Abstract

MEADOR, KRISTEN ANN. Ergonomic Interventions for an Ultrasound Transducer. (Under the direction of Dr. Gary A. Mirka and Dr. Sharon Joines.)

Sonographers face a number of occupational risk factors for musculoskeletal disorders (MSDs) when performing ultrasound procedures. Over 80% of sonographers experience work-related musculoskeletal symptoms. These musculoskeletal symptoms and injuries have been attributed to activities such as static shoulder abduction, constant applied pressure with the ultrasound transducer, awkward wrist postures, and repetitive twisting of the neck and trunk. The gripping of the transducer, particularly with a pinch grip, has been linked to hand and wrist pain and symptoms of carpal tunnel syndrome and other MSDs. The objective of this study was to design and fabricate ultrasound transducer interventions and evaluate their effectiveness in reducing the risk of upper extremity musculoskeletal disorders. The interventions were designed with the intent of reducing the pinch grip force. It was hypothesized that the transducer interventions would reduce the activity of the muscles of the upper extremity, primarily those of the hand and forearm as they are most engaged in the pinch grip.

The three transducer interventions and the control transducer were evaluated using electromyography (EMG) to determine their effect on the muscle activity of the upper extremity while the subject was engaged in a simulated ultrasound scanning task. The subject applied a given static pressure to an abdomen-like surface for 5 seconds per trial. Because sonographers manipulate the transducer at varying angles, the ultrasound task was performed at two different angles. As patient size plays a major role in the gripping and force application of the transducer, the experiment was performed in two parts under different

conditions to simulate a scan on a normal-sized patient and on an obese patient. Subjects completed a survey providing subjective feedback about each of the transducers.

Both independent variables, INTERVENTION and ANGLE, were significant in the normal and obese patient experiments, and there was no interaction effect. As hypothesized, the interventions significantly reduced the activity of several of the sampled muscles. Most notably, each intervention dramatically reduced muscle activity of the first dorsal interosseous (FDI), which provides much of the force in the pinch grip. The transducer harness, transducer cover, and wide grip transducer decreased FDI activity by 74%, 64%, and 50%, respectively, as compared to the control transducer, in the obese patient experiment. This indicates that the interventions effectively reduced the pinch grip force requirement as intended. The same trend was repeated in the survey results, which ranked the interventions ahead of the control in this order. Subjects also reported that the control caused the greatest pain and discomfort in the hand. While each of the interventions showed improvement over the control transducer, the harness may have performed the best, as its use significantly reduced the activity for the FDI (74%), flexor (10%), extensor (3.0%), deltoid (3.1%), and trapezius (3.5%) muscles in the obese patient experiment. However, the harness also resulted in the highest thenar muscle activity and its design has some limitations. Reducing FDI and extensor activity by 64% and 44% in the obese patient trials, the cover performed the best behind the harness. With each intervention having its own strengths and weaknesses, the best transducer design approach may be to integrate different aspects of the three interventions into a new design. This research has demonstrated that ultrasound transducer interventions can effectively reduce upper extremity muscle activity and, thus, reduce the risk of work-related MSDs, when the intervention design decreases the need to utilize a pinch grip.

Ergonomic Interventions for an Ultrasound Transducer

By

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Dedication

I dedicate this work to my incredibly amazing, loving, and supportive family to whom I am forever grateful. I know that no matter what life throws at me my family will always be there to offer their hands to pull me back up on my feet and their arms with which to embrace me. I look up to each of them as a source of inspiration and an example to follow. I do not think I will ever understand what I did to deserve such a wonderful family. However, of one thing I am certain, I have truly been blessed.

Biography

Kristen Meador was born and raised in Charlotte, North Carolina by her always loving and supportive parents, alongside her four siblings. With her family of seven, there was hardly a dull moment in the Meador household. She graduated from East Mecklenburg High School in 2001. Following the footsteps of her two older brothers and older sister, she went on to North Carolina State University for her undergraduate education, where her younger sister would also attend a few years later. And like her father and two brothers, she pursued a degree in engineering. She gained valuable work experience with two engineering summer internships during her time as an undergraduate student. Kristen earned her Bachelor's of Science degree in Biomedical Engineering with Summa Cum Laude and Valedictorian honors in the spring of 2005.

Kristen began her graduate studies at her alma mater in the fall of 2005. Sponsored by a traineeship from the National Institute of Occupational Safety and Health (NIOSH) and under the direction of her advisor, Dr. Gary Mirka, she worked towards a Master's of Science degree in Industrial Engineering with a concentration in Human Factors and Ergonomics. With a focus on physical ergonomics, she conducted research with others on the biomechanics of anterior load carriage. Her interest in design and ergonomic interventions influenced her topic choice for her thesis research. Upon her second graduation from NC State University, Kristen will begin her work as a Senior Associate Engineer for Caterpillar in Peoria, Illinois.

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1 Introduction

1.1 Ergonomics

Ergonomics can be simply defined as fitting the work to the worker. The primary goal of ergonomics is to improve worker performance and safety through the study and use of principles that govern the interaction between workers and their job environment (Chaffin et al., 1999). Specific aims in improving worker performance and efficiency include increased convenience of use, increased productivity, and reduced errors. In addition to improving safety, the application of ergonomics principles results in the reduction of fatigue and stress and improvement in comfort, user acceptance, job satisfaction, and quality of life. As a scientific discipline, ergonomics considers human capabilities, limitations, characteristics, motivation, and behavior and applies this information to the design of things, processes, and environments (Sanders and McCormick, 1993). There are two main branches of ergonomics: cognitive ergonomics and physical ergonomics. Cognitive ergonomics is concerned with how humans process information and how mental processes, such as perception and memory, affect human interactions with systems and other people. Physical ergonomics, also known as occupational biomechanics, examines the mismatching of human physical capacities and worker manual performance requirements. It is an applied discipline that seeks to enhance worker performance while minimizing the risk of musculoskeletal disorders through the study of the physical interaction of workers with their environments (Chaffin, 1999). The current study is concerned with physical ergonomics as it investigates musculoskeletal disorders related to the work of sonographers.

1.2 Work-related Musculoskeletal Disorders

Characterized by pain, discomfort, and other symptoms, work-related musculoskeletal disorders (WMSDs) are physical conditions affecting the soft tissues of the body caused at least partially by work-related factors. More specifically, musculoskeletal disorders involve the nerves, tendons, muscles, and supporting structures of the body. WMSDs have been found to be strongly related to biomechanical risk factors including repetition, force, posture, and vibration (NIOSH, 1997). These disorders include low back pain, tendonitis, tenosynovitis, thoracic outlet syndrome, bursitis, and carpal tunnel syndrome. Musculoskeletal symptoms such as fatigue and discomfort often precede the development of musculoskeletal injury. If the symptoms persist under certain conditions, they may result in musculoskeletal structure damage, impairments, or disabilities (Hagberg et al., 1995). The best way to prevent or control work-related musculoskeletal disorders is to design jobs, workstations, equipments, and tools to match anatomical, physiological, and psychological traits and capabilities of the worker (Habes and Baron, 1999).

The relationship between occupational factors and upper-extremity musculoskeletal disorders has been investigated for many years. Musculoskeletal injury has long been associated with certain industries such as meat processing and packing. Other industries exhibiting a high injury incidence include construction, clerical work, manufacturing, garment production, health care, forestry, mining, and the arts (Schoenfield et al., 1999). The Bureau of Labor Statistics (BLS) reported 4.2 million nonfatal injuries and illnesses for 2005, with 1.2 million cases requiring days away from work. Thirty percent of the injuries and illnesses with days away from work were attributed to WMSDs. Nearly 20% of these cases were in the health care and social assistance industry. Job tasks involving repetitive motion, such as grasping tools, resulted in the longest absences from work with a median of 19 days (BLS, 2006). The upper extremities are frequently affected by musculoskeletal disorders due to repeated trauma. One WMSD that commonly afflicts the upper extremity, including the shoulder, elbow, wrist, and hand, is tendonitis, inflammation of the tendon and the tendon sheath, characterized by painful or warm, swollen tendons (Schoenfield et al., 1999; Hagberg et al., 1995). Tenosynovitis is the inflammation of the synovial membrane of the tendon sheath (Hagberg et al., 1995). Another upper-extremity disorder is carpal tunnel syndrome, which is defined as the compression of the median nerve in the wrist, resulting in burning, pain, tingling, and numbness of the thumb, index, and long fingers and the lateral half of the palm (Moore, 1992; Hagberg et al., 1995). Carpal instability refers to a group of conditions resulting from injury to the carpus, the group of small marble-shaped bones in the wrist. These conditions range from a simple sprain to major fracture-dislocation (Stanley and Trail, 1994).

1.3 Sonography

Diagnostic medical sonography is a relatively new profession as its technology was not officially recognized by the American Medical Association until 1974 (Vanderpool et al., 1993). Since its first introduction in the late 1950s, ultrasound has become one of the most commonly used forms of diagnostic imaging in healthcare due to its easy-to-use, non-invasive nature. As compared to other imaging technologies such as computed tomography (CT) and magnetic resonance imaging (MRI), ultrasound yields immediate results cost effectively. Ultrasound uses harmless high-frequency sound waves to reflect real-time internal images of the body. Sonography is frequently used in obstetrics and gynecology for pelvic examinations of the uterus and fetus largely due to the absence of radiation.

Ultrasound is also used to evaluate vascular function and organs, such as the heart, kidneys, and liver. The ultrasound images enable doctors to locate the specific source of internal discomfort (Parhar, 2006).

The early primitive and cumbersome ultrasound systems evolved into more streamlined equipment and efficient procedures as the immense diagnostic capabilities of ultrasound were recognized (Vanderpool et al., 1993). With new and improved sonography technology, the number of ultrasounds requested and the duration of each patient procedure have significantly increased. Therefore, while the ultrasound waves are harmless to patients and sonographers, it is important to examine the work task and environment because such a shift in the frequency and duration of use of the technology can present potentially hazardous occupational health concerns for the sonographer, particularly musculoskeletal disorders of the upper extremity (Schoenfield et al., 1999; Vanderpool et al., 1993). In the most basic terms, during a sonogram, the patient lies down on an examination table, and the sonographer applies a water-based conductive gel to the skin of the patient on the area of the body to be examined to allow for better transmission of the sound waves. The sonographer, standing or sitting with the table at his or her side, moves a hand held transducer over the area of interest, applying pressure as needed to create a clear image on a computer monitor. The other hand operates the computer control panel, taking measurements and freezing and recording images.

1.4 Occupational Risk Factors of Sonography

A closer examination of an ultrasound scanning session reveals a host of physically demanding and strenuous movements and activities required of the sonographer. Ultrasound technicians assume and sustain awkward postures for an extended period of time while manipulating and applying pressure with the transducer against the patient. The transducer may be kept relatively still or moved over the body area being examined in repeated arcs (Russo et al., 2002). The sonographer experiences both static and dynamic loading of the muscles of the shoulder, neck, arm, and back as a result of these job activities. To support and fix the arm to hold the transducer steady against the patient requires static or sustained isometric contraction of these muscle groups. Fine dynamic or repetitive movements of the upper extremity, namely the shoulder, forearm, wrist, hand, and fingers are also necessary (Vanderpool et al., 1993). Other activities include lifting and positioning patients and prolonged sitting or standing. The use of awkward postures is exacerbated by incompatibility between the ultrasound equipment and other components of the workstation including stretchers, chairs, beds, and other non-adjustable equipment (Russo et al., 2002).

Epidemiological studies have provided evidence that sonography is an especially physically demanding occupation that has been linked to an alarmingly high incidence of work-related musculoskeletal disorders (WMSDs). A number of studies have cited that over 80% of sonographers experience work-related musculoskeletal symptoms at some point in their careers (Vanderpool et al., 1993; Pike et al., 1997; Russo et al., 2002; Schoenfield et al., 1997; Wihlidal and Kumar, 1997; Muir et al., 2004). Occupations where workers must generate low levels of muscle force or use static or awkward postures for extended periods of time have been linked to WMSDs (Pike et al., 1997; Hagberg et al., 1995). Such activities define the work of sonographers. Armstrong et al. (1984) reported that repeated exertions of a flexed or extended wrist and extreme anatomical changes significantly contribute to the development of upper-extremity musculoskeletal disorders. This would make it reasonable to conclude that the repetitive motions, static muscles, and/or awkward postures used in ultrasound place sonographers at a serious risk for such injuries (Schoenfield et al., 1999).

