strength. During a scaling experiment in 2009, it was found that participants overexerted by 10% to 15% with latex examination gloves (Gnaneswaran, 2010).

4.4 Design Factors of New Dental Scaler

After researching multiple factors that affect tooling in the dental industry, specific ergonomic design principles were incorporated into a new scaler design. The most important considerations in designing an instrument’s handle are size, shape, weight, and maneuverability.

When these design aspects are considered, force exertion can be reduced while maintaining neutral wrist positioning. Changes can make significant improvements in the industry because 78% of dentists reported that dental tools are used more than half of the working day (Rucker et al., 2002).

4.4.1 Diameter

The small diameter of some dental instrumentation requires use of smaller muscles in the hands. In a repetitive industry, such as in dentistry, it is suggested to spread the distribution of work throughout larger muscles (Konz et al., 2008). Ideally, this is why dental tools should have a larger grip to provide relief to the smaller muscles and fingers. This allows for an increase in precision while redistributing the force to the pads of the dentist's fingers. Switching the pressure from the finger tip to the pad will help move tension to the larger muscle groups in the hand. The tooling diameter must not be too large because the average opening width of a human mouth is limited to 30 mm to 40 mm (1.18 in to 1.58 in) measuring from the tip of the upper incisors to the tip of the lower incisors (Chen, 2009).

4.4.2 Compressibility

Another principle of ergonomics looks into making the grip surface compressible (Konz et al., 2008). The different grips of commonly used dental tools are seen in Figure 4-3 below.

Figure 4-3. Dental Tool Grips

It is very obvious that the grips on current dental tools are not always compressible. The tools should not be completely smooth in order to provide friction, yet resistance can be provided by other methods, such as glove selection. Friction is needed to provide stability for the dentist's fingers. In order to make the grip more comfortable for repetitive motions, the grip needs to be compressible. Compressible grips minimize the pressure on the hand and help reduce slippage. This will help reduce injuries to patients and dentists as the tools will not protrude into the patient's mouth.

A safe compressible grip will also help increase the contact area of the tool. This will also help increase the contact area closer to the tool tip. Then the second digit (index finger) can be moved closer to the operating point. This is important because this finger can detect very fine movements with the greatest accuracy (Dougherty, 2001). In the dental industry, accuracy is vital.

4.4.3 Redesign of Hand Scaler

A new hand scaler (A) was designed while taking into consideration tool diameter, compressibility, material, and weight. First, the diameter chosen was 10 mm since this was found to be optimal based on the least amount of muscle load and pinch force required in the 2006 study (Dong et al., 2006).

The next goal was to minimize the weight of the tool. The material utilized to achieve a minimum weight was a High-Strength Weldable Titanium tube with an outer diameter (OD) of 0.375 inches, inner diameter (ID) of 0.337 inches, and wall thickness of 0.019 inches. Aluminum was not selected because it is not as strong as titanium and steel even though it weighs less than both materials. The titanium tube was cut to yield a tool length of 165 mm (6.5 inches).

Then in order to make the grip contact area compressible different grips were considered. The variety originally considered can be seen below in Figure 4-4. In addition to pre-made grips, a multi-purpose rubber coating was considered because it would provide a non-slip grip that would be flexible and durable.

Figure 4-4. Possible Tool Grips

These grips ranged in length, thickness, shape, and weight as seen in Table 4-1. The grips that were not selected were eliminated based on length (red), excess bulk and weight (green and pink), and no grip pattern for increased friction (blue and red). The grip selected for Tool A was a black rubberized grip found on a BIC Velocity® Ball pen. It was then added on both ends of the handle near the tools shank.

Table 4-1. Grip Specifications

Grip	Outside Shape	Length	Thickness	Weight
Red	Circle	1.25”	0.066” – 0.082”	1.6 g
Blue	Circle	1.5”	0.062” – 0.078”	1.7 g
Pink	Triangle	1.5”	0.100”	2.8 g
Green	Square	1.5”	0.110”	2.3 g
Black	Circle	1.5”	0.060”	1.5 g

With this grip, the weight of the new tool is 17.3 grams. A dimensioned sketch of the new tool design can be seen in Figure 4-5 below. This tool will be referred to as Tool A throughout the experiment.

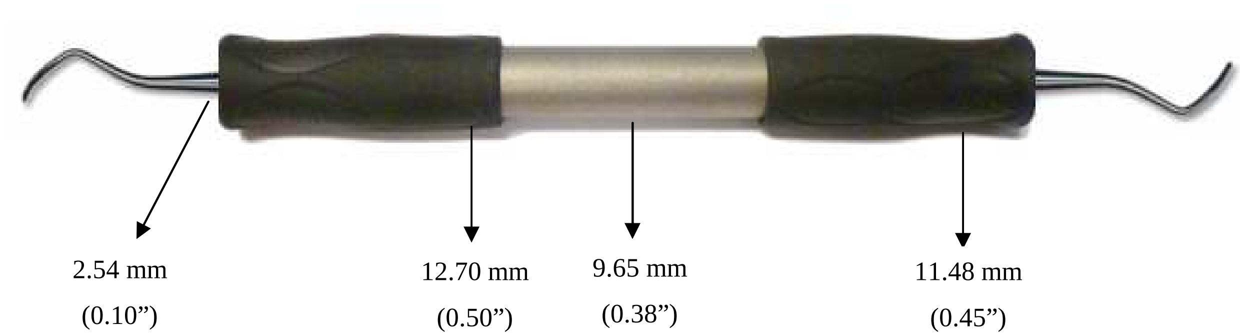


Figure 4-5. Redesigned Dental Scaler A

4.5 Design of Experiment

An experiment was designed to test the new tool with two dental scalers currently on the market. The purpose of this experiment is to examine the effect of increasing the diameter and compressibility in the finger grasp region on the change in grip strength and pinch strength. The experiment was approved by the Committee on Research Involving Human Subjects at Kansas

State University. The proposal number assigned was 5651 as seen in the approval letter in the Appendix C.

4.5.1 Control Tool B

The first hand scaler used as a control tool for the experiment was the Hu-Friedy sickle scaler (#4 Nevi Scaler Posterior DE, EverEdge #9) product code SCNEVI49 seen below in Figure 4-6. The diameters of specific segments measured using calipers are included in the picture. The tool handle is made of a hollow stainless steel alloy. The total length of the tool is 165mm (6.5in). This tool weighed 20.9 grams and will be referred to as Tool B throughout the experiment.

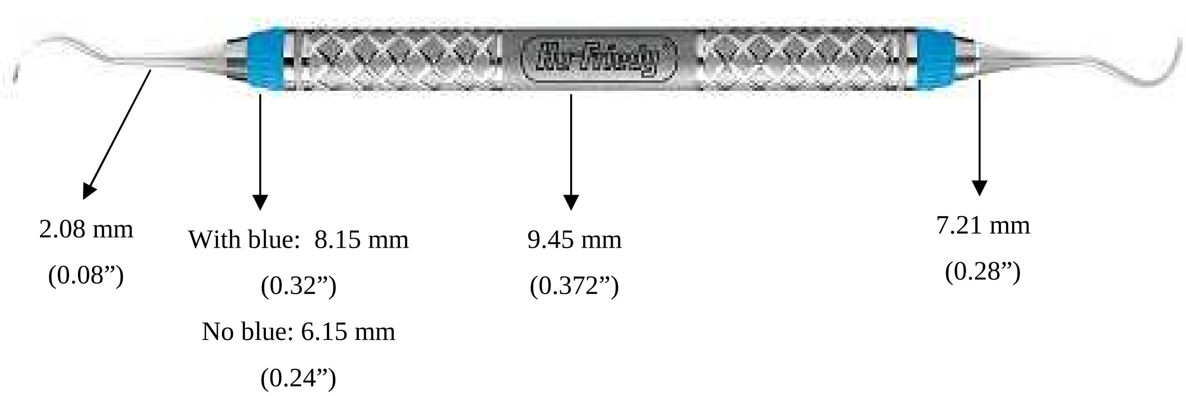


Figure 4-6. Control Tool B

4.5.2 Control Tool C

The second control tool, C, is a Montana Jack Scaler Rigid made by Paradise Dental Technologies (PDT). A dimensioned sketch of the tool can be seen in Figure 4-7. The length of Tool C is also165mm (6.5 in). This tool varies greatly from Control Tool B in weight and material composition. The Montana Jack Scaler Rigid weighs only 13.1 grams, which is 7.8 grams less than its Hu-Friedy equivalent. Control Tool C is also made of a medical-grade plastic resin that has been tested for all methods of sterilization. It also has a knurling pattern to help control pull and rotation with a lighter grasp required.

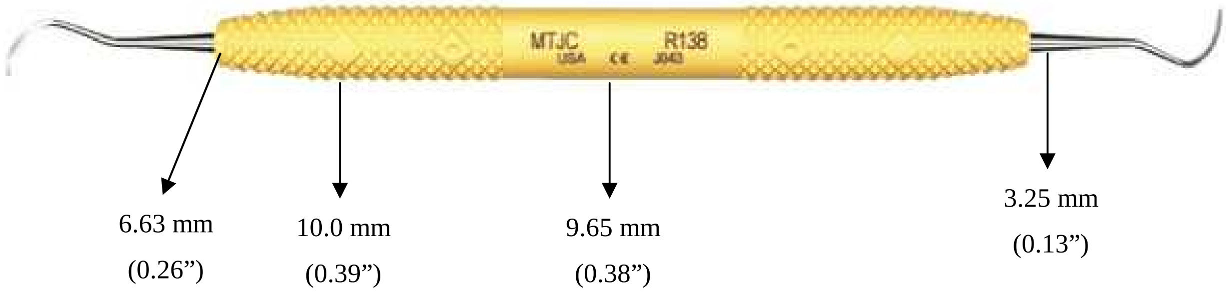


Figure 4-7. Control Tool C

4.5.3 Set-Up of Experiment

The experiment consisted of three 30 minute sessions. At the beginning of the first session a consent form was filled out by the subject. An example of the consent form can be seen in Appendix D. Next, background information about each individual was collected including: age, height, weight, frequency of exercise on average per week, dominant hand (left or right), and hand dimensions. The subjects were then required to watch two minutes of “Sickle Scaling,” a short video about dental scaling from the University of Michigan Dental School (University of Michigan, 2009) to provide a visual of stroke length and angles while scaling.