Habes and Baron (1999) further assessed the occupational hazards associated with sonography when a hospital prenatal unit requested a Health Hazard Evaluation (HHE) from the National Institute for Occupational Safety and Health (NIOSH) because its sonographers were experiencing neck, shoulder, and arm pain from performing sonograms. The investigators from NIOSH interviewed workers and conducted video analysis to assess the jobs. The main risk factors identified during trans-abdominal scans were awkward postures of the wrist and shoulder (mainly right shoulder flexion and abduction), long reaches, sustained static forces, and various pinch grips while manipulating the transducer. Patient size influenced the use of extreme wrist postures. Sonograms of patients early in their pregnancy term required primarily movements of the shoulder. Larger abdomens led to greater wrist flexion and extension. To quantify how much force sonographers typically apply with the transducer, the workers were asked to demonstrate the average and peak downward forces exerted during a scan with the use of a push/pull force meter. The typical pressure averaged 4 pounds and the peak force averaged 8.5 pounds. NIOSH also reported that the amount of force the shoulder can produce decreases with an increase in the shoulder abduction angle. The HHE report concluded with a number of recommendations including adjustable chairs, beds, and ultrasound equipment, elbow support for the sonographer, new transducer designs, and administrative controls such as short rest breaks during the procedure (Habes and Baron, 1999). Many studies, primarily consisting of subjective surveys, have been conducted to record the prevalence of symptoms and injuries among sonographers and to pinpoint their causes as they related to specific job tasks.

A study by Wihlidal and Kumar (1997) aimed to create a profile of work-related injuries among sonographers in Alberta, Canada. Information was elicited from diagnostic medical sonographers in a variety of areas in order to address sonographers in general. The researchers intended to answer questions about: 1) the similarities and differences in personal and professional characteristics of those with, and those without work-related symptoms, 2) the consequences of work-related symptoms, and 3) possible risk factors which sonographers may attribute to these injuries. Of 156 surveys, 96 were returned, for a response rate of 61.5%. Subjects were asked about the prevalence of work-related injury and symptoms, any doctors' diagnoses, and the consequences of injury, including absenteeism or reduced work hours, decreased ability to perform job responsibilities, changes made as a result of the injury (equipment, work station layout, lighting, job duties), and the use of services such as sick leave and worker's compensation. They were questioned about education concerning occupational injuries, job satisfaction, and the most important factor that could cause an increase in injuries in the near future. Eighty-five sonographers, or 88.5% of respondents, reported past or current work-related symptoms. This figure corresponded with 94% of the females and 54% of the males. Eighty-three of the respondents (86.5%) were females. The sample was then divided into two subgroups for those with and those without work-related symptoms. Among those reporting work-related symptoms, the most common conditions were pain between the shoulder blades, as experienced by 54.1% of the subgroup, and shoulder or upper arm pain (52.9%). Aside from neck pain (48.2%) and low back pain (37.6%), many of the more significant problems dealt with the upper extremity, including the hand, wrist, and elbow. These symptoms included hand or wrist pain (37.6%), numbness or tingling of the fingers (28.2%), and elbow pain (23.5%). Of the 85 with work-related symptoms, 35 had received one or more of the following diagnoses, listed in order of decreasing frequency: tendonitis (45.7%), epicondylitis (25.7%), bursitis (25.7%), other (25.7%), ganglions (17.1%), carpal tunnel syndrome (14.3%), and tenosynovitis (8.5%). The sonographers were asked to rate their level of involvement, on a scale of 1 to 5, with 1 being no involvement, in a given job activity and the perceived level of contribution to injury, also on a scale from 1 to 5, for each activity. Those activities scoring a level of involvement of 3 or greater were: gripping the transducer (4.7), applying sustained pressure with transducer (3.8), sustained twisting of neck and trunk (3.7), sustained shoulder abduction (3.5), repetitive twisting of neck and trunk to look from patient to monitor (3.5), and prolonged sitting (3.0). The correlation between the level of involvement and the perceived contribution to injury was significant at the $p \leq 0.05$ level for each activity with the exception of gripping the transducer. Symptoms of neck pain and pain between the shoulder blades were positively correlated with one another and with sustained shoulder abduction. Shoulder and upper arm pain, elbow pain, hand and wrist pain, numbness and tingling of the fingers and finger clumsiness were closely related to each other. To prevent or reduce work-related symptoms, the most common approach taken was to change the workstation layout, as done by 28.2% of the respondents. Only 9.4% changed their equipment, most likely due to the high cost, and only 4.7% changed their scanning technique. Increased workload/decreased staff was selected by the largest portion of respondents (41.2%) as the single most important factor that could increase the number of work-related injuries in coming years. Sustained posture/activity was the second most frequently chosen factor with 24.7% of the respondents (Wihlidal and Kumar, 1997).

Another survey study of sonographers concerning work-related musculoskeletal symptoms was conducted by Russo et al. in 2002. This study sought to address sonographers in general by targeting all sonographers working in British Columbia, conducting a variety of ultrasound exams. The 125-question survey was distributed to 232 sonographers and returned by 211 for a high response rate of 92% and a large representative sample size. A vast majority of the survey participants (91%) reported experiencing musculoskeletal discomfort or pain due to scanning, primarily in the neck, upper extremity, and back. Eighty percent reported that they were still in pain. The respondents were split into two groups: the high pain or discomfort (HPD) group or the low pain or discomfort (LPD) group. Nearly half (49%) of the respondents reported pain and discomfort frequency and severity at a level of 3 or higher on a 4-point scale to distinguish themselves as members of the HPD group. Seventy-four percent claimed to spend 10 minutes or more in one body position during scanning, and the obstetric ultrasound scans, the focus of this study, lasted nearly 30 minutes apiece on average. Sixty-five percent of respondents with musculoskeletal symptoms consulted a physician, and 62% received a diagnosis and treatment. This means that approximately one-third of the respondent population had been diagnosed with a musculoskeletal condition. The most common diagnoses were tendonitis (53%) and musculoskeletal injury (24%). Shoulder abduction, applying sustained pressure with the transducer, sustained twisting of neck/trunk, and repetitive twisting of neck/trunk were identified as the work tasks that most aggravated their symptoms. Twenty-four percent of respondents reported that a change in the scanning technique was the single most important intervention that resolved a work-related problem (Russo et al., 2002).

A study by Pike et al. (1997) echoed many of the findings of the previously discussed sonographer survey studies. Eighty-one percent of the 983 respondents reported that they had experienced musculoskeletal pain and discomfort during their sonography career, and 97% of those associated the pain and discomfort with the tasks of scanning. Ninety-one percent claimed that they were still experiencing the pain and discomfort, which had lasted in excess of 5 years on average. Again confirming the conclusions of other studies, the neck (74%), shoulder (74%), wrist (65%), hand/fingers (61%), and back (65% for lower back, 60% for upper back) were most frequently reported as the sites of pain and discomfort. The activities reported to most aggravate the pain and discomfort were applying pressure, shoulder abduction, and sustained twisting of the neck/trunk. Eighty-nine percent of the 52% of respondents who sought some kind of medical attention received a diagnosis for the problem. The most common diagnoses were other (37.0%), tendonitis (28.2%), musculoskeletal injury (17.9%), tension neck syndrome (16.5%) and carpal tunnel syndrome (16.1%) (Pike et al., 1997). Tendonitis was also cited as the most frequent diagnosis for both the Wihlidal and Kumar (1997) and Russo et al. (2002) studies. Another point of interest from the Pike et al. (1997) study is that the most common consequence of scanning-related pain or discomfort was painful performance of work duties, which was concluded in the Russo et al. (2002) study as well. Ninety percent of those in pain worked through the pain, with only the remaining 10% being absent from work. And 82% of respondents reported taking less than three breaks of 10 minutes or more per day (Pike et al., 1997). Long, physically demanding scans all day long with few breaks have clearly taken their toll on sonographers.

A report by Murphy and Russo (2000) provided an update on sonography ergonomic issues and compiled the results from three survey groups, two of which were the participants from the Russo et al. (2002) and Pike et al. (1997) studies, representing sonographers from the U.S. and Canada for a total of 1621 respondents. Cumulatively, the sonographers reported pain and discomfort in the neck (74%) and low and upper back (58%) and in the shoulder (76%), wrist (59%), hand/fingers (55%), upper arm (38%), and forearm (31%) of the scanning arm (Murphy and Russo, 2000). The same tasks associated with aggravated musculoskeletal symptoms in the Russo et al. (2002) study were cited in this summary report (Murphy and Russo, 2000; Russo et al., 2002).

Each of the survey studies discussed above made similar conclusions about the incidence of musculoskeletal symptoms and injuries among their respective sonographer populations and linked the symptoms to particular tasks and postures within the job. However, identifying a problem and its source is only the first step to finding a solution. While several studies included the occasional recommendation, they generally did not discuss their implementation nor did they evaluate the effectiveness of any intervention. These studies, among others, provide a strong motivation for further work. Another limitation of these studies is the subjective and qualitative nature of surveys. Two individuals who complete identical tasks and expose their bodies to very similar stresses may offer entirely different survey responses. Survey studies should be coupled with quantitative measures to provide a more accurate evaluation of occupational risk factors for musculoskeletal disorders. With so many risk factors, ranging from static shoulder abduction to constant applied pressure with the transducer to awkward wrist postures and repetitive twisting of the neck and trunk, and with so many symptoms and injuries, ranging from back and shoulder pain to tendonitis and carpal tunnel syndrome, it would be an extremely daunting task to address every one of them with solution recommendations and interventions in a single study (Wihlidal and Kumar, 1997; Schoenfield et al., 1999; Pike et al., 1997; Russo et al., 2002). Therefore, this research will focus on one issue, the gripping of the transducer while applying sustained pressure.

1.5 Gripping the Ultrasound Transducer

Sonographers must maintain a firm and secure grip on the transducer as they apply sustained pressures and manipulate and move the transducer across the body of the patient. The use of high hand force for job tasks has been considered a risk factor for WMSDs of the distal upper extremities (Hagberg et al., 1995). Wihlidal and Kumar (1997) reported that gripping the transducer was ranked the highest in terms of level of involvement for sonographer work-related activities. Applying sustained pressure with the transducer, ranked second on the list, was identified as another activity requiring a high level of involvement during scanning. This activity also had a significant correlation with its perceived contribution to injury (Wihlidal and Kumar, 1997). A survey study by Magnavita et al. (1999) found that uncomfortable transducer design was the best predictor for hand and wrist cumulative trauma disorder. Sonographers frequently use a pinch grip when handling the transducer, often with awkward wrist postures. The shape of the transducer determines the grip type. The trans-abdominal ultrasound transducer evaluated in a NIOSH Health Hazard Evaluation (HHE) report (Habes and Baron, 1999) was similar to the transducer model for this study. The 4-inch tall transducer had a 1 x 3 inch rounded rectangular profile when viewed from the top. The orientation of the transducer within the hand, which must be rotated to obtain different images, determined the type of grip used. The sonographer would grip the transducer with a thumb opposing fingertips pinch grip if holding it along the narrow side. A power grip, the most comfortable over the long term, was used when holding the transducer along the wide dimension. The transducer was most commonly held in the palm across the narrow dimension with the thumb on one side and three or four fingers on the other, creating a combination pinch/palmar grip. However, regardless of how it was held, the grip was either a narrow pinch or a power grip across a span that was too wide (Habes and Baron, 1999). The focus of the current study is the use of the transducer when oriented in the hand along the narrow side, requiring the pinch grip. The pinch grip is significantly less desirable than the power grip because it can only generate 15-25% of the force obtainable with a power grip and would, therefore, accelerate muscle fatigue (Rodgers, 1987, as cited in Habes and Baron, 1999). According to Grandjean (1988), the maximum gripping force can be increased fourfold by changing from a fingertip grip to a whole hand grip. Bao and Silverstein (2005) also confirmed that the maximum grip strength of the power grip far exceeded that of the pinch grip when 120 subjects (64 female, 56 male) used a palmar pinch grip with three fingers to apply a maximal pinch grip force on a dynamometer and used a power grip to apply a maximal power grip force on the dynamometer. The power grip strength was 276% and 230% greater than the pinch grip strength for the men and women, respectively (Bao and Silverstein, 2005).

Both the power and pinch grip forces are generated by a combination of extrinsic and intrinsic hand muscles. The intrinsic hand muscles include the interossei, the adductor pollicis, the hypothenar muscles, the lumbricals, and the thenar muscles of the thumb. Of these, this study will examine the first dorsal interosseous and the thenar muscle. The thenar and intrinsic hand muscles position the thumb for a pinch grip and work with the flexor pollicis longus muscle of the forearm to generate the necessary power. The adductor pollicis and first dorsal interosseous provide considerable force during the pinch grip. During the power grip, the thumb is positioned by the thenar muscles and stabilized by the first dorsal interosseous and the adductor pollicis muscles (Kozin et al., 1999). However, the power grip relies more on the larger, stronger extrinsic muscles, whereas the pinch grip relies more on the small intrinsic muscles of the hand (Mirka et al., 2002). The extrinsic hand muscles lie outside the hand and include the muscles of the forearm, such as the flexor digitorum superficialis and the extensor digitorum muscles to be investigated in this study. A study by Mirka et al. (2002) evaluated a hand tool intervention that changed a pinch grip to a power grip and found that the intervention significantly reduced the activity of the intrinsic hand muscles (thenar and first dorsal interosseous) but did not have a significant effect on the extrinsic muscles (flexor and extensor digitorum).