Each session consisted of four main tasks, a steadiness of the dominant hand test, grip and pinch strength measurements, a stress ball hand workout, and scaling. The grip strength meter used was a Jamar® digital hand dynamometer, and the pinch strength was measured using a Jamar® hydraulic pinch gauge. The steadiness of the dominant hand test consisted of the subject drawing three “straight” lines perpendicular to the lines already drawn on the paper. Three lines would be drawn before and after while maximum deviation from a true straight line was averaged. In addition, activities completed in the last 24 hours utilizing the subjects arm and dominant hand were recorded. The sequence of tasks performed can be seen below.

1. Steadiness of the dominant hand
2. Grip Strength measurement (3 times)
3. Pinch Strength measurement (thumb, index finger, middle finger – 3 times)
4. Stress ball dominant hand for 5 minutes
5. Scaling for 10 minutes
    a. Remove all purple nail polish
    b. 3 minutes per chair position (middle, right, left)

6. Steadiness of the dominant hand
7. Grip Strength measurement (3 times)
8. Pinch Strength measurement (thumb, index finger, middle finger – 3 times)

The scaling tool utilized for each session was randomly assigned to each subject with at least seven subjects starting with each tool (A, B, and C). The remaining two sessions the tooling would be rotated to eliminate the effect of tool order on the subject's performance and preference choice. As previously mentioned, Tool A is the new scaler with black rubber grips while Tool B and C are the control scalers.

In order to replicate a patient-like environment, an eight inch Styrofoam ball was used to reproduce a human head. The mouth was simulated utilizing a typodont. The typodont was a Nissin model P15DP-TR.56C.1 (GSF) made in Japan. A picture of the typodont can be seen below in Figure 4-8.

Figure 4-8. Typodont

Material was carved out so the typodont could be opened to the appropriate position simulating a mouth opening. This would act as a simulation of a person holding their mouth open during a dental procedure. The set-up of the experiment can be seen in Figure 4-9 below.

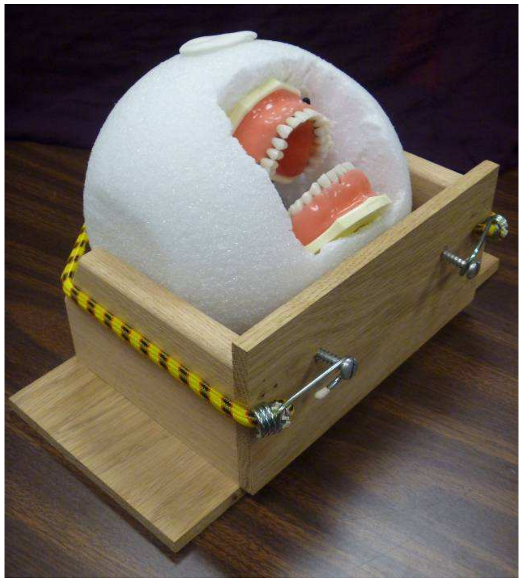


Figure 4-9. Replicated Human Head with Typodont

At the end of the third session, an absolute and relative rating system was utilized to determine the best alternative. First, the subject was asked to rank the scalers in order of preference. Then the individual was asked by how much they preferred one tool over another. An example of the data collection sheet can be seen in the Appendix E.

4.6 Results of Experiment

4.6.1 Subjects

The subjects consisted of 23 volunteers from the Industrial Ergonomics class taught in the Fall at Kansas State University. There were 13 males and 10 females who volunteered to participate in three different sessions of approximately 30 minutes each. The ages of the subjects ranged from 20 to 23 years old with a mode of 21. Each subject's height and weight were also provided to calculate body mass index (BMI) in a similar manner based on the equation below with the breakdown by BMI category summarized in Table 4-2 below.

$$BMI = 703 \times \frac{weight(lbs)}{(height(in))^2}$$

Table 4-2. Experiment Results of Body Mass Index

BMI Category	BMI	Male (n=13)	Male %	Female (n=10)	Female %
Underweight	Below 18.5	0	0.0%	0	0.0%
Normal	Between 18.5 to 24.9	11	84.6%	7	70.0%
Overweight	Between 25 to 29.9	2	15.4%	3	30.0%
Obese	30 or Above	0	0.0%	0	0.0%

The male and female height and weight were compared to anthropometric dimensions of nude U.S. adult civilians in a study completed in 1989 (Gordon et al., 1989). The percentile calculations can be seen in Appendix F. The z-values for the male average and female average were calculated using the following equation:

$$Z = \frac{x - \mu}{\sigma}$$

The male height was in the 81st percentile while weight was in the 51st percentile. The female height was in the 76th percentile while weight was in the 60th percentile. This shows that the male and female subjects in the experiment are above average in height while males were at the mean in weight and females slightly above the mean in weight.

In addition to height and weight each subject was asked to estimate the average number of days per week that they exercise. The choices were 0, 1, 2, 3, 4, or ≥ 5 days per week. The number of responses per option can be seen in Table 4-3 below. Majority of males on average worked out two days per week while majority of females responded with three days per week.

Table 4-3. Average Days per Week of Exercise

Number of Days	Male (n=13)	Male %	Female (n=10)	Female %
0	2	15.4%	1	10.0%
1	1	7.7%	1	10.0%
2	5	38.4%	2	20.0%
3	0	0.0%	4	40.0%
4	3	23.1%	0	0.0%
≥ 5	2	15.4%	2	20.0%

Next, the dominant hand was recorded for each contributor along with hand breadth, hand length, and wrist width measured. The number of right hand dominant people was 19 out of the 23 total subjects. This accounts for 82.6% of the experiment population while there were four left handed individuals making up the remaining 17.4% of the population. This experimental population of left handed individuals is higher than the 10% of the population who is left hand dominant (Konz et al., 2008). A summary of the hand breadth, hand length, and wrist width can be seen in Table 4-4 below.

Table 4-4. Summary of Hand Dimensions (inches)

Dimension	Male Range	Male Average	Female Range	Female Average
Hand Breadth	3.25 – 4.00	3.625	2.75 – 3.50	3.125
Hand Length	7.00 – 8.5	7.625	6.50 – 7.25	6.875
Wrist Width	1.75 – 2.50	2.270	1.50 – 2.50	2.088

Similarly to the height and weight, male and female hand breadth and lengths were compared to hand dimensions of nude U.S. adult civilians (Gordon et al., 1989). The z-values for the male average and female average were calculated using the following equation:

$$Z = \frac{x - \mu}{\sigma}$$

The male hand breadth was in the 66th percentile while hand length was in the 50th percentile. The female hand breadth was in the 50th percentile while hand length was in the 27th percentile. This shows that the male subjects in the experiment are above average in hand length while at the mean in hand length. Female subjects were also at the mean in terms of hand breadth yet considerably below the average in terms of hand length.

4.6.2 Experiment

The simulated patient and typodont was set-up on a table that was 27 inches tall. A desk lamp (34 watts) was provided to create more illumination in the oral cavity where the subjects would be working. The neck of the lamp provided adjustable light that would account for the range of heights for all subjects aimed to reproduce the effect of overhead lighting similar to the dental work environment. The subjects were also provided an adjustable chair and taught how to properly adjust it so that their knees were bent at a 90 degree angle with feet flat on the floor during the experiment.

Each subject started at the 12 o'clock position seated directly behind the patient. At this position they were instructed to scale the anterior teeth utilizing a pulling motion with stroke lengths of 2 mm to 3 mm. The subjects were then instructed to switch positions to work on different quadrants of the mouth. Each position, middle, right, and left, were each scaled for 3 minutes and 20 seconds. Figure 4-10, below, shows all three tools being utilized in the 12 o'clock position by three different subjects. Other pictures from the experiment can be seen in Appendix G.

Figure 4-10. Tool A (left), B (middle), C (right)

4.6.3 Statistical Analysis of Δ Grip Strength

During the experiment, the change (Δ) in grip strength (GS), change in pinch strength (PS), and change in max deviation from a straight line before and after were all measured. A paired t-test and Analysis of Variance (ANOVA) was used to test for significance. The p-values were calculated using Minitab 15 with full results in Appendix H. The value of α chosen for statistical analysis was 0.10.

In order to perform statistical analysis four categorical variables, gender, dominant hand, BMI, and average number of days of exercise per week, were coded during data entry. The code definitions can be seen below in Table 4-5.

Table 4-5. Coded Variables

Variable	0	1
Gender	Female	Male
Dominant Hand	Left	Right
BMI	Normal	Overweight
Exercise	0 – 2.5 days	2.6 – ≥ 5 days

Before and after scaling each person was required to test their GS three times with the average calculated and recorded. The Δ GS was calculated as the reading before minus the reading after. The average, standard deviation, and range for the GS change can be seen summarized in Table 4-6 below. The positive ΔGS values occurred when the subject's grip strength decreased after scaling. On the contrary, GS would be a negative value if the person increased from their before test to the after test. One possible reason for negative values could be due to the subject not having a strong grasp on the meter during the initial readings.

Table 4-6. Summary of Δ Grip Strength (lbs)

	Δ GS Tool A	Δ GS Tool B	Δ GS Tool C
Average	6.22	3.58	5.16
Standard Deviation	5.94	6.85	6.36
Range	-10.03 – 16.27	-8.70 – 16.50	-8.80 – 16.47

The change in grip strength calculation aimed to look for the tool that would cause the least change in grip strength. This was evaluated using a paired t-test. Tool A versus B, Tool A versus Tool C, and Tool B versus C yielded p-values of 0.094, 0.537, and 0.447, respectively. With $\alpha = 0.10$ the only significant p-value was Tool A versus B. This translates to a conclusion of failing to reject the null hypothesis. The null and alternative hypothesis for the paired t-test for Tool A versus Tool B can be seen below.

$$H_0: \Delta GS_A = \Delta GS_B$$

$$H_A: \Delta GS_A \neq \Delta GS_B$$

The significant Δ GS for Tool A versus Tool B was investigated further by looking at the Δ GS based on gender. The significant p-value comes from the male population with a p-value of 0.076 meaning that the Δ GS for Tool A is not equal to the Δ GS for Tool B when α is 0.10. The 90% confidence interval is (0.05, 5.22). The remaining p-values for Δ GS based on gender were not significant (p-values > α).

Pearson's correlation coefficient (r) was also calculated to look for linear relationships between gender and Δ GS. The coefficient will range between -1 and +1 with a value of 0 meaning no linear relationship or correlation. The closer the value is to ±1 the more tightly the data points fall on a line whether positively or negatively correlated. Table 4-7 below shows no correlation between gender and change in grip strength since all p-values are above α.

Table 4-7. Δ GS Correlation p-values

	r	p-value
Gender vs. ΔGS_A	0.187	0.392
Gender vs. ΔGS_B	-0.116	0.598
Gender vs. ΔGS_C	0.180	0.412

An Analysis of Variance (ANOVA) test was also completed to look at the effect of factors and covariates on the response of change in grip strength. The factors tested were gender, BMI, exercise, and tool. The covariates included were hand breadth, hand length, and wrist width. The ANOVA test showed that only the interaction of gender and BMI is significant ($p < 0.10$). The residual plots for change in grip strength can be seen below in Figure 4-11.

The normal probability plot shows that the residuals can be assumed to be normally distributed with no unusual values or outliers. There also does not appear to be any pattern in the residual versus fitted value plot with an equal number of residuals above and below zero. The residuals also appear to be normally distributed as shown in the lower left histogram with no apparent skewness.

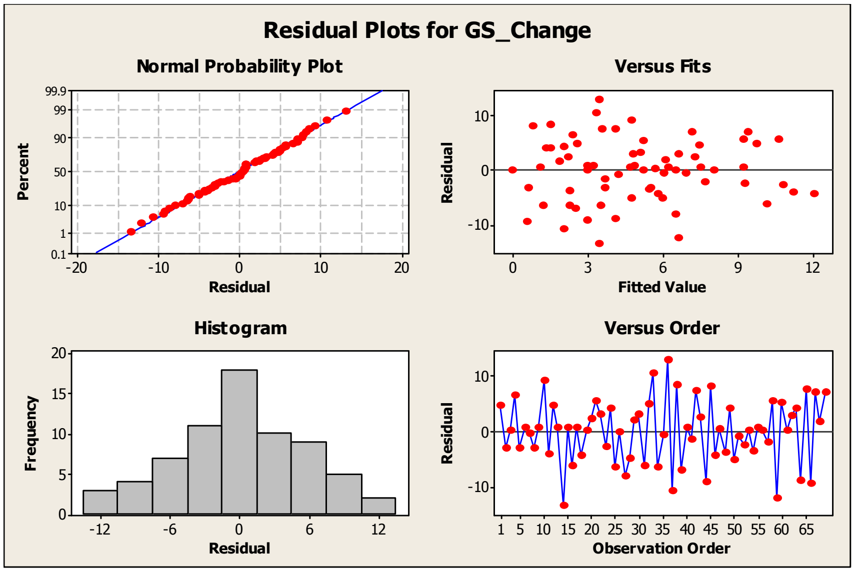


Figure 4-11. Change in Grip Strength Residual Plots

4.6.4 Statistical Analysis for Δ Pinch Strength

Similar test procedures were followed for the subject's pinch strength (PS) testing. The Δ PS was tested for the thumb, index, and middle finger before and after. At first glance, it appears that the Δ PS for the thumb and middle finger is greater with Tool A and for the index finger with Tool B. The data can be seen in Table 4-8 below.

Table 4-8. Summary of Change in Pinch Strength (lbs)

Δ PS	Average	Standard Deviation	Range
Thumb Tool A	1.39	2.22	-3.00 – 8.00
Index Tool A	0.67	2.65	-3.00 – 5.00
Middle Tool A	0.93	2.51	-3.00 – 6.00
Thumb Tool B	0.48	1.93	-6.00 – 4.00
Index Tool B	1.02	1.92	-2.00 – 5.00
Middle Tool B	0.85	1.13	-1.00 – 3.00
Thumb Tool C	0.74	1.40	-2.50 – 3.50
Index Tool C	0.37	2.08	-4.50 – 4.00
Middle Tool C	0.61	1.71	-3.00 – 3.50

The Δ PS was also tested for statistical significance using a paired t-test. All p-values were greater than 0.10 (α). Therefore, no difference in pinch strength before and after was found from one tool to another. The p-values can be seen in Table 4-9 below.

Table 4-9. Δ PS P-values

Tool	Thumb	Index	Middle
A vs. B	0.117	0.599	0.877
A vs. C	0.276	0.674	0.606
B vs. C	0.635	0.174	0.634

Correlation was also analyzed between gender and Δ PS for each finger. The results show similar findings as all p-values except one were not significant at $\alpha = 0.10$. There is a correlation between gender and the change in pinch strength for the index finger when subjects were using Tool B. The r value for this scenario is 0.407. The coefficient of determination, r^2, can then be calculated to be 16.6% which is the proportion of the variance of one variable that is predictable from the other variable. This value is still low and will require more statistical analysis. Table 4-10 shows the remaining correlation p-values.

Table 4-10. Δ PS vs. Gender Correlation p-values

	Tool A		Tool B		Tool C	
	r	p-value	r	p-value	r	p-value
Thumb	0.037	0.867	-0.196	0.370	0.154	0.484
Index	0.262	0.228	0.407	0.054	0.224	0.305
Middle	0.280	0.195	0.077	0.725	-0.126	0.565

An ANOVA general linear model was also tested for each specific change in pinch strength. The only significant factor was the interaction of exercise (0, 1) and tool (1, 2, 3) for the Δ PS for the middle finger (p-value = 0.011).

4.6.5 Statistical Analysis for Steadiness Test

The final test was to look at how tool design would affect the steadiness of the subject's hand. Each subject was asked to draw three straight lines perpendicular to the lines provided on the half sheet of paper before and after scaling. A straight line was then drawn with the same starting point as the subjects. The maximum deviation was measured in fractions of an inches for each line with the average of all three recorded. The change in steadiness was then measured as the average deviation after minus before. A positive value would signify the individual's line deviated more after than before while a negative value more before than after.

The data was found to have two values deemed outliers that were at least three standard deviations from the mean associated with a particular tool. The average was calculated with and without the outliers along with the standard deviation and can be seen below in Table 4-11.

Table 4-11. Maximum Average Line Deviation (inches)

Tool	Average (with outliers)	Average (without outliers)	Standard Deviation (without outliers)
A	0.00099	-0.0115	0.0547
B	-0.0082	-0.0082	0.0675
C	0.00544	-0.0137	0.0672

A paired t-test was calculated for the maximum average line deviation for Tool A, B, and C without the two outliers. Similarly to the change in grip strength test, each pair was tested. The three pairings, A versus B, A versus C, and B versus C, yielded p-values of 0.972, 0.742, and 0.818, respectively. All p-values were not statistically significant meaning that there is no statistical difference between the mean line deviation before and after.

4.6.6 Absolute versus Relative Rating

Finally, at the end of the third session, an absolute and relative rating system was utilized to determine the subjects preferred tool. First, the subject was asked to rank the scalers in order of preference in an absolute rating method. The tool determined to be most favorable by subject preference was Tool A followed by B, then C with 12, 6, and 5 first place rankings, respectively. This shows that 52.2% of the subjects preferred Tool A over B and C. The absolute rating also shows that Tool B and C had very similar ranking schemes by the subjects. The overall distribution of tool rankings can be seen in Table 4-12 below.

Table 4-12. Absolute Ranking

Place	Tool A	Tool B	Tool C
1	12	6	5
2	4	9	10
3	7	8	8

Next, each subject was asked by how much they preferred one tool over another. The scale of 1 to 10 was used. The full relative ranking scale can be seen below in Table 4-13.

Table 4-13. Relative Ranking Scale

Scale	Meaning
9 - 10	Absolutely better
7 - 8	Significantly better
5 - 6	Much better
3 - 4	Somewhat better
1 - 2	Equal to

The two values collected were preference and amount in order to determine the subject's relative rating. The data was then reduced to an eigenvector, which is then normalized by preference. The average of each normalized row is then the amount of preference.

An example would be if a person preferred A to C and C to B. This person would then provide a numerical value for how much they preferred A to C, C to B, and A to B. These values would then be transformed into matrices, such as, [1,9], [3,1], and [1,10]. This shows that the subject favored Tool A the most, yet found Tool C to only be slightly more favorable than Tool B.

Next, an eigenvector (w) was calculated for the entire population. The w is 0.8615, 0.1279, and 0.0106 for Tool A, B, and C, respectively. The calculations for each step can be seen in Appendix I. This shows by how much Tool A is preferred over Tool B and C.

An Analysis of Variance (ANOVA) test was completed to look at the effect of the factors and covariates on the response of tool preference based on each individual's eigenvector. Again, the factors tested were gender, BMI, exercise, and tool, and the covariates included were hand breadth, hand length, and wrist width. The ANOVA test shows that tool and the interaction of gender and tool are significant ($p < 0.10$). The residual plots for tool preference can be seen below in Figure 4-12.

The normal probability plot appears to follow the normal line yet there is a slight curvature in the tails. This does not mean that the residuals are not normal because there were less than 50 subjects. The residuals versus fits values appear to fan out showing a pattern of increasing residuals with increasing fits.

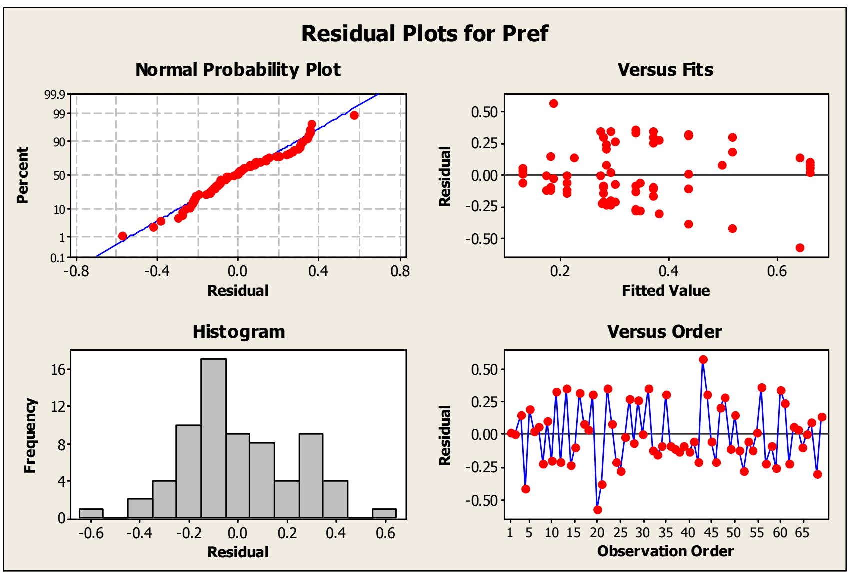


Figure 4-12. Tool Preference Residual Plots

The interaction between tool and gender trend was evaluated utilizing a main effect and interaction chart. First, the main effects chart was plotted to show the difference among level means for this particular factor. As seen in Figure 4-13, the line is steeper between Tool 1 (A) and Tool 2 (B) and Tool 3 (C) showing a greater magnitude of the main effect.