Returning attention to the specific challenges in sonography, the forces needed to grip and manipulate the transducer are even higher if the ultrasound conducting gel works its way onto the transducer (Habes and Baron, 1999). This is often a problem with obese patients because sonographers must apply more force and push deeper into the tissue to obtain a clear image. Patient obesity presents a major problem for sonographers because the increased body mass limits the ultrasound imaging capabilities due to acoustic noise that occurs when the ultrasound beam echoes from the surrounding fatty tissue (Parhar, 2006). Therefore, patient size is another factor to consider when examining the gripping of the transducer as it influences the force to be applied to the patient.

Vanderpool et al. (1993) conducted a survey study to examine the prevalence of carpal tunnel syndrome (CTS) and other WMSDs in cardiac sonographers. In doing so, the authors identified risk factors, most notably hand grip pressure. As with the other reviewed studies, 80% of respondents reported musculoskeletal injury symptoms, including back and neck pain. Fifty-seven percent of the 101 respondents reported experiencing between one and four CTS symptoms, and 63% had experienced CTS symptoms at some point in their careers. The CTS symptoms included the following: "(1) tingling in the thumb and/or index and middle fingers, (2) numbness in the thumb and/or index and middle fingers, (3) shooting sensations in the thumb and/or index and middle fingers, (4) burning pain in the thumb and/or index and middle fingers while working, (5) numbness in hands upon awakening, (6) pain at night in wrist and/or hand, (7) changes in muscle bulk of the palm of hand, and (8) clumsy fingers" (Vanderpool et al., 1993). Even though a majority experienced CTS symptoms, only 17% of the survey participants missed work, 31% had received medical treatment, 4% received workers' compensation, and 3% were diagnosed with carpal tunnel syndrome. A significant positive correlation was found between CTS symptoms and using high grip pressure with the ultrasound transducer. But low and medium grip pressures did not have a significant relationship with reports of CTS symptoms. This suggests that a lower grip force may decrease the likelihood of developing musculoskeletal injuries (Vanderpool et al., 1993).

A 1999 study by Schoenfield et al., which surveyed sonographers in the areas of obstetrics and gynecology to evaluate the prevalence of work-related disorders, focused on the handling and manipulation of the ultrasound transducer. The authors used the term 'transducer user syndrome' to label the musculoskeletal conditions and injuries associated with ultrasound scanning and its repetitive movements, static contractions, and awkward positions. The study aimed to investigate how wrist dysfunctions and injuries related to work load and scanning techniques, among other objectives. Procedures and techniques involved in the survey included the percentage of scanning time using specific motions of the wrist, hand grip pressures, positions while scanning, and maintained postures. Forty-four (86%), 34 of whom were female, of the 51 survey recipients answered the questionnaire. At least one or more combined musculoskeletal disorder symptoms were reported by 86% of the respondents. Fifty-seven percent of the respondents reported experiencing between one and four symptoms. During at least some point in their sonography career, 65% had suffered symptoms of carpal tunnel syndrome. The sonography duties ultimately resulted in missed work for five (12%) respondents, necessary orthopedic treatment for 15 (34%), a CTS diagnosis for two (4.5%), and a carpal instability diagnosis for one (2.3%). Survey results indicated that twisting and pushing wrist motions correlated with an increased incidence of carpal tunnel syndrome and carpal instability symptoms. Like the Vanderpool et al. (1993) study, using a high grip pressure was significantly positively correlated with the number of CTS symptoms, but those using low or medium grip pressure did not experience more symptoms. The authors concluded that continuous high grip pressure and prolonged and repetitive maneuvering of the transducer could eventually lead to musculoskeletal disorders including tendonitis of the hand and wrist, carpal tunnel syndrome, and carpal instability. Other findings included a negative correlation between upright posture and symptoms and a positive correlation between twisted posture and symptoms. The authors promoted sitting by sonographers because standing correlated with increased musculoskeletal stress (Schoenfield et al., 1999).

1.6 Intervention Strategy for the Ultrasound Transducer

Biomechanical risk factors including repetition, posture, force, and vibration have shown to be strongly linked to the development of work-related musculoskeletal disorders (WMSDs) (NIOSH, 1997). Addressing these factors should be the strategy focus in creating new interventions for the problem of high grip force of the ultrasound transducer. Vibration is not a factor in the task of ultrasound scanning, and the design of the transducer would have little effect on repetition. Therefore, interventions should focus on grip posture and force.

One intervention strategy is to examine hand posture in gripping the transducer, namely the handgrip span. A number of studies have researched the effects of handgrip span on the performance of different gripping tasks. This performance has been evaluated in terms of dependent variables such as maximum grip force, muscle fatigue, heart rate, and blood pressure. A major finding from these studies is the idea of an optimal handgrip span where the greatest grip force can be exerted (Petrofsky et al., 1980, Blackwell et al., 1999, Shivers et al., 2002). This can be explained by the muscle length-tension relationship which describes changes in the amount of force a muscle can exert based on sarcomere length. A sarcomere, a single contractile unit within a myofibril, is an arrangement of parallel thick (myosin) and thin (actin) filaments connected by crossbridges that span the gaps between them. The overlap of these filaments determines the length of the sarcomere. The change in the overlap as the filaments slide past each other, resulting in muscle contraction, is described by the sliding filament theory. According to this theory, the force a muscle can generate is directly proportional to the number of crossbridges formed. If the sarcomere is extended to a relaxed state, the filaments hardly overlap with few crossbridges. Therefore, the beginning of the contraction cannot generate much force because the sliding filaments can only interact minimally. If the sarcomere is too short at the beginning of a contraction, the crossbridges are too overlapped and the filaments can only slide a short distance, reducing the number of crossbridges that can form (Silverthorn, 2004). When the sarcomeres are stretched to the length where the greatest number of actin-myosin crossbridges can form, the hand span is optimal (Petrofsky et al., 1980).

Petrofsky et al. (1980) studied the effect of handgrip span on the performance of an isometric hand grip task. Handgrip span was evaluated in terms of its influence on grip strength, endurance, surface electromyography (EMG) of the active muscle, blood pressure, and heart rate. Subjects exerted maximal voluntary contractions (MVC) on a strain gauge hand grip dynamometer consisting of two poles that could be adjusted to six different distances apart ranging from 3.2 to 8.0 cm. For each subject, trials were performed at the 4.4 cm and 6.6 cm grip spans, as well as, the optimal grip span for that individual, based on the distance resulting in the highest MVC force. For both male and female subjects, the greatest force was exerted at a grip span between 5 and 6 cm. In addition to the MVC trials, subjects performed fatiguing contractions at 25, 40, 55, or 70% MVC at all three of the grip spans. There was no significant change in endurance, measured as the time required to reach fatigue, across the different grip spans at the same relative load (Petrofsky et al., 1980).

Blackwell et al. (1999) examined the effect of grip span on maximum isometric grip force and fatigue of the flexor digitorum superficialis (FDS) muscle during contractions sustained at 60-65% of subjects' maximal voluntary contraction (MVC). The effect of grip span on these factors is important to consider because activities may require a given grip force, so it would be prudent to optimize grip span to allow for the greatest potential grip force. Using a grip dynamometer set at four different grip spans, subjects performed isometric gripping contractions with pronated right forearm resting on a horizontal surface. The greatest grip strengths were recorded at the two middle settings of 130 mm and 160 mm grip circumference, which equate to approximately 4.1 cm and 5.1 cm diameter. The authors concluded that each muscle involved in grip formation should be at its optimal length to produce the greatest force and, therefore, recommend that designs vary grip sizes based on hand sizes. Muscle fatigue was also investigated in this study through the use of EMG. The power of the EMG signal shifts to a lower frequency as the muscle fatigues. The FDS muscle was sampled because it is a prime finger flexor used in the power grip. With the fatigue trials, a similar drop in the median frequency was demonstrated for all four grip spans, suggesting that the rate of fatigue is similar for all settings when gripping at the same relative force. Therefore, it was found that the rate of FDS muscle fatigue is independent of muscle length, much like the conclusions on endurance in the Petrofksy et al. (1980) study (Blackwell et al., 1999).

The study by Shivers et al. (2002) examined the lateral pinch grip, which is more similar to the pinch/palmar grip used by sonographers when gripping a transducer than the power grip used in the previously discussed research. Like the Blackwell et al. (1999) and Petrofsky et al. (1980) studies, the experiment by Shivers et al. aimed to discover the effect of grip span. Rather than using set grip span distances for each subject, 11 grip spans were tested based on the maximum functional lateral pinch grip span distance of each individual, 0% to 100% in increments of 10%. The maximum functional lateral pinch grip span was taken to be 70% of the distance from the interphalangeal joint of the thumb to the distal interphalangeal joint of the index finger when the thumb was maximally abducted. The study found that grip strength significantly increased with increasing grip span. Grip strength at the maximum functional grip span was 40% greater than that measured at the minimum pinch grip distance (Shivers et al., 2002). These results further support the earlier studies showing that a small grip span reduces grip strength. While the pinch grip is frequently used and the grip span can be optimized as concluded in this study, the nature of the pinch grip is a hazard in itself as it has lower force capabilities than other grip types (Rodgers, 1987; Bao and Silverstein, 2005; Grandjean, 1988).

The NIOSH HHE report (Habes and Baron, 1999) on the job of sonographers at a hospital prenatal unit recognized a connection between the transducer design and musculoskeletal symptoms in the hand and wrist. As discussed earlier, the transducer in use was similar to the model for this study with its elliptical scan head, which forced a narrow pinch grip in one orientation and a wide power grip in the other. NIOSH investigators made a number of recommendations for the improvement of the current transducer design. They encouraged a design that employs the stronger power grip at all times. While the transducer in the study could be held with a power grip, when held along the 3 inch wide edge, the thin edge of the transducer would dig into the thenar muscle of the thumb and the soft tissue of the proximal fingers (Habes and Baron, 1999). A study by Ayoub and LoPresti (1971) found that the most desirable handle shape is round or elliptical and 1.5 inches (3.8 cm) in diameter, and the narrow side of the transducer in the NIOSH investigation required a 1 inch pinch grip. In the HHE report recommendations, the authors suggested the addition of an auxiliary handle to, or the modification of the existing handle of, the trans-abdominal transducer to allow the use of a power grip while maneuvering and handling the tool. The handle, which should be 1.5 inches in diameter and at least 4 inches in length, should be fashioned such that it is elliptical or round in shape without affecting the imaging hardware inside the transducer. To support the thenar portion of the handle, a flared edge at the bottom of the handle is recommended. The handle texture should be as slip resistant as possible while still being able to be cleaned and disinfected. To minimize weight and torque, the transducer cable should be made as thin as possible. The NIOSH investigators recommended that the transducer handle be equipped with a strap that would attach the tool to the hand and allow the sonographer to relax his or her grip between periods of exertion. The sonographer would be able to relax his or her hand without letting loose of the transducer (Habes and Baron, 1999).

1.7 Objectives

The primary objective of this study is the design, fabrication, and evaluation of three different ultrasound transducer interventions as they compare to the existing transducer design, or control. The motivation behind the transducer intervention designs is the reduction of the pinch force requirement. It is hypothesized that the transducer interventions will reduce the activity of the muscles of the upper extremity, primarily those of the hand and forearm as they are most engaged in the pinch grip. It also expected that the subjects will prefer the interventions to the control transducer and will cite less pain and discomfort associated with their use.

2 Methodology

2.1 Overview of Experiment

This study aimed to evaluate the effectiveness of ergonomic interventions for ultrasound technicians in reducing the risk of developing upper extremity musculoskeletal disorders. Three ultrasound transducer interventions were tested to focus on the use of high grip pressure while applying sustained force with the transducer during a scanning procedure. The interventions were evaluated along with the control transducer through the use of electromyography (EMG) to determine their effect on muscle activity of the upper extremity while the subject was engaged in a simulated ultrasound scanning task. Because sonographers manipulate the transducer at varying angles, the ultrasound task was performed at two different angles. As patient size plays a major role in the gripping and force application of the transducer, the experiment was performed in two parts to meet differing conditions to simulate a scan on a normal-sized patient and on an obese patient. In addition to quantitative measures, the interventions were assessed subjectively via participant surveys following the experiments.

2.2 Engineering Design of Intervention Prototypes

Ideas and concepts for transducer interventions were formulated based on a combination of information from existing literature and observations and discussions with sonographers. The goal of each intervention was to reduce the pinch grip forces used to grasp the transducer during an ultrasound scan.

2.2.1 Control Transducer

The ultrasound transducer most frequently used for prenatal abdominal scans at the Duke Fetal Diagnostic Center (Figure 2.1) was the model for this study and the foundation for the design of the interventions. Because the transducer was not available for use in the experiment, a replica was made. The borrowed transducer was scanned with the Roland PICZA 3D Laser Scanner (Roland DGA Corporation, Irvine, CA) and imported as a three dimensional computer image. The 3D computer model was processed, cleaned up for errors and smoothed, using Magics (Materialise, Leuven, Belgium) and Geomagic Studio 7.0 (Geomagic, Inc., Research Triangle Park, NC) software. It was prepared for the build using 3D Lightyear (3D Systems Corporation, Rock Hill, SC) software and then made into a physical model using the SLA-190 (3D Systems), a stereolithography rapid prototyping machine. The model, composed of a plastic resin, weighed significantly less than the actual transducer. To increase the weight accordingly, a hole was drilled into the hollow internal honeycomb structure of the prototype, and a mixture of steel powder, epoxy resin, and epoxy hardening agent was injected into the transducer until it reached the appropriate weight. The finished control transducer, as used in the experiment, is shown in Figure 2.2 being held as the subjects were instructed, with the index and middle finger resting on the small curved surface where the transducer head widens and the thumb doing the same on the other side. The surface gives minimal support for the fingers to rest on, forcing the pinch/palmar grip when the transducer must be held along the narrow width. During scans, the transducer is alternated between grips about the narrow and wide width. The narrow width grip is more common and more problematic and, thus, it is the only transducer orientation used in the current study.