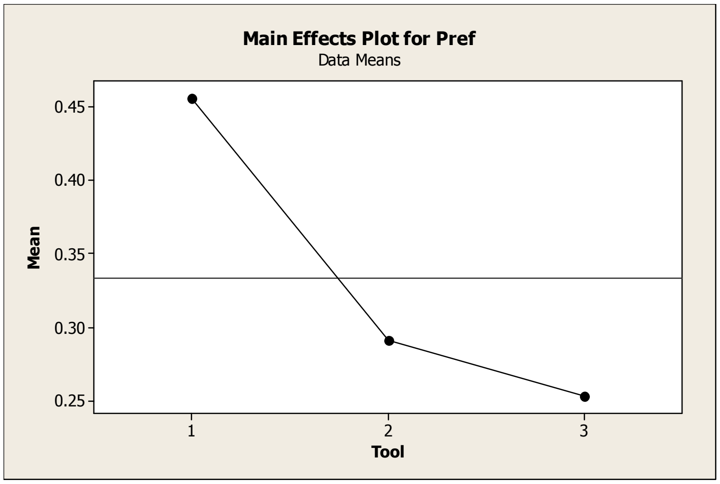


Figure 4-13. Main Effects Plot for Tool Preference

Next, an interaction plot between gender and tool was generated as seen in Figure 4-14 below. This shows that tool preference is dependent on gender. This interaction plot shows that females (0) prefer Tool A the most, then B, then C based on the preference mean. On the other hand, males (1) were indifferent in tool preference.

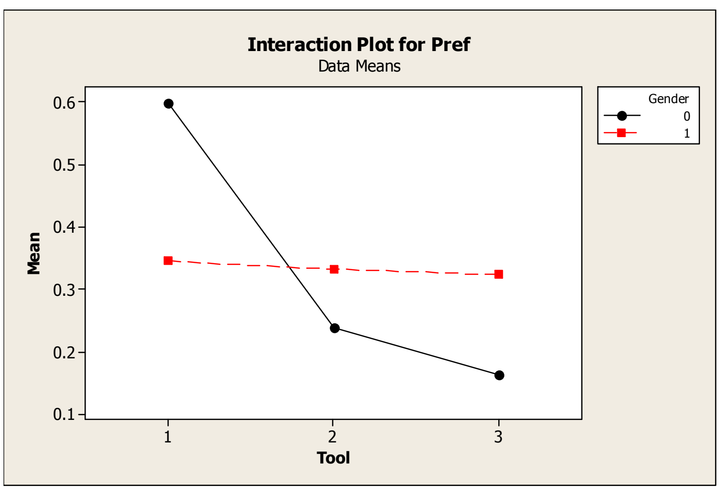


Figure 4-14. Interaction Plot for Tool Preference

The contrasts between each tool preference were calculated using Two-Sample T-Tests. The overall mean of Tool A, B, and C are 0.455, 0.291, and 0.254, respectively. The mean was found to be statistically significant between Tool A versus B (p-value = 0.046) and Tool A versus C (p-value = 0.013). The difference in the mean of Tool B versus Tool C was found to not be significant (p-value = 0.573).

4.6.7 Summary of Comments

While ranking the tools during the third session and during the experiment, each subject was also asked to provide comments based on tool design. The comments were then analyzed for each tool to look for trends.

Overall, more females preferred the grips added to Tool A, although both genders commented on how they would have liked a gradual thinning towards the working end of the tool in the shank region similar to Tool B and C. Others believed that the "compressible, textured" grip on Tool A provided them with "more control" to keep the tool from slipping and protruding into the gum of the typodont. Another comment regarding Tool A was the diameter size being larger. This was why one subject who ranked Tool A as last stated, "Tool A had a better grip when working on the anterior teeth, but it was hard to reach and keep my fingers on the grip for posterior teeth."

Many subjects preferred Tool B even though they did note it was the heaviest due to the metal material. The participants who preferred B tended to be males and females with hand dimensions in higher percentiles. The smooth round handles of Tool A and B were also preferred over the knurling pattern on Tool C. One subject noted that, "Tool C had a pointy grip, which hurt my fingers after 10 minutes." Although, another participant liked the length and grip pattern on Tool C but, "If Tool A's [grip] was longer, I would have liked that tool the most."

4.6.8 Summary of Experiment

The experiment only found some statistically significant results. This could be due to the relatively short amount of time spent scaling (10 minutes) and fatigue with the stress ball (5 minutes). The true effect of dental scaling for a longer period of time was not captured.

No statistically significant values were found for the change in grip strength and pinch strength except Tool A versus B where the effect was found to come from the male population. No change in the maximum average line deviation test shows that grip pattern and tool weight does not affect an individual's steadiness during the 15 minute experiment task.

On the other hand, absolute rating preference found Tool A as the most preferred followed by a close race for second with Tool B and C. The eigenvector, w, was calculated to find out by how much each tool was preferred over the other yielding values of 0.8615, 0.127, and 0.0106 for Tool A, B, and C, respectively. Overall, the comments from the subjects during and after the experiment showed similar results to the trends and statistical analysis.

CHAPTER 5 - Conclusion

Overall, it has been shown that cumulative trauma disorders (CTDs) in the dental industry stem from repetitive motions performed on a daily basis. With repetitive motions in scaling, polishing, and flossing comes the excessive use of small muscles and a precision grip on dental tools all similar in design. Other sources of CTDs in the dental industry are fixed working postures, raised arms, and awkward positioning.

The history of the dental industry and current trends in the last 50 years have made huge strides towards a more ergonomic work environment. The introduction of four-handed dentistry in the 1960s and the switch from designing heavy, expensive tools to lighter, more functional tools utilizing new technology in metal and resins has helped.

However, as addressed in the literature review, not all factors affecting the dental industry have been addressed. Currently, a major shift being tracked is the increase in females entering the dental industry as dentists. On the contrary, dental hygiene is a profession dominated by females while schools are seeking new marketing techniques to help bring more males into this field. As the distribution of gender shifts for dentists and hygienists, tool and workstation design need to accommodate for all anthropometric dimensions.

In addition to the gender shift, is the increasing development of CTDs. Up to 75 percent of people in the dental industry have some form of repetitive stress injury (Virtanen, 2001). This increase in injuries related to work is the motive for why the percentage of dentists retiring early and reducing hours is increasing.

Another important factor that plays a role in tool design is sterilization and material composition. Decontamination and safety of the patient are crucial in an industry that deals with the necessity to eliminate cross-contamination of bacteria, blood, and saliva from one patient to the next. Materials selected for tool design must be able to withstand high temperature and pressure required for proper cleansing. Current dental tools are mostly made out of stainless steel, yet more dental manufacturing companies have recently been experimenting with resins and composites to help lighten the handle.

Based on the literature review findings, a survey was designed and distributed to dentists in Kansas, Missouri, and Texas to help identify one tool to redesign based on ergonomic principles. There were 24 total responses (18 males and 6 females). Survey results were then compared to a similar study from the University of Kentucky involving dental hygienists. The most frequent sources of pain in both surveys were in the neck, lower back, and wrist/hand regions. The tool most commonly associated with this pain from the survey results was identified as the hand scaler.

Since dental scaling is estimated to represent 50% of dental hygienists daily tasks (Bramson et al.,1998), a new dental scaling tool was designed. The plan was to apply ergonomic principles of handtool design to redesign a scaler. The goal of the scaler design would be to help decrease the weight of standard stainless steel tools while increasing the compressibility in the grip region of the handle. The key constraint was that the tool had to be designed to be usable in the current dental work environment (the patient's mouth). This also means that the patient's maximum mouth opening and precision required must be factored into design characteristics.

A new dental scaler (Tool A) was made out of a titanium tube with added compressibility in the handle design with the addition of two rubber grips. This tool was designed to be the same length as the two control tools (6.5 inches) yet weighed less than the stainless steel alternative (Tool B). The metal was in contrast with the material utilized for the second control (Tool C), which was made out of a medical grade resin.

An experiment was designed to test the new dental tool versus two control tools varying in weight and material composition. Grip strength, pinch strength, and hand steadiness before and after were tested and utilized as the responses for the experiment. In addition, each subject (n=23) was required to rank the tools in terms of preference based on absolute and relative rating scales. The results of the experiment found that the eigenvector associated with subject preference was significant (p-value > 0.10). Also, the interaction between tool type and gender was significant. This interaction term showed that more females preferred Tool A to B and C while male's responses were consistent across all three tools tested. The remaining responses, change in grip strength and pinch strength, had no clear trend in statistically significant results.

5.1 Improvements

There are many improvements that could be made to the experiment. First, the scaling task should have been longer than 10 minutes with a 5 minute fatigue period. This could possibly explain the non-statistically significant differences in the change in grip strength and pinch strength. Second, artificial calculus could have been administered to the scaling area utilizing a paint mask and syringe to further standardize the scaling task instead of utilizing a nail polish only on one tooth.

Another area of improvement could have been in the workstation design and subjects selected for the experiment. An improvement would have been to use dental hygiene students or those currently practicing as experimental subjects in order to reduce variability and decrease the likelihood of a learning curve effect that could have been experienced by the Industrial Engineering student subjects. Although, with this change in subjects, the possibility of finding male subjects would decrease, which could affect tool design due to larger not accounted for if a shift in gender does occur in the future for dental hygienists. Taken as a whole, dental hygienists would have been more accustomed to the task.

The introduction of magnification could also have helped focus the subjects on tool design and not on other pain associated with the awkward, static positions. Last, it could have made the data more robust if a dental chair-mounted typodont was utilized to further adjust the height of the simulated patient's oral cavity to fit the subject.

5.2 Areas of Future Research

Since the tool preference results were statistically significant in the experiment, the addition of different compressible materials to the scaler handle should be researched further. The main design features in this research to be accounted for are if the grip material is reusable or single-use meaning it would have to be disposed of after each patient. If reusable, this will need to be a rubber-like material able to withstand temperatures of 250°F if sanitizing the instruments with an autoclave, 270°F with heat/chemical vapor, or 320°F with dry heat. On the other hand if the material composition does not allow for sanitation, an economic analysis of a disposable tool grip would need to be completed.

Another area of future research is the effect of tool weight. This experiment tested three tools weighing 13.1 grams (Tool C), 17.3 grams (Tool A), and 20.9 grams (Tool B). Based on absolute and relative rating, this experiment found that the 17.3 gram tool was preferred. Other research has limited the weight of the tool to a minimum of 15 grams in weight. Future research should utilize a standardized handle design to eliminate possible preferences based on material selection, grip pattern, and texture. The overall effect of minimizing weight should be tested to find the optimal tool weight similar to the Dong et al., 2006 study who found the 10 mm diameter to require the least amount of muscle load and pinch force.

Another important design feature to be researched further is a scaler similar to Tool A in weight, length, and grip type with a tapered shank from the handle towards the working end. An example of what this would potentially look like can be seen in Figure 5-1 below drawn in SolidWorks. By increasing the area of the tool shank, fatigue, pinch strength, and force required should be tested.

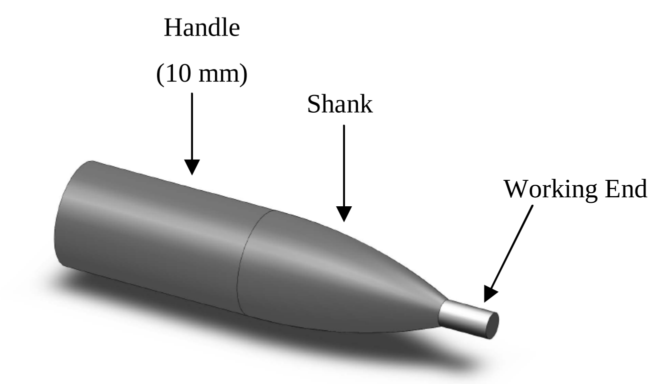


Figure 5-1. Redesign of Tool A Handle

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Appendix A - Survey of Musculoskeletal Disorders and Tool Design in the Dental Industry

Survey of Musculoskeletal Disorders

Stacey Ahern

Dr. Margaret Rys

Industrial and Manufacturing Systems Engineering

Kansas State University

The following survey is entirely voluntary. The focus of the study is on the prevalence of work related musculoskeletal disorders due to the repetitive nature of daily tasks in the dental industry. It will be used to help pinpoint the source and frequency of pain or injuries (neck, back, and upper and lower extremities) associated with daily dental procedures and tasks. It will also help identify concerns in current dental tooling design. The responses will be used to provide a statistical background and comments of the current state of ergonomics in the dental industry.

Your input to the survey will be used to help reduce injuries related to current tooling and other areas in the dental industry. It is hoped that the results of the survey will aid in the redesign of dental tooling and instrumentation while reducing the risk of work related injuries.

Please provide answers to all questions to the best of your knowledge. Open and honest input is valued. It is important to note that all individual survey responses will remain confidential and will only be used in statistical and design analysis as a group.

If you have any questions, do not hesitate to contact Stacey Ahern, telephone: (913) 485-2273 or email: slahern@ksu.edu. A summary of the survey requests will be provided by separate request.

Thank you in advance for your input.

2010 Dentist Work Environment Survey

Background Information

Gender: Male ○ Female ○
Dominant Tool Hand: Right ○ Left ○

Height: [ ] ft [ ] in

Weight: [ ] lbs

Age: (Please choose)

Years of Experience: (Please choose)

# of working days per week (Please choose)

# of working hours per day (Please choose)

# of patients per day [ ]

Please check appropriate background.

- ☐ General Dentist
- ☐ Dental Public Health
- ☐ Endodontics
- ☐ Oral and Maxillofacial Pathology
- ☐ Oral and Maxillofacial Radiology
- ☐ Oral and Maxillofacial Surgery
- ☐ Orthodontics and Dentofacial Orthopedics
- ☐ Pediatric Dentistry
- ☐ Periodontics
- ☐ Prosthodontics
- ☐ other (please specify) [ ]

Dental Tool Design

Please select the tools that cause the most discomfort or pain.

- ☐ explorer
- ☐ high speed handpiece
- ☐ slow speed handpiece
- ☐ Perio probes
- ☐ OS forceps
- ☐ hand scalers
- ☐ mouth mirror
- ☐ Endo hand files
- ☐ operative instruments (burnishers, carvers)
- ☐ operative instruments (plastic instruments)
- ☐ other (please specify) [ ]

Which of the tools listed above would you recommend for redesign and why?

[ ]

Do you have any suggestions for a tool redesign (i.e. tool diameter, grip, angle)? ○ Yes ○ No

If yes, please provide additional comments below:

[ ]

For endodontic procedures, do you use rotary? ○ Yes ○ No

If yes, how often during the endodontic procedure do you still need hand files? (Please choose)

Work Related Activities - Dentist

Please check the associated body parts that you are currently or have experience discomfort, soreness, or pain. With each checked body part please fill out the corresponding questions after.

Body Part	Current or Past Pain	Frequency of pain (daily or weekly)	Estimated # of Days Missed per Year	Tool or Procedure that is the Source of Pain
Neck	☐	N/A		
Shoulder(s)	☐	N/A		
Upper Back	☐	N/A		
Lower Back	☐	N/A		
Elbow	☐	N/A		
Forearm	☐	N/A		
Hip	☐	N/A		
Wrist/hand	☐	N/A		
Upper Leg	☐	N/A		
Knee	☐	N/A		
Lower Leg	☐	N/A		
Ankle	☐	N/A		

Have you sought medical help for injuries/pain related to work? ○ Yes ○ No

If yes, please provide additional comments below:

Please select all preventative measure(s) you have taken to reduce discomfort (check all that apply):

- ☐ stretching
- ☐ reduced work hours
- ☐ bandage or brace
- ☐ chiropractor
- ☐ improved posture
- ☐ ergonomic instruments
- ☐ lumbar/chair supports
- ☐ personal relaxation
- ☐ prescription medication
- ☐ workstation adjustment
- ☐ over-the-counter medication
- ☐ more frequent breaks
- ☐ other (please specify)

Please select the amount of time sitting versus standing during the following procedures:

Procedure	% of time sitting	% of time standing
hygiene checks		
restorative dentistry		
crown/bridge work		
endodontic		
removable work		
oral surgery		
orthodontics		

Any additional comments?

Any questions?

Feel free to email me at slahern@ksu.edu.

Thank you for your input.

submit reset

Appendix B - Proposal 5453 IRB Review Letter

University Research
Compliance Office
203 Fairchild Hall
Lower Mezzanine
Manhattan, KS 66506-1103
785-532-3224
Fax: 785-532-3278
www.k-state.edu/research/comply

TO: Malgorzata Rys
IMSE
2015 Durland

Proposal Number: 5453

FROM: Rick Scheidt, Chair
Committee on Research Involving Human Subjects

DATE: May 4, 2010

RE: Proposal Entitled, "Redesign of Dental Tooling Survey"

The Committee on Research Involving Human Subjects / Institutional Review Board (IRB) for Kansas State University has reviewed the proposal identified above and has determined that it is EXEMPT from further IRB review. This exemption applies only to the proposal - as written – and currently on file with the IRB. Any change potentially affecting human subjects must be approved by the IRB prior to implementation and may disqualify the proposal from exemption.

Based upon information provided to the IRB, this activity is exempt under the criteria set forth in the Federal Policy for the Protection of Human Subjects, **45 CFR §46.101, paragraph b, category: 2, subsection: ii.**

Certain research is exempt from the requirements of HHS/OHRP regulations. A determination that research is exempt does not imply that investigators have no ethical responsibilities to subjects in such research; it means only that the regulatory requirements related to IRB review, informed consent, and assurance of compliance do not apply to the research.

Any unanticipated problems involving risk to subjects or to others must be reported immediately to the Chair of the Committee on Research Involving Human Subjects, the University Research Compliance Office, and if the subjects are KSU students, to the Director of the Student Health Center.

Appendix C - Proposal 5651 IRB Review Letter

University Research
Compliance Office
203 Fairchild Hall
Lower Mezzanine
Manhattan, KS 66506-1103
785-532-3224
Fax: 785-532-3278
www.k-state.edu/research/comply

TO: Malgorzata Rys
IMSE
2015 Durland

Proposal Number: 5651

FROM: Rick Scheidt, Chair
Committee on Research Involving Human Subjects

DATE: November 15, 2010

RE: Proposal Entitled, "Redesign of Dental Scaler"

The Committee on Research Involving Human Subjects / Institutional Review Board (IRB) for Kansas State University has reviewed the proposal identified above and has determined that it is EXEMPT from further IRB review. This exemption applies only to the proposal - as written – and currently on file with the IRB. Any change potentially affecting human subjects must be approved by the IRB prior to implementation and may disqualify the proposal from exemption.

Based upon information provided to the IRB, this activity is exempt under the criteria set forth in the Federal Policy for the Protection of Human Subjects, **45 CFR §46.101, paragraph b, category: 2, subsection: ii.**

Certain research is exempt from the requirements of HHS/OHRP regulations. A determination that research is exempt does not imply that investigators have no ethical responsibilities to subjects in such research; it means only that the regulatory requirements related to IRB review, informed consent, and assurance of compliance do not apply to the research.

Any unanticipated problems involving risk to subjects or to others must be reported immediately to the Chair of the Committee on Research Involving Human Subjects, the University Research Compliance Office, and if the subjects are KSU students, to the Director of the Student Health Center.

Appendix D - Experiment Consent Form

KANSAS STATE UNIVERSITY
INFORMED CONSENT

PROJECT TITLE: Redesign of Dental Scaler

APPROVAL DATE OF PROJECT: ____ **EXPIRATION DATE OF PROJECT:** ____

PRINCIPAL INVESTIGATOR: CO-INVESTIGATOR(S): Dr. Malgorzata Rys / Stacey Ahern

CONTACT AND PHONE FOR ANY PROBLEMS/QUESTIONS: malrys@ksu.edu / (785) 532-3733

IRB CHAIR CONTACT/PHONE INFORMATION: Rick Scheidt / (785) 532-3224

SPONSOR OF PROJECT: Not applicable.

PURPOSE OF THE RESEARCH: To examine the effect of increasing the diameter and compressibility in finger grasp region on a dental scaling tool.

PROCEDURES OR METHODS TO BE USED: Subjects will be using control tool and re-designed dental scaling tool on a typodont (model of the oral cavity) for 10 minutes per session. Grip and pinch strength will be tested before and after along with relative and absolute ranking of the tools to find optimal weight/compressibility of dental scalers.

LENGTH OF STUDY: 3 sessions of 30 minutes

RISKS ANTICIPATED: Risk associated with utilizing hand muscles in a repetitive manner for 10 minute time increment.

BENEFITS ANTICIPATED: New scaler design can increase comfort while reducing injuries associated with tool design in dental industry.

EXTENT OF CONFIDENTIALITY: Names will not be associated with specific data collected. All information will be summarized in a generic manner in report.

IS COMPENSATION OR MEDICAL TREATMENT AVAILABLE IF INJURY OCCURS: Not applicable.