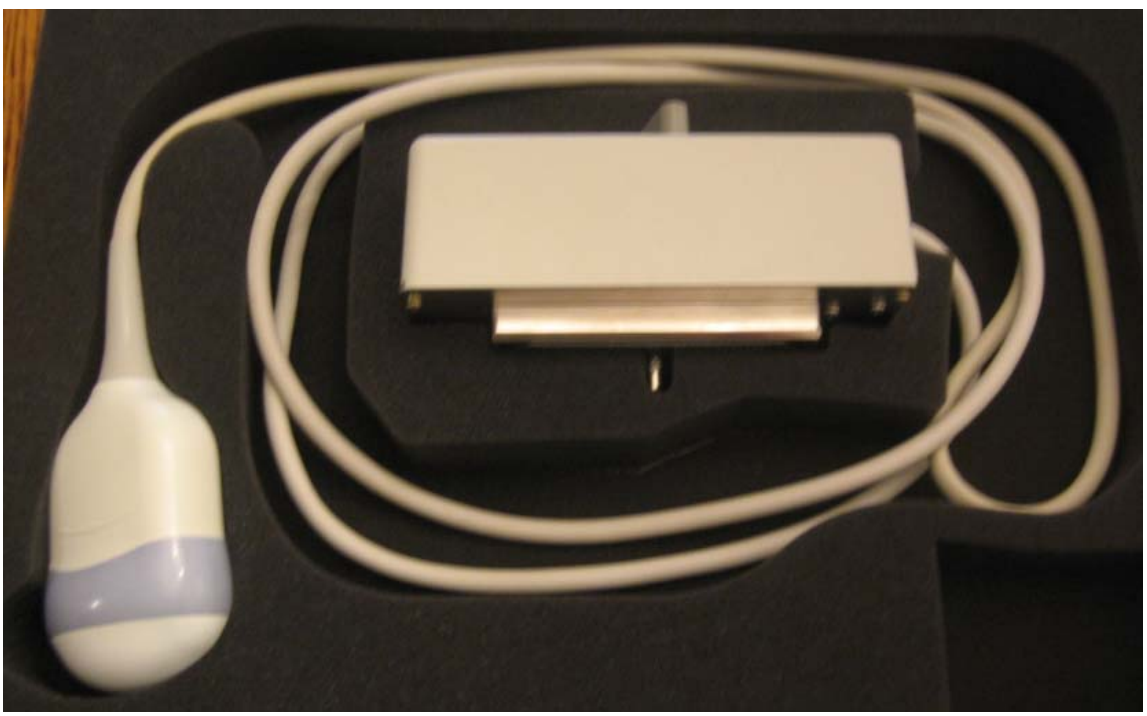


Figure 2.1. Ultrasound transducer. This functioning ultrasound transducer, used in the Duke Fetal Diagnostic Center, served as the model for the control and interventions used in the current study. The transducer is one unit as shown; the cable cannot be detached from the large box-like unit for connection to the ultrasound machine.

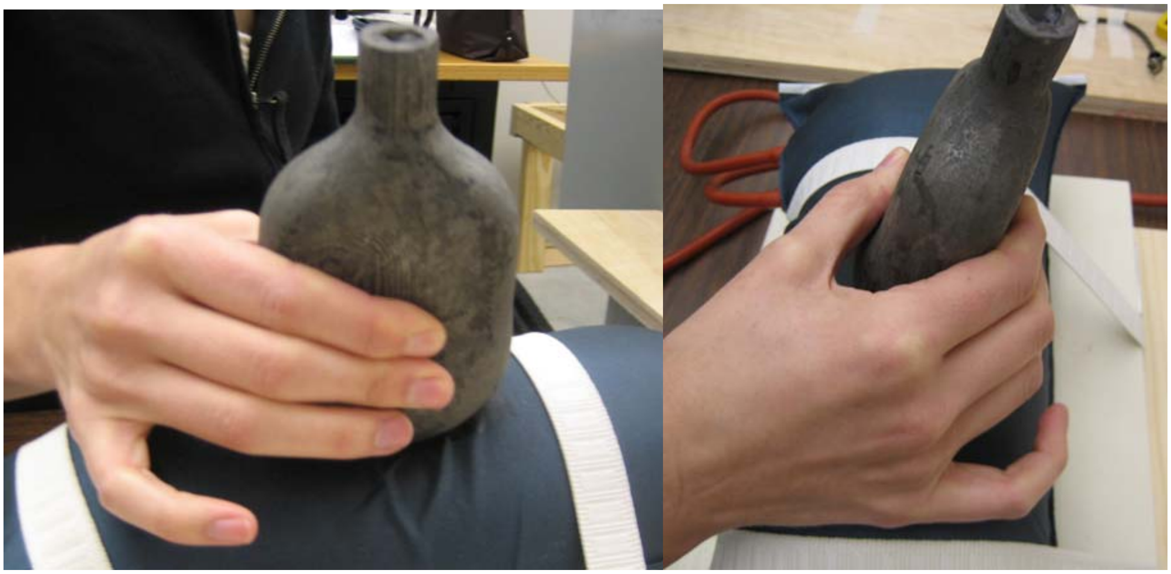


Figure 2.2. Control transducer. A rapid prototyped replica of an actual ultrasound transducer was made for use as the control transducer. Subjects were instructed to use a pinch/palmar grip with index and middle finger placed as shown.

2.2.2 Transducer Cover

The first intervention, the transducer cover, is a hard plastic shell that snugly fits over the transducer (Joines et al., 2007). The cover, created by a rapid prototyping machine, has a ledge along the bottom perimeter, near the scanning head, that is intended for the sonographer to push his or her fingers down upon to exert pressure on the patient. With the substantial ledge to allow for a downward push and to support the fingers, it is hypothesized that the transducer cover will reduce the need to pinch and grip. The downward force will be supplied primarily by the larger, stronger muscles of the upper arm and shoulder rather than the hand and forearm, and the hand will no longer need to maintain the high level of friction with the transducer surface as required when gripping the control. Another purpose of the cover ledge is to prevent the fingers from getting slippery from ultrasound gel migrating upward onto the transducer. This frequently occurs with scans of obese patients as a sonographer must push with higher force deeper into the gel-covered tissue of an obese patient to acquire a good image. Slick gel on the surface of a transducer makes it more difficult to grip and requires more force to do so, and the cover ledge serves to stop this gel. The cover has a large slit opening such that the cable can be passed through and the cover can then be slid down on top of the transducer. This was necessary as the cable of the real transducer cannot be disconnected from its large connection unit (see Figure 2.1). The cover intervention is pictured in Figure 2.3. Subjects were instructed to push down on the ledge with their fingers as opposed to pinching and gripping the transducer.

Figure 2.3. Transducer cover. The cover intervention featured a support ledge to be pushed down upon as shown.

2.2.3 Transducer Harness

The next intervention, the transducer harness, is intended to reduce the need to pinch and grip the transducer by attaching the fingers to the transducer itself by way of nylon strap finger loops. Instead of gripping the transducer and relying on the friction between the hand and the transducer to apply force, the harness calls for a downward pull. As with the cover, it is hypothesized that this downward force will utilize the larger, stronger muscles of the upper arm and shoulder rather than the hand and forearm. One side of the harness has a loop fit for the thumb, and the other side has a larger loop fit for two fingers, either the middle and ring finger or the index and middle finger. The finger loops are attached to a nylon strap that wraps across the top of the transducer such that when one pulls down with their fingers, the nylon strap transfers that downward force across the top of the transducer. The nylon strap with finger loop holes is secured onto the transducer via an elastic band that fits around the transducer. The elastic allows the harness to be stretched onto the bottom of the transducer so the harness can be easily placed on and removed. A second nylon strap is secured across the other side of the top of the transducer using a snap button. Aside from reducing the pinch force requirement, the harness has another benefit in that it allows the hand to completely relax between force exertions during a scan without having to set down the transducer. With any other transducer or intervention, during the course of what could be a very long scan, the sonographer is likely to keep the transducer held in their hand at all times, even if not exerting pressure on the patient. But with the harness, the transducer is simply attached to the hand. The harness is shown in Figure 2.4.

Figure 2.4. Transducer harness. The thumb and two middle fingers were secured to the transducer through the finger loops of the harness intervention as shown. Subjects were instructed to pull down on the loops rather than pinch and pull down on the transducer.

2.2.4 Wide Grip Transducer

The final intervention, the wide grip transducer, is intended to change the pinch grip to a power grip through the expansion of the transducer diameter. With the pinch grip, an object is held between the distal joints of the fingers and the opposing thumb. The fingers are wrapped around the object, which is held in the palm of the hand, with the power grip (cylindrical grip). A pinch grip relies on the intrinsic hand muscles, whereas the power grip uses the larger, more powerful muscles of the arm and shoulder (Mirka et al., 2002). As the power grip can produce significantly higher force, the pinch grip requires more muscle exertion than the power grip to produce the same force (Rodgers, 1987; Bao and Silverstein, 2005; Grandjean, 1988). Therefore, a pinch grip is more likely to cause injury than the power grip. The wide grip transducer was designed by modifying the 3D computer model of the real transducer generated from the laser scan. Using SolidWorks (SolidWorks Corporation, Concord, MA) CAD (computer aided design) software, the gripping width of the transducer was expanded to 5 cm based on literature on the optimal grip span, as discussed previously in the Introduction (Blackwell et al., 1999; Petrofsky et al., 1980; Shivers et al., 2002). As with the control transducer, the wide transducer was created on the SLA-190 rapid prototyping machine, and steel power and epoxy were injected inside to increase the weight to that of the real transducer. Subjects were instructed to wrap their fingers around the transducer with their index and middle finger resting on the small curved lip or ledge, as instructed with the pinch grip of the control transducer, and to hold the transducer back in the palm of their hand. Figure 2.5 shows the wide grip transducer after it has been created on the SLA machine, but prior to adding the steel weight, as well as a photograph of the completed transducer in use.

Figure 2.5. Wide grip transducer. The image on the left shows the wide grip transducer prior to the addition of the steel weight, and the right image shows the intervention held with fingers wrapped around in a power grip.

2.3 Subjects

Nine healthy female subjects with no previous incidence of upper extremity injury or current shoulder, arm, or hand pain or discomfort volunteered for the study. None of the subjects had experience performing ultrasound scans. Only females were asked to participate because the large majority of sonographers are female, as shown in a number of survey studies where anywhere from 72% to 89% of respondents were female (Vanderpool et al., 1993; Muir et al., 2004; Wihlidal and Kumar, 1997; Russo et al., 2002). Female subjects were also used because studies have reported a higher percentage of females experiencing work-related symptoms than males, most likely due to a difference in physical strength (Vanderpool et al., 1993; Wihlidal and Kumar, 1997). All subjects were right-handed as the experimental task apparatus was set up for right-handed scanning. The subject group had a mean age of 25.3 years (standard deviation 3.74 years), a mean height of 168.0 cm (standard deviation 7.25 cm) and a mean whole body mass of 62.2 kg (standard deviation 10.4 kg). Participants provided written informed consent prior to participation.

2.4 Apparatus

2.4.1 Experimental Task Apparatus

To simulate an abdominal fetal ultrasound scan, subjects were seated with a table to their right side such that their right arm could be laterally abducted to apply pressure on an abdomen-like apparatus. An inflated blood pressure cuff with an analog pressure gauge was used to simulate an abdomen and control the pressure applied by the subject. The blood pressure cuff was secured to a wooden board hinged to another board, which was clamped to the table. The hinge allowed for a 45 degree wooden wedge to be inserted, changing the scanning angle. While sonographers must scan and apply force from many different angles, only two angles were selected for this study. Force was applied perpendicular to the 0 and 45 degree surfaces to simulate scanning directly over the top of the abdomen and on the far lateral side of the abdomen, which requires the most reaching. The seated subjects were faced towards a monitor on top of a cabinet in front of them during the trials to keep them seated forward to simulate the use of the ultrasound monitor and keyboard. A video camera was set up to provide a live feed of the blood pressure gauge to the monitor. Subjects viewed the monitor to maintain the appropriate pressure. This was intended to simulate an actual ultrasound where a sonographer would view the monitor while scanning. The experimental task apparatus as described can be seen in Figure 2.6. The experimental setup is shown in use at the 0 degree angle in Figure 2.7 and at the 45 degree angle in Figure 2.8.

Figure 2.6. Experimental task apparatus. Abdomen-like surface (inflated blood pressure cuff) is positioned at 45 degrees.

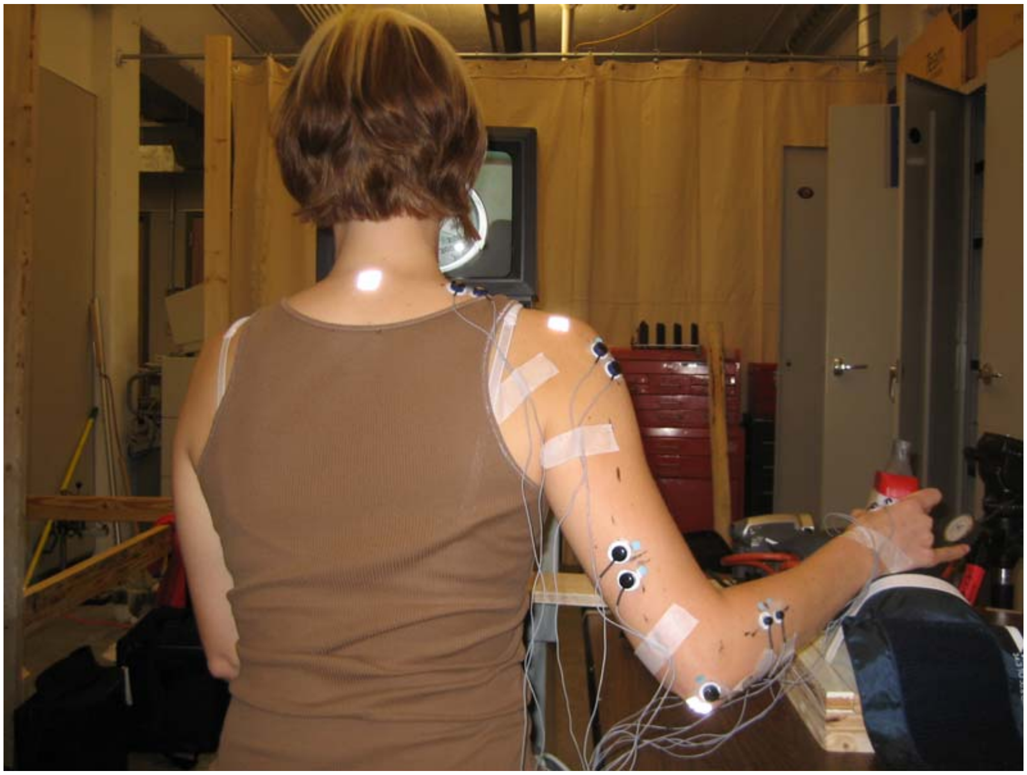


Figure 2.7. Experimental task setup, 0 degrees. A seated subject applies pressure against an abdomen-like surface at a 0 degree angle while viewing the pressure gauge on a monitor.

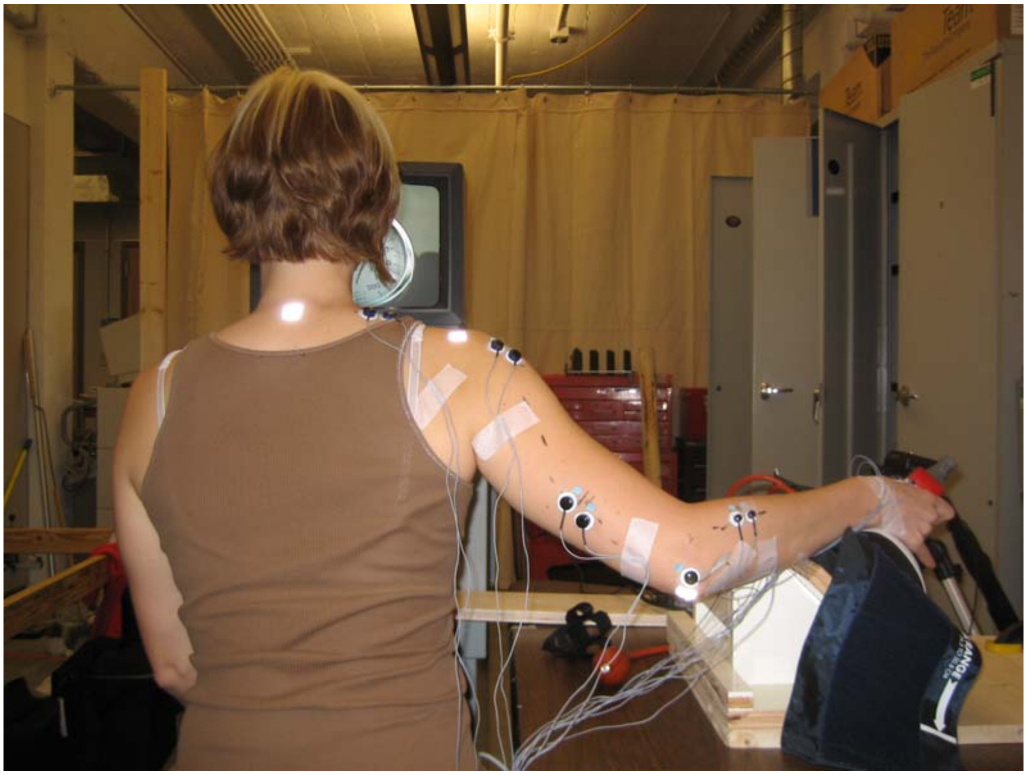


Figure 2.8. Experimental task setup, 45 degrees. A seated subject applies pressure against an abdomen-like surface at a 45 degree angle while viewing the pressure gauge on a monitor.

2.4.2 Data Collection Apparatus

Electromyography (EMG) was used to quantify the muscle activity of the right upper extremity during the simulated ultrasound tasks. Seven pairs of surface electrodes were used to measure the activity of seven different muscles of the right hand, arm, and shoulder. These electrodes were placed on the skin over the thenar, first dorsal interosseous (FDI), flexor digitorum superficialis, extensor digitorum, lateral deltoid, trapezius, and triceps brachii (lateral head) muscles. The electrode locations for several of these muscles were marked as dictated by Zipp (1982). While the electrodes were positioned such that the most powerful signal came from the specific muscles listed, it is important to note that other overlying and underlying muscles may have also contributed to the EMG signal. The electrodes placed over the flexor digitorum superficialis likely received some signal from the more superficial flexor carpi radialis and from the flexor digitorum profundus, which lies beneath it. EMG activity may have been recorded from the abductor pollicis longus muscle beneath the extensor digitorum (Marieb, 1989). Shielded cables connected to the electrode pairs would then send their potential difference to a main amplifier (BIOPAC Systems) to increase the gain and to apply a 500 Hz low-pass filter and a 1 Hz high-pass filter. The signal was collected for 5-second trials at a 1024 Hz sampling rate. A LabVIEW (National Instruments Corporation, Austin, TX) program was used to control the timing of the data collection and save the data. The EMG data was further processed using MATLAB 7.0 (The MathWorks, Inc., Natick, MA) software after the completion of the experiment.

The EMG data was normalized to the maximum EMG activity for each muscle of interest for each subject in order to compensate for intersubject variation. Subjects performed maximum voluntary contractions (MVCs) using two dynamometers to provide static resistance and measure the applied force to ensure a consistent MVC between two exertions (values within 10% of each other). The EMG signal was normalized using the higher of the two MVCs for each muscle. A pinch grip dynamometer was used for the thenar and FDI MVCs. For the thenar muscle, the subject pinched the dynamometer between her thumb and fingertips. The subject pinched the dynamometer between her thumb and index finger (between the second and third knuckle) for the FDI MVC. The BTE (Baltimore Therapeutic Equipment) PRIMUS dynamometer (Figure 2.9) was used to apply static resistance for the MVCs for the flexor, extensor, deltoid, and tricep muscles and measure the applied torque. Subjects were asked to push as hard as possible against a bar locked in place to activate the muscle of interest. The subject stood with her right elbow bent at 90 degrees and her forearm placed supine on an arm rest and secured with a strap with a bar placed just above her hand. She would then push her hand upward with the bar hitting across her fingers between the first and second knuckles for the flexor MVC, as shown in Figure 2.10. The process was the same for the extensor but with a pronated forearm. For the deltoid, the subject stood next to a vertically hanging static bar and pushed the back of her hand against the bar as if attempting to laterally abduct the right shoulder. With right arm bent at 90 degrees, the subject made a fist and pushed down on a horizontal static bar to engage the triceps muscle. For the trapezius muscle, the subject pulled up on a static bar with arms held locked in place and trying to shrug shoulders upward.

Figure 2.9. BTE PRIMUS dynamometer.

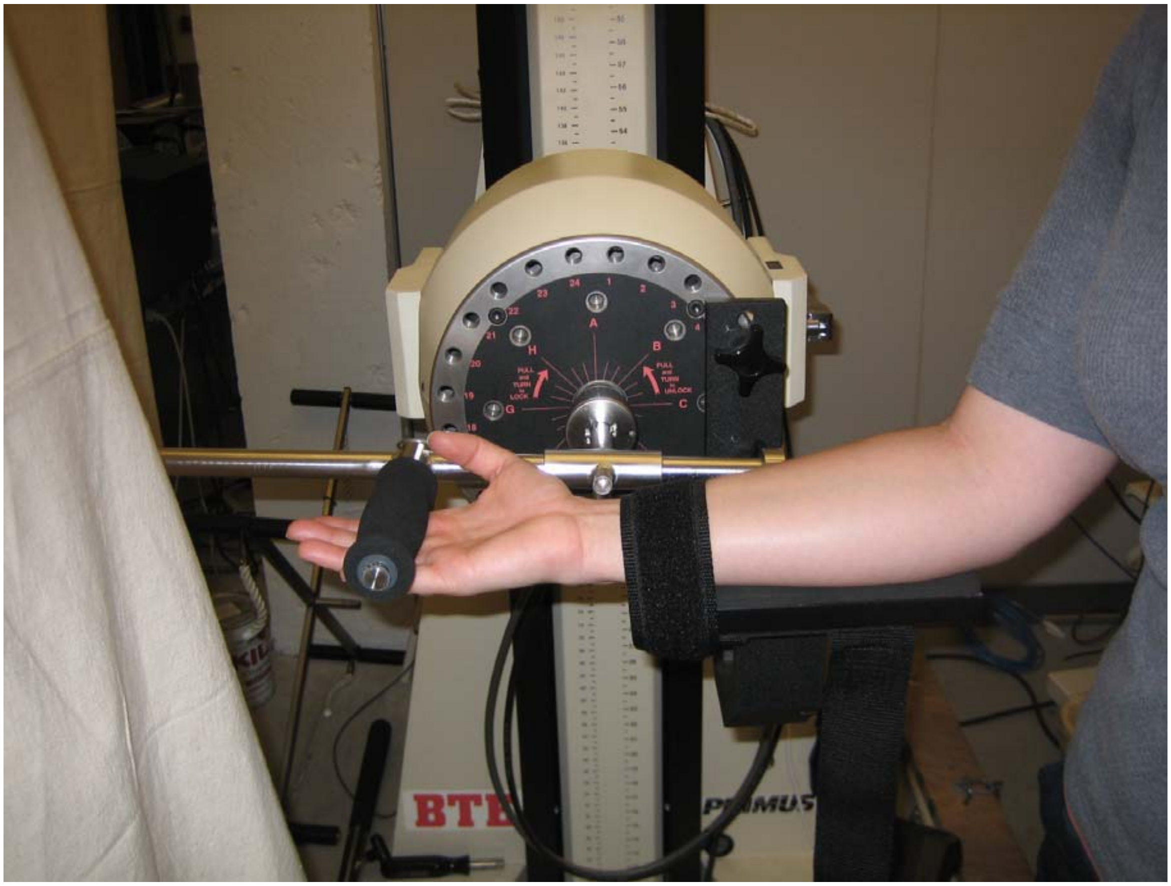
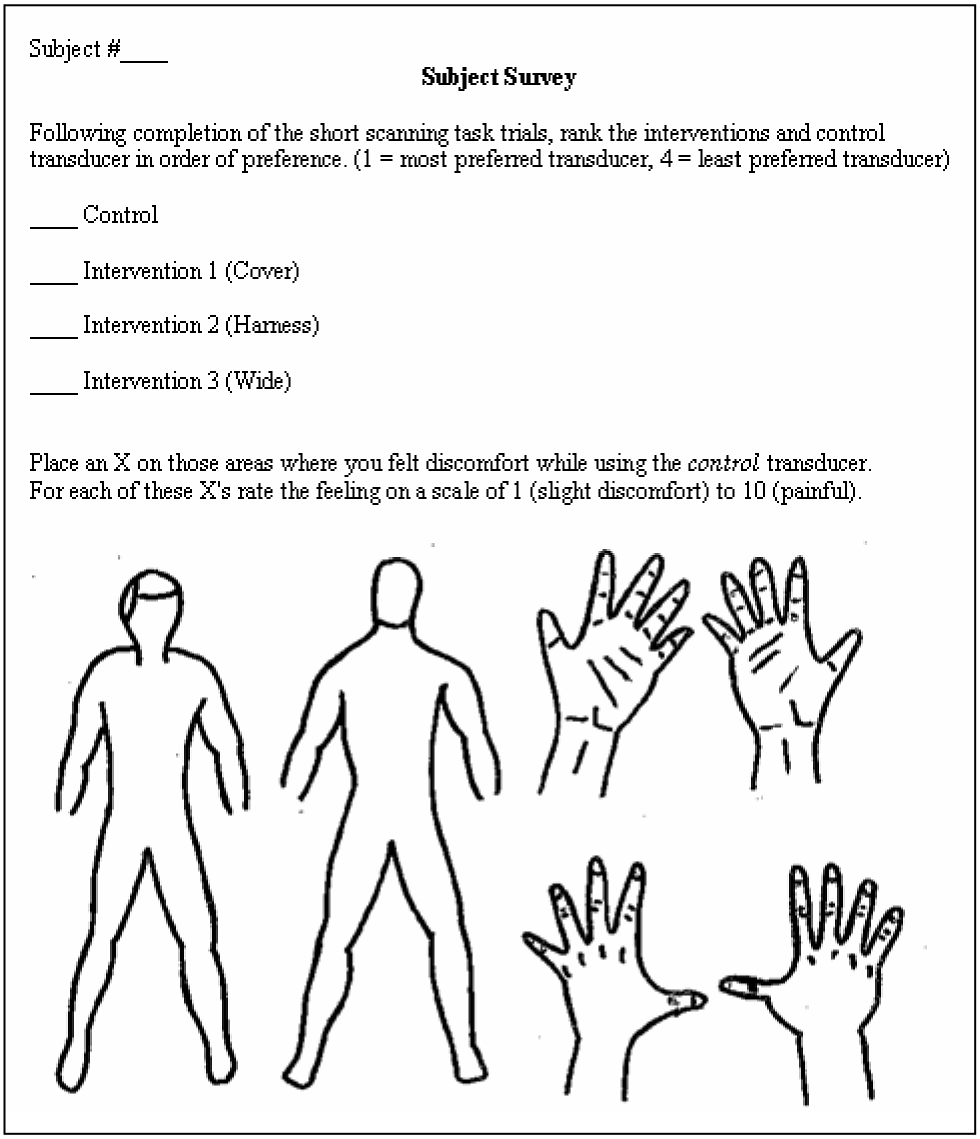