PARENTAL APPROVAL FOR MINORS: All participants must be at least 18 years old.

TERMS OF PARTICIPATION: I understand this project is research, and that my participation is completely voluntary. I also understand that if I decide to participate in this study, I may withdraw my consent at any time, and stop participating at any time without explanation, penalty, or loss of benefits, or academic standing to which I may otherwise be entitled.

I verify that my signature below indicates that I have read and understand this consent form, and willingly agree to participate in this study under the terms described, and that my signature acknowledges that I have received a signed and dated copy of this consent form.

(Remember that it is a requirement for the P.I. to maintain a signed and dated copy of the same consent form signed and kept by the participant

Participant Name: ______________________________

Participant Signature: ______________________________ **Date:** ________________

Witness to Signature: (project staff) ______________________ **Date:** ________________

Appendix E - Experiment Data Collection Sheet

Name: Age: Weight (lbs): Height (in):

How many days do you exercise per week? 0 1 2 3 4 >5

Session 1: (Date/Time) ________________
In the last 24 hours, list activities using arms/dominant hand.

Session 2: (Date/Time) ________________
In the last 24 hours, list activities using arms/dominant hand.

Session 3: (Date/Time) ________________
In the last 24 hours, list activities using arms/dominant hand.

Session 1						
	Before			After		
Grip Strength						
Pinch Strength						
Session 2						
	Before			After		
Grip Strength						
Pinch Strength						
Session 3						
	Before			After		
Grip Strength						
Pinch Strength						

Put scalers in order of preference (1 being most preferred)

(1) __________
(2) __________
(3) __________

By how much do you prefer A to B (circle one number):

1	2	3	4	5	6	7	8	9	10
equal to		somewhat better		much better		significantly better		absolutely better	

By how much do you prefer B to C (circle one number):

1	2	3	4	5	6	7	8	9	10
equal to		somewhat better		much better		significantly better		absolutely better	

By how much do you prefer A to C (circle one number):

1	2	3	4	5	6	7	8	9	10
equal to		somewhat better		much better		significantly better		absolutely better	

Appendix F - Percentile Calculations

Subject	Gender	Hand Breadth (in)	Hand Length (in)	Weight (lbs)	Height (in)
1	Male	3.75	8	160	69
2	Male	3.875	7.875	190	71
6	Male	3.5	8	195	75
8	Male	3.25	7	130	66.5
10	Male	3.5	7.625	182	73
11	Male	4	8.5	180	72
12	Male	3.75	7.75	180	74
13	Male	3.375	7.375	175	72
14	Male	3.5	7.5	172	71
15	Male	3.625	7.25	170	71
16	Male	3.75	7	165	71.5
21	Male	3.75	7.375	160	71
22	Male	3.5	7.875	190	72
	min	3.25	7	130	66.5
	max	4	8.5	195	75
	avg	3.625	7.625	173	71.46
	x	9.21	19.37	78.64	181.51
	μ	9.04	19.38	78.49	175.58
	σ	0.42	0.98	12.6	6.68
	Z	0.40	-0.01	0.012	0.888
	Percentile	0.65	0.49	0.50	0.81

Subject	Gender	Hand Breadth (in)	Hand Length (in)	Weight (lbs)	Height (in)
3	Female	3.5	7	160	66
4	Female	3.25	7.25	140	65.5
5	Female	3	7	137	67
7	Female	3.25	6.75	135	65
9	Female	3	7	135	69
17	Female	3	6.75	130	64
18	Female	2.75	6.75	125	64
19	Female	3	6.5	120	62
20	Female	3.25	6.625	175	68
23	Female	3.25	7.125	180	69
	min	2.75	6.5	120	62
	max	3.5	7.25	180	69
	avg	3.125	6.875	143.7	65.95
	x	7.9375	17.4625	65.3182	167.5130
	μ	7.94	18.05	62.01	162.94
	σ	0.38	0.97	13.8	6.36
	Z	-0.007	-0.606	0.240	0.719
	Percentile	0.50	0.27	0.59	0.76

Appendix G - Experiment Pictures

Figure G-1. Front View Using Tool A

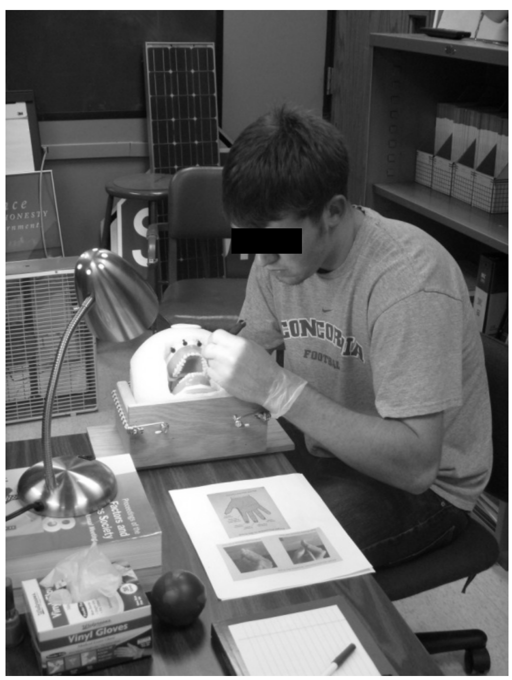

Figure G-2. Side View Using Tool A

Figure G-3. Angled View Using Tool A

Figure G-4. Experiment Set-Up

Appendix H - Statistical Analysis of Experiment in Minitab 15

∆ GS MALES & FEMALES

Paired T-Test and CI: GS_A, GS_B

```
Paired T for GS_A - GS_B

             N  Mean  StDev  SE Mean
GS_A        23  6.22   5.94     1.24
GS_B        23  3.58   6.85     1.43
Difference  23  2.64   7.22     1.50


90% CI for mean difference: (0.05, 5.22)
T-Test of mean difference = 0 (vs not = 0): T-Value = 1.75  P-Value = 0.094
```

Paired T-Test and CI: GS_A, GS_C

```
Paired T for GS_A - GS_C

             N  Mean  StDev  SE Mean
GS_A        23  6.22   5.94     1.24
GS_C        23  5.16   6.36     1.33
Difference  23  1.06   8.07     1.68


90% CI for mean difference: (-1.83, 3.95)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.63  P-Value = 0.537
```

Paired T-Test and CI: GS_B, GS_C

```
Paired T for GS_B - GS_C

             N   Mean  StDev  SE Mean
GS_B        23   3.58   6.85     1.43
GS_C        23   5.16   6.36     1.33
Difference  23  -1.58   9.79     2.04


90% CI for mean difference: (-5.08, 1.93)
T-Test of mean difference = 0 (vs not = 0): T-Value = -0.77  P-Value = 0.447
```

Δ *GS FEMALES*

Paired T-Test and CI: GS_A F, GS_B F

Paired T for GS_A - GS_B

	N	Mean	StDev	SE Mean
GS_A	10	4.98	4.12	1.30
GS_B	10	4.47	4.15	1.31
Difference	10	0.51	5.87	1.86

90% CI for mean difference: (-2.89, 3.91)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.27 P-Value = 0.790

Paired T-Test and CI: GS_A F, GS_C F

Paired T for GS_A F - GS_C F

	N	Mean	StDev	SE Mean
GS_A F	10	4.98	4.12	1.30
GS_C F	10	3.89	7.19	2.27
Difference	10	1.09	8.69	2.75

90% CI for mean difference: (-3.94, 6.12)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.40 P-Value = 0.701

Paired T-Test and CI: GS_B F, GS_C F

Paired T for GS_B F - GS_C F

	N	Mean	StDev	SE Mean
GS_B F	10	4.47	4.15	1.31
GS_C F	10	3.89	7.19	2.27
Difference	10	0.58	6.39	2.02

90% CI for mean difference: (-3.13, 4.29)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.29 P-Value = 0.781

Δ *GS MALES*

Paired T-Test and CI: GS_A M, GS_B M

Paired T for GS_A M - GS_B M

	N	Mean	StDev	SE Mean
GS_A M	13	7.17	7.05	1.95
GS_B M	13	2.90	8.48	2.35
Difference	13	4.27	7.94	2.20

90% CI for mean difference: (0.35, 8.20)
T-Test of mean difference = 0 (vs not = 0): T-Value = 1.94 P-Value = 0.076

Paired T-Test and CI: GS_A M, GS_C M

Paired T for GS_A M - GS_C M

	N	Mean	StDev	SE Mean
GS_A M	13	7.17	7.05	1.95
GS_C M	13	6.14	5.75	1.59
Difference	13	1.03	7.93	2.20

90% CI for mean difference: (-2.89, 4.95)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.47 P-Value = 0.648

Paired T-Test and CI: GS_B M, GS_C M

Paired T for GS_B M - GS_C M

	N	Mean	StDev	SE Mean
GS_B M	13	2.90	8.48	2.35
GS_C M	13	6.14	5.75	1.59
Difference	13	-3.24	11.75	3.26

90% CI for mean difference: (-9.05, 2.57)
T-Test of mean difference = 0 (vs not = 0): T-Value = -0.99 P-Value = 0.340

Correlation Between Gender & Δ GS

```
Correlations: Gender, GS_A

Pearson correlation of Gender and GS_A = 0.187
P-Value = 0.392


Correlations: Gender, GS_B

Pearson correlation of Gender and GS_B = -0.116
P-Value = 0.598


Correlations: Gender, GS_C

Pearson correlation of Gender and GS_C = 0.180
P-Value = 0.412
```

ANOVA - Δ GS

General Linear Model: GS_Change versus Gender, BMI, Exercise, Tool

Factor	Type	Levels	Values
Gender	fixed	2	0, 1
BMI	fixed	2	0, 1
Exercise	fixed	2	0, 1
Tool	fixed	3	1, 2, 3

Analysis of Variance for GS_Change, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Hand_Breadth	1	48.78	1.14	1.14	0.03	0.871
Hand_Length	1	2.01	8.45	8.45	0.20	0.659
Wrist	1	57.54	54.88	54.88	1.28	0.264
Gender	1	3.12	67.96	67.96	1.58	0.214
BMI	1	39.79	61.46	61.46	1.43	0.237
Exercise	1	0.16	37.85	37.85	0.88	0.353
Tool	2	80.97	88.53	44.26	1.03	0.364
Gender*BMI	1	80.14	140.41	140.41	3.27	0.077
Gender*Exercise	1	1.71	5.39	5.39	0.13	0.725
Gender*Tool	2	54.18	82.68	41.34	0.96	0.389
BMI*Exercise	1	61.97	61.97	61.97	1.44	0.235
BMI*Tool	2	33.39	46.86	23.43	0.54	0.583
Exercise*Tool	2	123.46	123.46	61.73	1.44	0.247
Error	51	2192.73	2192.73	42.99		
Total	68	2779.94				

S = 6.55704   R-Sq = 21.12%   R-Sq(adj) = 0.00%

Term	Coef	SE Coef	T	P
Constant	-19.60	21.33	-0.92	0.362
Hand_Breadth	1.114	6.846	0.16	0.871
Hand_Length	1.283	2.893	0.44	0.659
Wrist	4.577	4.051	1.13	0.264

Unusual Observations for GS_Change

Obs	GS_Change	Fit	SE Fit	Residual	St Resid
14	-10.0333	3.4346	2.9085	-13.4679	-2.29 R
36	16.5000	3.4449	2.4485	13.0551	2.15 R
59	-5.6000	6.6280	2.4485	-12.2280	-2.01 R

R denotes an observation with a large standardized residual.