Figure 2.10. Maximum voluntary contraction (MVC) for the flexor digitorum superficialis muscle. A subject pushes her hand, positioned as shown, upward against a static bar.

In addition to the quantitative measure of the intervention effectiveness via EMG, the interventions were assessed subjectively with a survey completed by subjects following the ultrasound task experimental trials. The survey asked the subject to rank the interventions and control in order of preference and included a discomfort survey for each transducer. Subjects were to mark and rank areas where they experienced pain or discomfort on a diagram of the human body and the hands. The level of discomfort was ranked on a scale of 1 (slight discomfort) to 10 (painful). The first page of the survey, which included the ranking of interventions and the discomfort survey for the control transducer, is shown below in Figure 2.11. The complete survey can be found in Appendix B.


Subject #____

Subject Survey

Following completion of the short scanning task trials, rank the interventions and control transducer in order of preference. (1 = most preferred transducer, 4 = least preferred transducer)

____ Control

____ Intervention 1 (Cover)

____ Intervention 2 (Harness)

____ Intervention 3 (Wide)

Place an X on those areas where you felt discomfort while using the *control* transducer. For each of these X's rate the feeling on a scale of 1 (slight discomfort) to 10 (painful).

Figure 2.11. Subject survey.

2.5 Independent Variables

The independent variables in both the normal and obese patient experiments were INTERVENTION and ANGLE. INTERVENTION had four levels: the control and the three interventions, the cover, the harness, and the wide grip transducer. ANGLE had two levels: 0 degrees and 45 degrees, the angles at which the abdomen-like surface was set.

2.6 Dependent Variables

The dependent variables for both experiments were the normalized EMG (nEMG) data for each of the seven muscles of interest as averaged over each 5-second trial and the results of the subjective survey as completed by each participant. These averaged nEMG signals included the thenar (thenar), first dorsal interosseous (FDI), flexor digitorum superficialis (flexor), extensor digitorum (extensor), lateral deltoid (delt), trapezius (trap), and triceps brachii (tricep) muscles. The survey, which asked the subject to rank the interventions and control in order of preference and included a discomfort survey for each transducer, is shown in Figure 2.11 and in Appendix B. The two parts of the survey represented two subjective dependent variables. The first was the preference ranking value (1 = most preferred transducer, 4 = least preferred transducer) for the interventions and control. The second survey dependent variable was the level of discomfort, on a scale of 1 (slight discomfort) to 10 (painful), on any area of the body, as associated with the use of each transducer.

2.7 Experimental Procedures

The subject was given an overview of the protocol and instructed in the physical requirements of the experimental task, ensuring that the subject was fit to be a participant (without upper extremity injury or pain), upon arrival to the lab. An informed consent form (Appendix A) was presented to the subject to be signed. The subject was then led through a few minutes of stretching exercises for the neck and the right arm and shoulder to reduce any risk of muscle strain during the experiment. Anthropometric data including height, weight, and hand grip span were measured and recorded. Hand grip span was measured as the distance between the interphalangeal joint of the thumb and the distal interphalangeal joint of the index finger with the thumb maximally abducted (Shivers et al., 2002).

Surface electrodes were then prepared and placed on the seven muscles of interest on the seated subject. The electrodes were applied to the skin over the thenar muscle of the thumb, the first dorsal interosseous muscle of the hand, the flexor and extensor digitorum superficialis muscles of the forearm, the lateral deltoid, the trapezius, and the tricep muscle of the right arm. The subject was then asked to perform maximum voluntary contractions (MVCs) for each of the muscle groups, as previously described, with one minute rest between each exertion.

Upon completion of the MVCs, the subject performed both the normal and obese patient experiments separately, with the order of experiments randomized such that half of the subjects performed the normal patient task first and half performed the obese patient task first. The experiment intended to simulate an ultrasound scan on a normal-sized patient required the subject to apply a constant pressure of 5 mmHg to the abdomen-like surface, whereas the experiment for the obese patient required an applied pressure of 12 mmHg. These pressures were determined based on discussions with several sonographers and pilot work. The normal and obese patient experiments differed in one other aspect. For the obese "patient," the subject applied ultrasound gel to the surface of the control and wide grip transducers to simulate the upward migration of the gel from the skin of the patient onto the transducer as a sonographer must push with higher force deeper into the tissue of an obese patient to acquire a good image. The subject was instructed to wipe off her hand to remove the gel before using the transducer cover because the design with the ledge was intended to prevent the gel from reaching the gripping hand. Aside from the level of force and the use of gel on the transducer, the obese and normal patient experiments were performed the same.

The subject applied constant pressure to the simulated abdomen apparatus for 5 seconds for each combination of independent variables. These conditions included using each of the 4 intervention types (including the control) held at the two different angles (0 and 45 degrees). Each combination of conditions was replicated 3 times for a total of 24 trials (4 interventions*2 angles*3 repetitions) per experiment and 48 trials overall. Within each experiment, the trials and conditions were completely randomized. A rest break of 10 seconds was given between trials with 1 minute rest every 10 trials to reduce the risk of the development of muscle fatigue. The subjects were instructed how to hold each specific transducer as intended by its design. Before recording the 5 seconds of EMG data for each trial, the subject was told to ramp up to the designated pressure. The subject verbally confirmed when the pressure was achieved, and recording would begin. At the completion of the 48 trials, the subjects were asked to fill out the subjective survey.

2.8 Data Processing

All electromyography (EMG) data from each subject were high-pass filtered at 10 Hz, low-pass filtered at 500 Hz, and notch filtered at 60 Hz and its harmonics to eliminate ambient electrical noise. Upon further inspection of the EMG data in the frequency domain, it was found that, for some subjects, there were irregular peaks appearing fairly consistently. In cases where these peaks were clearly indicative of noise, a notch filter was applied at that particularly frequency across all the data for that subject. The signals were rectified and averaged across the 5-second trial. The EMG data from the trials were normalized relative to the EMG data from the MVCs for each muscle of interest. The MVC EMG data were filtered in the same manner as the trial EMG data. However, rather than averaging over the 5-second maximum exertion, the MVC signals were smoothed using a 1/8 second window, and the maximum value for the smoothed data was used for the normalization.

As previously discussed, the ranking of the interventions and control and the discomfort survey values for each transducer represented two subjective dependent variables from the survey (Figure 2.11 and Appendix B). Because three areas on the discomfort survey body diagrams were most commonly marked, the discomfort dependent variable consisted of three values, each ranked 1 (slight discomfort) to 10 (painful), per transducer per subject to coincide with the three body regions. These three areas were the hand (more specifically, the thenar and FDI muscle region), shoulder (deltoid and trapezius) and the tricep, or backside of the upper arm. If multiple places were marked and rated within one of these three areas, the discomfort values were averaged.

2.9 Statistical Analysis

The statistical model for each of the two experiments was as follows:

$Y_{ijkm} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + \varepsilon_{ijkm}$, where

Y_{ijkm} = activity for a given muscle for INTERVENTION i, ANGLE j, Subject k, Replicate m

μ = overall mean

α_i = INTERVENTION, where i = 1, 2, 3, 4 for control, cover, harness, and wide transducers

β_j = ANGLE, where j = 1, 2 for 0 and 45 degrees

γ_k = Subject (blocking variable), where k = 1, 2, 3, 4, 5, 6, 7, 8, 9

$(\alpha\beta)_{ij}$ = INTERVENTION i x ANGLE j interaction

m = Replicate, where m = 1, 2, 3

ε_{ijkm} = random error

Multivariate Analysis of Variance (MANOVA) was used to determine if INTERVENTION, ANGLE, and the INTERVENTION x ANGLE interaction had a significant impact on the EMG activity of all muscle groups as a whole. The MANOVA was followed up with an Analysis of Variance (ANOVA) for the independent variables found to be significant with a p-value less than 0.05 in the MANOVA. The ANOVA was used to determine the statistical effect of these independent variables on each specific muscle of interest. Following an initial ANOVA, the assumptions of this statistical analysis were tested and verified using the graphical approach recommended by Montgomery (2005). The three assumptions were tested by examining the residuals of the dependent variables. The normality assumption was tested by graphing the residuals on a normal quantile plot to check that the data points fell within the normal distribution curves. The independence assumption was tested by plotting the residuals over time to verify that the residuals were structureless with no obvious pattern. The homogeneity assumption was tested with a graph of the residuals versus the predicted residuals to check again that no pattern, such as an outward opening funnel, existed (Montgomery, 2005). The assumption of homogeneity of variances was violated in several cases, and, therefore, a natural log transformation was applied to each dependent variable for both the normal and obese patient experiments with the exception of the data for the thenar muscle. The natural log transformations successfully met all assumptions of ANOVA. As with the MANOVA, a p-value of less than 0.05 was used as the criterion for a significant effect for the ANOVA. When such a significant effect was found, the Tukey-Kramer post hoc analysis was performed to determine the relationship of significance between the levels of the independent variable. In a few cases, the Tukey-

Kramer test did not find significant relationships, contradicting the ANOVA results. The Student t-test analysis, a more liberal analysis, was used in these instances.

3 Results

The assumptions of the statistical analysis were tested and verified using the graphical approach recommended by Montgomery (2005). Examples of these graphical test results can be found in Appendix C. A natural log transformation was applied to each dependent variable where the assumption of homogeneity of variances was violated.

3.1 EMG results: Normal Patient Experiment

Both INTERVENTION and ANGLE had statistically significant effects on muscle activity. The EMG results for each muscle of interest in the normal patient experiment are summarized in Table 3.1 below. A natural logarithm (ln) transformation of each muscle group except for the thenar muscle was used in the statistical analysis because the raw data violated at least one of the assumptions of ANOVA.

Table 3.1. Normal patient trial results

Parameter		MANOVA	thenar	ln FDI	ln flexor	ln extensor	ln delt	ln trap	ln tricep
Intervention	F	8.4	29.7	35.2	6.0	16.8	0.4	0.2	0.8
	p	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	0.781	0.864	0.483
Angle	F	71.0	0.0	0.2	23.0	16.9	14.7	475.6	373.7
	p	<0.001*	0.994	0.649	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
Intervention *Angle	F	0.9	--	--	--	--	--	--	--
	p	0.535	--	--	--	--	--	--	--

*indicates statistical significance at the p<0.05 level

INTERVENTION had a significant effect on each of the investigated muscles distal to the elbow. The mean normalized EMG (nEMG) values for each muscle and intervention are shown in Figure 3.1. The statistical significance between each intervention is denoted by the letter or letters above each column. The levels of intervention type that are not connected by the same letter were statistically different from one another. For example, the muscle activity for the thenar muscle was statistically greater when using the harness as compared to all other transducers. The thenar muscle activity associated with the use of the cover was significantly greater than both the wide grip transducer and the control, and there was no statistically significant difference between the wide and the control for the thenar muscle. With the harness, EMG activity for the thenar muscle was 16.9%, 48.4%, and 71.1% greater than with the cover, control, and wide transducers, respectively. Use of the control transducer resulted in significantly greater FDI muscle activity. The control FDI EMG data was 53.9% greater than the wide, 106% greater than the cover, and 194% greater than the harness. The wide grip transducer required significantly less flexor activity than the other three transducers, which resulted in 9.39% (harness), 13.3% (control), and 18.8% (cover) more EMG activity. The cover intervention reduced the amount of extensor activity as compared to the wide and harness, both 27.9% greater, and the control, 37.8% greater.

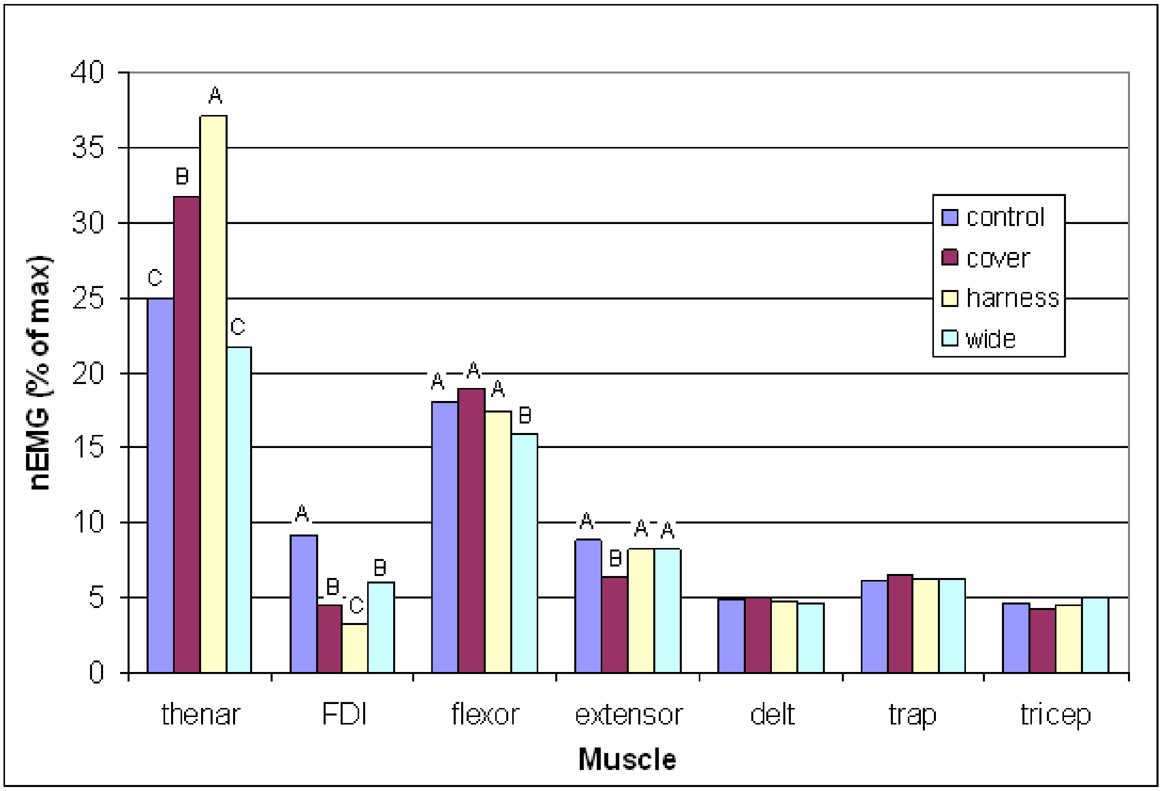


Figure 3.1. Effect of INTERVENTION on muscle activity (nEMG) for the normal patient experiment. Levels not connected by the same letter are significantly different at $p<0.05$.

The angle of the abdomen-like surface had a significant effect on the EMG activity for each of the muscles of interest except for the hand muscles. The mean nEMG values for each muscle and angle are shown in Figure 3.2. Again, statistically significant difference is indicated by different letters above the columns in the bar graph. EMG activity is statistically greater at the 45 degree angle as compared to the 0 degree angle for the flexor, deltoid, and trapezius muscles by 17.1%, 14.0%, and 130%, respectively. The 0 degree position results in 20.9% and 45.6% higher muscle activity for the extensor and tricep muscles than the 45 degree angle.

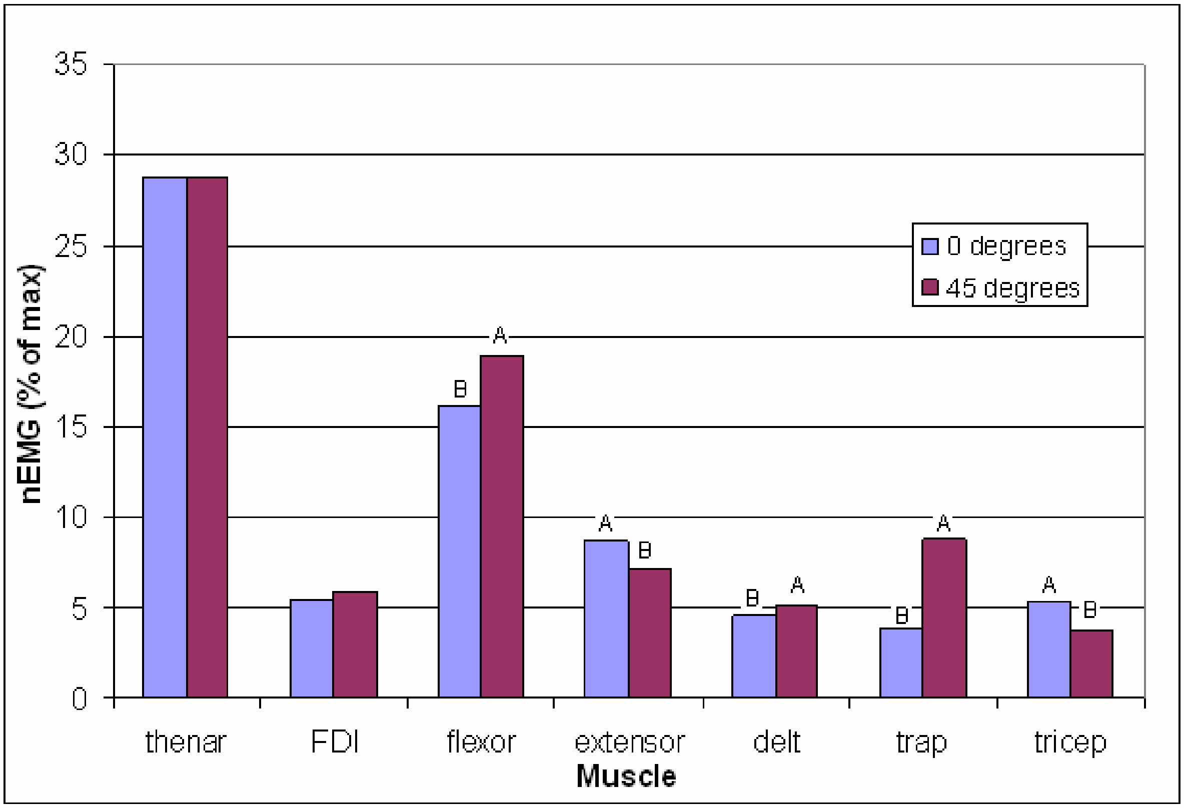


Figure 3.2. Effect of ANGLE on muscle activity (nEMG) for the normal patient experiment. Levels not connected by the same letter are significantly different at $p<0.05$.

3.2 EMG Results: Obese Patient Experiment

Like the normal patient experiment, both INTERVENTION and ANGLE had statistically significant effects on muscle activity for the obese patient trials. The EMG results for each muscle of interest in the obese patient experiment are summarized in Table 3.2 below. A natural logarithm (ln) transformation of each muscle group except for the thenar muscle was used in the statistical analysis because the raw data violated at least one of the assumptions of ANOVA.

Table 3.2. Obese patient trial results

Parameter		MANOVA	thenar	ln FDI	ln flexor	ln extensor	ln delt	ln trap	ln tricep
Intervention	F	9.6	3.7	62.7	2.9	30.5	6.2	6.1	1.0
	p	<0.001*	0.013*	<0.001*	0.035*	<0.001*	<0.001*	<0.001*	0.376
Angle	F	110.4	4.0	1.8	32.3	8.4	73.4	51.4	686.3
	p	<0.001*	0.046*	0.180	<0.001*	0.004*	<0.001*	<0.001*	<0.001*
Intervention *Angle	F	1.0	--	--	--	--	--	--	--
	p	0.407	--	--	--	--	--	--	--

*indicates statistical significance at the $p<0.05$ level

INTERVENTION had a significant effect on each of the investigated muscles with the exception of the tricep. The mean normalized EMG (nEMG) values for each muscle and intervention are shown in Figure 3.3. The levels of intervention type that are not connected by the same letter were statistically different from one another. Thenar muscle activity was 20.0% greater with the harness than with the wide grip transducer. Use of the control transducer required 101%, 181%, and 285% higher FDI muscle activity than the use of the wide, cover, and harness transducers, respectively. Both the harness and wide transducers required significantly less flexor activity than the control. The mean flexor EMG value for the control was 11.1% and 9.57% higher than the same value for the harness and wide interventions. The cover resulted in the lowest extensor activity, followed by the harness and wide. The control extensor EMG data was 22.7% greater than the wide, 42.0% greater than the harness, and 77.6% greater than the cover. For both the deltoid and the trapezius, the use of the harness required significantly less muscle activity than the control with a difference of 45.2% and 53.3%, respectively.

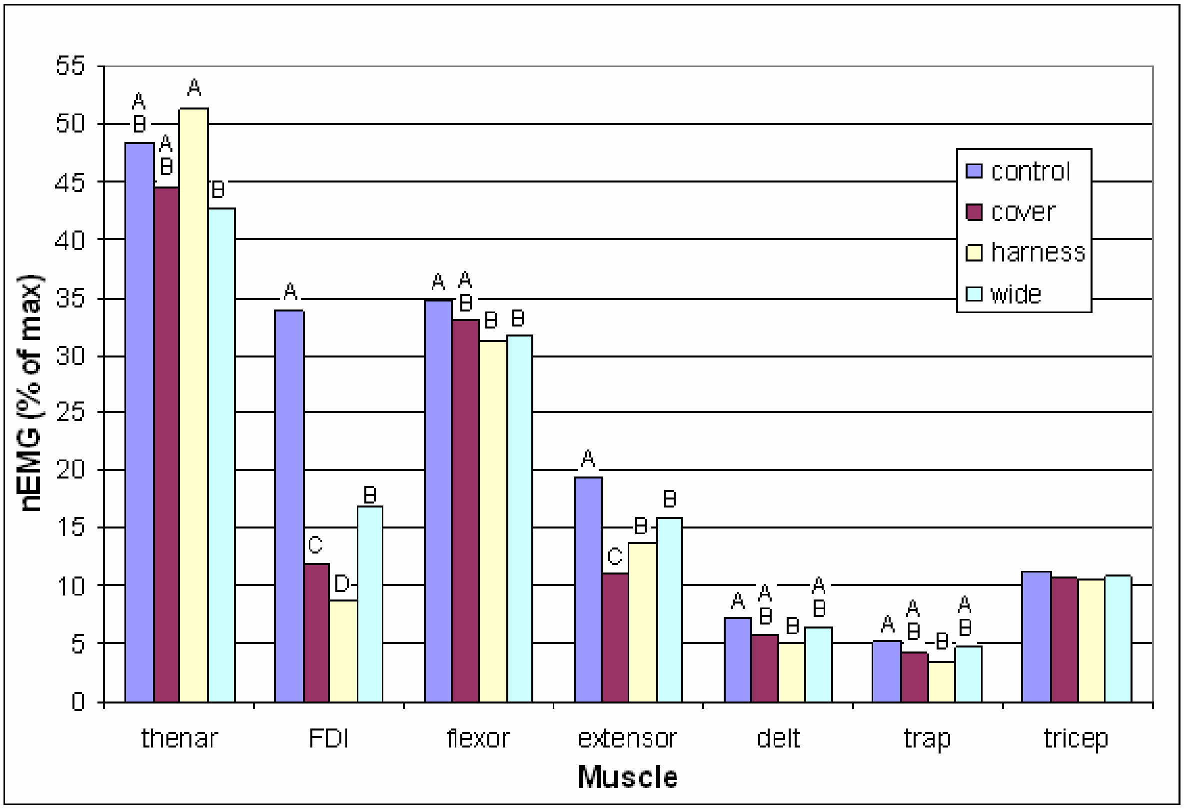


Figure 3.3. Effect of INTERVENTION on muscle activity (nEMG) for the obese patient experiment. Levels not connected by the same letter are significantly different at $p<0.05$.