Δ *PS Thumb*

Paired T-Test and CI: PST_A, PST_B

Paired T for PST_A - PST_B

	N	Mean	StDev	SE Mean
PST_A	23	1.391	2.221	0.463
PST_B	23	0.478	1.928	0.402
Difference	23	0.913	2.683	0.559

90% CI for mean difference: (-0.047, 1.874)
T-Test of mean difference = 0 (vs not = 0): T-Value = 1.63 P-Value = 0.117

Paired T-Test and CI: PST_A, PST_C

Paired T for PST_A - PST_C

	N	Mean	StDev	SE Mean
PST_A	23	1.391	2.221	0.463
PST_C	23	0.739	1.397	0.291
Difference	23	0.652	2.798	0.583

90% CI for mean difference: (-0.350, 1.654)
T-Test of mean difference = 0 (vs not = 0): T-Value = 1.12 P-Value = 0.276

Paired T-Test and CI: PST_B, PST_C

Paired T for PST_B - PST_C

	N	Mean	StDev	SE Mean
PST_B	23	0.478	1.928	0.402
PST_C	23	0.739	1.397	0.291
Difference	23	-0.261	2.602	0.543

90% CI for mean difference: (-1.192, 0.671)
T-Test of mean difference = 0 (vs not = 0): T-Value = -0.48 P-Value = 0.635

Δ *PS Index Finger*

Paired T-Test and CI: PSI_A, PSI_B

Paired T for PSI_A - PSI_B

	N	Mean	StDev	SE Mean
PSI_A	23	0.674	2.653	0.553
PSI_B	23	1.022	1.922	0.401
Difference	23	-0.348	3.128	0.652

90% CI for mean difference: (-1.468, 0.772)
T-Test of mean difference = 0 (vs not = 0): T-Value = -0.53 P-Value = 0.599

Paired T-Test and CI: PSI_A, PSI_C

Paired T for PSI_A - PSI_C

	N	Mean	StDev	SE Mean
PSI_A	23	0.674	2.653	0.553
PSI_C	23	0.370	2.085	0.435
Difference	23	0.304	3.420	0.713

90% CI for mean difference: (-0.920, 1.529)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.43 P-Value = 0.674

Paired T-Test and CI: PSI_B, PSI_C

Paired T for PSI_B - PSI_C

	N	Mean	StDev	SE Mean
PSI_B	23	1.022	1.922	0.401
PSI_C	23	0.370	2.085	0.435
Difference	23	0.652	2.228	0.465

90% CI for mean difference: (-0.146, 1.450)
T-Test of mean difference = 0 (vs not = 0): T-Value = 1.40 P-Value = 0.174

∆ *PS Middle Finger*

Paired T-Test and CI: PSM_A, PSM_B

```
Paired T for PSM_A - PSM_B

             N   Mean  StDev  SE Mean
PSM_A       23  0.935  2.510    0.523
PSM_B       23  0.848  1.133    0.236
Difference  23  0.087  2.653    0.553


90% CI for mean difference: (-0.863, 1.037)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.16  P-Value = 0.877
```

Paired T-Test and CI: PSM_A, PSM_C

```
Paired T for PSM_A - PSM_C

             N   Mean  StDev  SE Mean
PSM_A       23  0.935  2.510    0.523
PSM_C       23  0.609  1.712    0.357
Difference  23  0.326  2.991    0.624


90% CI for mean difference: (-0.745, 1.397)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.52  P-Value = 0.606
```

Paired T-Test and CI: PSM_B, PSM_C

```
Paired T for PSM_B - PSM_C

             N   Mean  StDev  SE Mean
PSM_B       23  0.848  1.133    0.236
PSM_C       23  0.609  1.712    0.357
Difference  23  0.239  2.373    0.495


90% CI for mean difference: (-0.611, 1.089)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.48  P-Value = 0.634
```

Correlation between Δ PS (Thumb, Index, Middle)

Correlations: Gender, PST_A, PSI_A, PSM_A, PST_B, PSI_B, PSM_B, PST_C, ...

	Gender	PST_A	PSI_A	PSM_A	PST_B	PSI_B	PSM_B	PST_C	PSI_C
PST_A	0.037								
	0.867								
PSI_A	0.262	0.297							
	0.228	0.169							
PSM_A	0.280	0.247	0.430						
	0.195	0.255	0.041						
PST_B	-0.196	0.169	0.074	-0.113					
	0.370	0.440	0.737	0.608					
PSI_B	0.407	-0.476	0.093	0.142	-0.110				
	0.054	0.022	0.673	0.519	0.616				
PSM_B	0.077	-0.093	0.081	0.096	0.118	0.007			
	0.725	0.674	0.713	0.662	0.591	0.975			
PST_C	0.154	-0.152	0.065	-0.336	-0.205	-0.053	-0.191		
	0.484	0.487	0.768	0.117	0.349	0.811	0.382		
PSI_C	0.224	0.009	-0.029	0.033	0.098	0.384	0.020	-0.032	
	0.305	0.967	0.897	0.881	0.656	0.071	0.928	0.886	
PSM_C	-0.126	0.236	0.053	0.033	-0.037	-0.035	-0.366	0.079	0.014
	0.565	0.277	0.809	0.880	0.866	0.873	0.086	0.720	0.951

Cell Contents: Pearson correlation
P-Value

ANOVA - Δ PS Thumb

General Linear Model: PS_Thumb, PS_Index, ... versus Gender, BMI, ...

Factor	Type	Levels	Values
Gender	fixed	2	0, 1
BMI	fixed	2	0, 1
Exercise	fixed	2	0, 1
Tool	fixed	3	1, 2, 3

Analysis of Variance for PS_Thumb, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Hand_Breadth	1	0.042	4.783	4.783	1.22	0.275
Hand_Length	1	0.999	5.344	5.344	1.36	0.249
Wrist	1	6.922	10.727	10.727	2.73	0.104
Gender	1	0.344	1.443	1.443	0.37	0.547
BMI	1	0.113	0.520	0.520	0.13	0.717
Exercise	1	5.472	10.456	10.456	2.67	0.109
Tool	2	10.174	10.627	5.313	1.35	0.267
Gender*BMI	1	0.253	3.278	3.278	0.84	0.365
Gender*Exercise	1	1.099	0.010	0.010	0.00	0.959
Gender*Tool	2	4.257	4.324	2.162	0.55	0.580
BMI*Exercise	1	5.495	5.495	5.495	1.40	0.242
BMI*Tool	2	3.053	2.140	1.070	0.27	0.762
Exercise*Tool	2	5.026	5.026	2.513	0.64	0.531
Error	51	200.077	200.077	3.923		
Total	68	243.326				

S = 1.98068   R-Sq = 17.77%   R-Sq(adj) = 0.00%

Term	Coef	SE Coef	T	P
Constant	-3.046	6.442	-0.47	0.638
Hand_Breadth	-2.283	2.068	-1.10	0.275
Hand_Length	1.0200	0.8740	1.17	0.249
Wrist	2.024	1.224	1.65	0.104

Unusual Observations for PS_Thumb

Obs	PS_Thumb	Fit	SE Fit	Residual	St Resid	
6	8.00000	2.57480	0.93534	5.42520	3.11	R
18	-3.00000	1.83492	1.04897	-4.83492	-2.88	R
31	-6.00000	-0.37600	0.84610	-5.62400	-3.14	R
45	4.00000	0.75094	1.23748	3.24906	2.10	R

R denotes an observation with a large standardized residual.

ANOVA - Δ PS Index Finger

Analysis of Variance for PS_Index, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Hand_Breadth	1	4.509	0.460	0.460	0.09	0.761
Hand_Length	1	11.463	2.034	2.034	0.41	0.524
Wrist	1	3.840	0.561	0.561	0.11	0.737
Gender	1	21.116	3.163	3.163	0.64	0.427
BMI	1	9.202	8.111	8.111	1.64	0.206
Exercise	1	3.387	0.260	0.260	0.05	0.820
Tool	2	4.899	1.208	0.604	0.12	0.885
Gender*BMI	1	0.549	0.623	0.623	0.13	0.724
Gender*Exercise	1	7.147	1.811	1.811	0.37	0.548
Gender*Tool	2	1.169	0.644	0.322	0.07	0.937
BMI*Exercise	1	5.593	5.593	5.593	1.13	0.292
BMI*Tool	2	2.943	2.157	1.079	0.22	0.805
Exercise*Tool	2	8.732	8.732	4.366	0.88	0.420
Error	51	252.002	252.002	4.941		
Total	68	336.551				

S = 2.22288   R-Sq = 25.12%   R-Sq(adj) = 0.16%

Term	Coef	SE Coef	T	P
Constant	-2.928	7.230	-0.40	0.687
Hand_Breadth	-0.708	2.321	-0.31	0.761
Hand_Length	0.6294	0.9808	0.64	0.524
Wrist	0.463	1.373	0.34	0.737

Unusual Observations for PS_Index

Obs	PS_Index	Fit	SE Fit	Residual	St Resid
55	-4.00000	0.24320	0.98356	-4.24320	-2.13 R

R denotes an observation with a large standardized residual.

ANOVA - Δ PS Middle Finger

Analysis of Variance for PS_Mid, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Hand_Breadth	1	3.141	4.657	4.657	1.46	0.233
Hand_Length	1	0.038	1.611	1.611	0.50	0.481
Wrist	1	0.611	0.514	0.514	0.16	0.690
Gender	1	0.264	0.008	0.008	0.00	0.960
BMI	1	2.247	0.001	0.001	0.00	0.983
Exercise	1	6.061	0.452	0.452	0.14	0.708
Tool	2	1.312	0.480	0.240	0.08	0.928
Gender*BMI	1	2.188	3.371	3.371	1.05	0.309
Gender*Exercise	1	9.679	4.936	4.936	1.54	0.220
Gender*Tool	2	9.670	3.603	1.802	0.56	0.572
BMI*Exercise	1	1.625	1.625	1.625	0.51	0.479
BMI*Tool	2	1.312	0.318	0.159	0.05	0.951
Exercise*Tool	2	31.572	31.572	15.786	4.94	0.011
Error	51	162.939	162.939	3.195		
Total	68	232.659				

S = 1.78742   R-Sq = 29.97%   R-Sq(adj) = 6.62%

Term	Coef	SE Coef	T	P
Constant	-3.757	5.814	-0.65	0.521
Hand_Breadth	2.253	1.866	1.21	0.233
Hand_Length	-0.5601	0.7887	-0.71	0.481
Wrist	0.443	1.104	0.40	0.690

Unusual Observations for PS_Mid

Obs	PS_Mid	Fit	SE Fit	Residual	St Resid
1	-4.50000	-0.57824	0.81354	-3.92176	-2.46 R
6	6.00000	2.37942	0.84408	3.62058	2.30 R
22	-1.00000	2.83884	1.11674	-3.83884	-2.75 R

R denotes an observation with a large standardized residual.

Line Steadiness (A,B,C)

Paired T-Test and CI: Line_A, Line_B

```
Paired T for Line_A - Line_B

             N     Mean   StDev  SE Mean
Line_A      20  -0.0115  0.0547   0.0122
Line_B      20  -0.0109  0.0691   0.0154
Difference  20  -0.0005  0.0661   0.0148


90% CI for mean difference: (-0.0261, 0.0250)
T-Test of mean difference = 0 (vs not = 0): T-Value = -0.04  P-Value = 0.972
```

Paired T-Test and CI: Line_A, Line_C

```
Paired T for Line_A - Line_C

             N     Mean   StDev  SE Mean
Line_A      20  -0.0115  0.0547   0.0122
Line_C      20  -0.0182  0.0672   0.0150
Difference  20   0.0068  0.0905   0.0202


90% CI for mean difference: (-0.0282, 0.0418)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.33  P-Value = 0.742
```

Paired T-Test and CI: Line_B, Line_C

```
Paired T for Line_B - Line_C

             N     Mean   StDev  SE Mean
Line_B      22  -0.0090  0.0661   0.0141
Line_C      22  -0.0137  0.0684   0.0146
Difference  22   0.0047  0.0952   0.0203


90% CI for mean difference: (-0.0302, 0.0397)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.23  P-Value = 0.818
```

Tool Preference

Table H-1. Individual Eigenvectors

Subject	Tool A	Tool B	Tool C
1	0.4440	0.0675	0.4885
2	0.2746	0.0683	0.6571
3	0.7837	0.1617	0.0546
4	0.0982	0.5679	0.3339
5	0.7047	0.2355	0.0598
6	0.3139	0.6279	0.0583
7	0.7234	0.2062	0.0704
8	0.0653	0.7263	0.2084
9	0.7671	0.0900	0.1429
10	0.0931	0.2092	0.6977
11	0.7591	0.1880	0.0529
12	0.0726	0.6752	0.2521
13	0.6434	0.2828	0.0738
14	0.0561	0.2633	0.6806
15	0.3338	0.1416	0.5247
16	0.7481	0.1951	0.0569
17	0.7453	0.0699	0.1848
18	0.6902	0.1492	0.1606
19	0.8257	0.0887	0.0856
20	0.0680	0.7601	0.1719
21	0.0524	0.5791	0.3685
22	0.6270	0.2923	0.0807
23	0.5753	0.0586	0.3661
Average	0.4550	0.2915	0.2535

Two-Sample T-Test and CI: Pref A, Pref B

```
Two-sample T for Pref A vs Pref B

         N   Mean  StDev  SE Mean
Pref A  23  0.455  0.299    0.062
Pref B  23  0.291  0.235    0.049


Difference = mu (Pref A) - mu (Pref B)
Estimate for difference:  0.1635
95% CI for difference:  (0.0034, 0.3236)
T-Test of difference = 0 (vs not =): T-Value = 2.06  P-Value = 0.046  DF = 41
```

Two-Sample T-Test and CI: Pref A, Pref C

Two-sample T for Pref A vs Pref C

	N	Mean	StDev	SE Mean
Pref A	23	0.455	0.299	0.062
Pref C	23	0.254	0.219	0.046

Difference = mu (Pref A) - mu (Pref C)
Estimate for difference: 0.2015
95% CI for difference: (0.0452, 0.3578)
T-Test of difference = 0 (vs not =): T-Value = 2.61 P-Value = 0.013 DF = 40

ANOVA – Tool Preference

General Linear Model: Pref versus Gender, BMI, Exercise, Tool

Factor	Type	Levels	Values
Gender	fixed	2	0, 1
BMI	fixed	2	0, 1
Exercise	fixed	2	0, 1
Tool	fixed	3	1, 2, 3

Analysis of Variance for Pref, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Hand_Breadth	1	0.00000	0.00000	0.00000	0.00	1.000
Hand_Length	1	0.00000	0.00000	0.00000	0.00	1.000
Wrist	1	0.00000	0.00000	0.00000	0.00	1.000
Gender	1	0.00000	0.00000	0.00000	0.00	1.000
BMI	1	0.00000	0.00000	0.00000	0.00	1.000
Exercise	1	0.00000	0.00000	0.00000	0.00	1.000
Tool	2	0.52730	0.42305	0.21153	3.09	0.054
Gender*BMI	1	0.00000	0.00000	0.00000	0.00	1.000
Gender*Exercise	1	0.00000	0.00000	0.00000	0.00	1.000
Gender*Tool	2	0.55653	0.41213	0.20607	3.01	0.058
BMI*Exercise	1	0.00000	0.00000	0.00000	0.00	1.000
BMI*Tool	2	0.01683	0.01060	0.00530	0.08	0.926
Exercise*Tool	2	0.17236	0.17236	0.08618	1.26	0.293
Error	51	3.49067	3.49067	0.06844		
Total	68	4.76369				

S = 0.261619   R-Sq = 26.72%   R-Sq(adj) = 2.30%

Term	Coef	SE Coef	T	P
Constant	0.3333	0.8509	0.39	0.697
Hand_Breadth	-0.0000	0.2732	-0.00	1.000
Hand_Length	0.0000	0.1154	0.00	1.000
Wrist	-0.0000	0.1616	-0.00	1.000

Unusual Observations for Pref

Obs	Pref	Fit	SE Fit	Residual	St Resid
20	0.067983	0.642357	0.157596	-0.574374	-2.75 R
43	0.760083	0.185542	0.157596	0.574541	2.75 R

R denotes an observation with a large standardized residual.

Paired T-Test and CI: Pref A, Pref B

```
Paired T for Pref A - Pref B

              N    Mean   StDev  SE Mean
Pref A       23  0.4550  0.2992   0.0624
Pref B       23  0.2915  0.2346   0.0489
Difference   23   0.164   0.491    0.102


90% CI for mean difference: (-0.012, 0.339)
T-Test of mean difference = 0 (vs not = 0): T-Value = 1.60  P-Value = 0.125
```

Paired T-Test and CI: Pref A, Pref C

```
Paired T for Pref A - Pref C

              N    Mean   StDev  SE Mean
Pref A       23  0.4550  0.2992   0.0624
Pref C       23  0.2535  0.2191   0.0457
Difference   23  0.2015  0.4690   0.0978


90% CI for mean difference: (0.0335, 0.3694)
T-Test of mean difference = 0 (vs not = 0): T-Value = 2.06  P-Value = 0.051
```

Paired T-Test and CI: Pref B, Pref C

```
Paired T for Pref B - Pref C

              N    Mean   StDev  SE Mean
Pref B       23  0.2915  0.2346   0.0489
Pref C       23  0.2535  0.2191   0.0457
Difference   23  0.0380  0.3414   0.0712


90% CI for mean difference: (-0.0843, 0.1602)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.53  P-Value = 0.599
```

Appendix I - Relative Rating Calculations

Table I-1. Absolute and Relative Ratings by Subject

		Relative Rating									
Subject	Absolute Rating	A vs B	B vs C	A vs C	A p B	B p A	B p C	C p B	A p C	C p A
1	CAB	[1,6]	[3,8]	[3,1]	6			8		1
2	CAB	[1,5]	[3,8]	[3,3]	5			8		3
3	ABC	[1,10]	[2,5]	[1,10]	10		5		10	
4	BCA	[2,5]	[2,2]	[3,4]		5	2			4
5	ABC	[1,6]	[2,7]	[1,8]	6		7		8	
6	BAC	[2,3]	[2,8]	[1,8]		3	8		8	
7	ABC	[1,5]	[2,4]	[1,8]	5		4		8	
8	BCA	[2,8]	[2,6]	[3,5]		8	6			5
9	ACB	[1,7]	[3,2]	[1,7]	7			2	7	
10	CBA	[2,4]	[3,7]	[3,5]		4		7		5
11	ABC	[1,8]	[2,6]	[1,10]	8		6		10	
12	BCA	[2,7]	[2,4]	[3,5]		7	4			5
13	ABC	[1,3]	[2,5]	[1,7]	3		5		7	
14	CBA	[2,7]	[3,4]	[3,9]		7		4		9
15	CAB	[1,3]	[3,3]	[3,2]	3			3		2
16	ABC	[1,8]	[2,6]	[1,9]	8		6		9	
17	ACB	[1,7]	[2,5]	[1,10]	7		5		10	
18	ACB	[1,5]	[3,1]	[1,4]	5			1	4	
19	ACB	[1,9]	[3,1]	[1,10]	9			1	10	
20	BCA	[2,8]	[2,8]	[3,4]		8	8			4
21	BCA	[2,9]	[3,2]	[3,9]		9		2		9
22	ABC	[1,3]	[2,5]	[1,6]	3		5		6	
23	ACB	[1,8]	[3,8]	[1,2]	8			8	2	
				sum	93	51	71	44	99	47

Step 1: Pairwise Comparison Matrix

	A	B	C
A	1	42	52
B	0.0238095	1	27
C	0.0192308	0.037037	1
	1.0430403	43.037037	80

Step 2: Normalized Preferences

	A	B	C	row mean (w)
A	0.9587357	0.9759036	0.65	0.8615
B	0.022827	0.0232358	0.3375	0.1279
C	0.0184372	0.0008606	0.0125	0.0106
				1.0000