The angle of the abdomen-like surface had a significant effect on the EMG activity for each of the muscles with the exception of the FDI. The mean nEMG values for each muscle and angle are shown in Figure 3.4. EMG activity was statistically greater at the 0 degree angle as compared to the 45 degree angle for the thenar, extensor, deltoid, and tricep muscles by 9.05%, 13.5%, 68.0% and 132%, respectively. The 45 degree position resulted in 17.0% and 64.9% higher muscle activity for the flexor and trapezius muscles than the 0 degree angle.

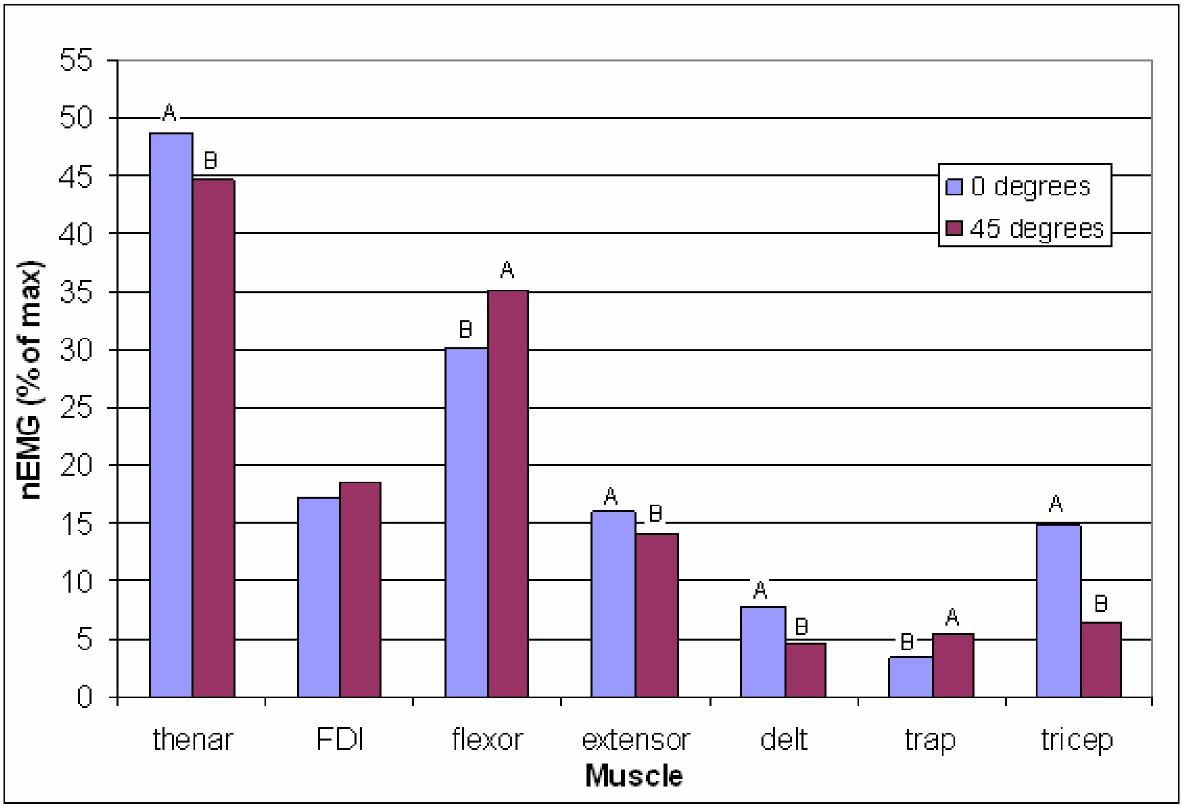


Figure 3.4. Effect of ANGLE on muscle activity (nEMG) for the obese patient experiment. Levels not connected by the same letter are significantly different at $p<0.05$.

3.3 Subjective Survey

The subject survey was given to each participant following the completion of all experimental trials. The first survey question asked the subject to rank the interventions and control transducer in order of preference (1 = most preferred transducer, 4 = least preferred transducer). The harness was the most preferred transducer with an average ranking of 1.33, followed by the cover (2.0), the wide (3.0), and the control (3.67). These results are shown below in Table 3.3.

Table 3.3. Interventions ranked by subjective preference (1 = most preferred transducer, 4 = least preferred transducer)

Subject	Intervention			
	control	cover	harness	wide
S01	4	3	1	2
S02	4	3	1	2
S03	4	1	2	3
S04	4	2	1	3
S05	3	2	1	4
S06	3	2	1	4
S07	3	1	2	4
S08	4	1	2	3
S09	4	3	1	2
Average	3.67	2.0	1.33	3.0

The second portion of the survey consisted of four discomfort surveys, one for each transducer. Three areas of discomfort were frequently reported: the hand (more specifically, the thenar and FDI muscle region), the shoulder (trapezius and deltoid), and the tricep. Discomfort was ranked on a scale of 1 (slight discomfort) to 10 (painful). The harness received the lowest discomfort scores for the hand and tricep areas, while the control resulted in the lowest average discomfort for the shoulder. The reported hand discomfort for the control transducer was more than twice the discomfort level for the transducer with the next highest score. The results are shown below in Table 3.4.

Table 3.4. Discomfort survey summary (ct = control, cv = cover, h = harness, w = wide)

Subject	hand (thenar & FDI)				shoulder (trap & delt)				tricep			
	ct	cv	h	w	ct	cv	h	w	ct	cv	h	w
S01	3	4	0	2	3	2.5	3	2	0	2	1	0
S02	8	2	1.5	0	0	0	0	0	6.5	4	2	3
S03	8	4	5	6	0	2	2	2.5	0	0	0	0
S04	6	0	1	0	0	0	0	0	3	1.5	1.5	1
S05	1.5	1.5	1	2.5	0	0	0	0	3	4	3	3
S06	6	4.5	3.5	4.5	4	4	3	4	0	0	0	0
S07	2	0	1	3	0	0	0	0	0	0	0	0
S08	3	0	0	0	0	0	0	0	2	2	1	2
S09	1	1	0	1	1	1	1	1	0	0	0	0
Average	4.28	1.89	1.44	2.11	0.89	1.06	1.00	1.06	1.61	1.50	0.94	1.00

4 Discussion

The main objective of this study was to design and evaluate different ultrasound transducer interventions as they compared to the current transducer design used in the sonography practice. Each intervention design was intended to reduce the high pinch grip forces by changing the posture of the hand and/or the way in which pressure was applied with the transducer. The experiment simulated the force application with the transducer for the ultrasound of both a normal-sized and an obese patient. Through the examination of the muscle activity of the upper extremity using EMG, both INTERVENTION and ANGLE were found to have a significant effect on a number of muscles for both the normal and obese patient experiments. While the evaluation of INTERVENTION was the primary goal, it was important to also consider ANGLE and determine whether it had an interaction with INTERVENTION because sonographers must examine the abdomen from a variety of angles.

4.1 Normal Patient Experiment

INTERVENTION had a significant effect on each of the muscles of interest of the hand and forearm. This indicates that the interventions influenced the grip of the transducer because the intrinsic and extrinsic hand muscles work together to form a grip (Kozin et al., 1999). At least one of the interventions significantly reduced muscle activity as compared to the control for each investigated muscle distal to the elbow, with the exception of the thenar muscle. Both the harness and the cover resulted in higher thenar muscle EMG data than the control. This may be explained by the change in direction of motion by the muscle when using these two interventions. The primary motion of the thumb is to adduct toward the fingers. The harness and cover, however, required a downward motion, rather than drawing the thumb inward. The cover fared better than the harness, perhaps because of the more rigid support of the thenar muscle with the cover ledge. While the difference is not statistically significant, the wide transducer reduced thenar muscle activity as it changed the pinch grip to a stronger power grip, as was shown in the Mirka et al. (2002) study. It is clear that the interventions reduced the pinch grip, as hypothesized, because the first dorsal interosseous (FDI), which provides much of the force required in a pinch grip (Kozin et al., 1999), was the muscle most affected by the use of the interventions. Use of the control transducer required 54%, 106%, and 194% higher FDI activity than the use of the wide, cover, and harness transducers, respectively. Again, the use of the wide grip transducer acted like the intervention in the Mirka et al. (2002) study, which also significantly reduced FDI activity. The use of the cover reduced the need to pinch to grip the transducer as intended because the subjects focused on pushing against the ledge for support instead, as instructed. The harness performed significantly better than the wide transducer and the cover in terms of FDI activity because, with the fingers directly attached, the need to grip the transducer was dramatically reduced. As far as the flexor muscle, only the wide grip transducer resulted in a significant reduction in EMG activity. The power grip, as used with the wide intervention, can generate substantially more force than a pinch grip, and, therefore, less flexor muscle activity is required to generate the same force as compared to the control (Rodgers, 1987; Bao and Silverstein, 2005; Grandjean, 1988). The use of the cover significantly reduced extensor muscle activity. The deltoid, trapezius, and triceps muscles were not significantly influenced by INTERVENTION in the normal patient experiment.

ANGLE significantly affected EMG activity of each muscle of interest, with the exception of the intrinsic hand muscles. It is reasonable to assume that the way in which the hand grips the transducer does not change much with the angle of the surface to which force is applied because the hand grip is a function of the transducer design. Therefore, ANGLE has little to no influence on the activity of the thenar and FDI muscles. However, the angle of the simulated abdomen surface obviously changes the angle of the upper arm, as seen in Figures 2.7 and 2.8, thereby affecting the muscle activity of the deltoid, trapezius, and tricep. Wrist movement, directed by the flexor and extensor muscles, must also change to adapt to different surface angles. The 45 degree angle calls for greater shoulder abduction, which has been identified as an occupational risk factor for sonographers in a number of studies (Russo et al., 2002; Murphy and Russo, 2000; Wihlidal and Kumar, 1997; Habes and Baron, 1999). The lateral deltoid is actively involved in shoulder abduction, explaining its increase in muscle activity for the 45 degree angle. When the simulated abdomen was positioned at 45 degrees, its height was elevated and the task required a slightly shrugged shoulder, unlike the more relaxed position with the 0 degree angle. Therefore, the trapezius, which is responsible for the lifting of the shoulder, was significantly more active at the 45 degree angle. The tricep was more active at the 0 degree angle as it is better positioned for elbow extension, the primary role of the triceps muscle. For the 45 degree angle, flexor activity was greater, indicating that the wrist was flexed further inward as the arm pulled the transducer against the "abdomen" and toward the body. The 0 degree angle, on the other hand, only called for a downward push. Because wrist flexion and extension are opposing actions, where flexor activity increased, extensor activity decreased.

4.2 Obese Patient Experiment

In the obese patient experiment, INTERVENTION had a significant effect on each muscle of interest, with the exception of the tricep. In addition to an increase in pressure from

5 mmHg to 12 mmHg, the obese patient experiment differed from the normal patient experiment in that ultrasound gel was added to the handle surface of the wide and control transducers to simulate the upward migration of gel during scans that require deeper pressure into the tissue. As seen in the results, the increased force requirement and extra gripping challenge with the gel increased EMG activity across all sampled muscles from the normal to the obese trials. For the thenar muscle, the only statistically significant difference was that between the wide grip transducer and the transducer harness, which required 20% more muscle activity. As with the normal patient experiment, this can likely be attributed to the less natural downward pull of the thumb in the harness. The wide transducer again performed better in terms of lower thenar EMG activity than the control due to the change from pinch to power grip, and the cover performed better than the control, in contrast to the normal patient experiment, likely due to the added difficulty in gripping with the gel. Aside from the tricep, which had no significant results, and the thenar muscle, every other studied muscle exhibited the highest activity with the use of the control. The single most significant result that can be taken from this study is the variation in FDI activity as a function of INTERVENTION in the obese patient experiment. Use of the control required 101%, 181%, and 285% more FDI activity than the use of the wide, cover, and harness transducers, respectively. This dramatic drop in the FDI EMG signal, like in the normal patient experiment, indicates a significant reduction in the hazardous pinch grip force, which was the primary goal of this research. Each intervention was significantly different from one another for the FDI muscle. To further support the hypothesis of a reduced pinch grip, both the harness and wide transducer significantly reduced activity of the flexor digitorum superficialis, and all three interventions significantly reduced the extensor digitorum activity, with the transducer cover

outperforming the others. These two extrinsic hand muscles are critical in the formation of a hand grip. A significant effect due to intervention was not expected for the other muscles in question, but the deltoid, trapezius, and tricep muscles were examined, nonetheless, because the upper arm and shoulder are very active during ultrasound scanning, and they have been frequently cited as areas of pain and discomfort (Murphy and Russo, 2000; Muir et al., 2004). The results revealed that the harness significantly reduced deltoid and trapezius activity as compared to the control transducer. This may mean that the straps across the top of the harness helped to deliver some of the downward force that would have otherwise been delivered by the shoulder, as was the intent of the design. On the other hand, this decrease in shoulder force may be attributed to the increased thenar activity exhibited by the harness. Overall, the harness demonstrated the greatest impact on the obese patient ultrasound task as it most reduced the activity of the FDI, flexor, deltoid, and trapezius muscles.

ANGLE had a significant effect on each investigated muscle in the obese patient experiment, with the exception of the FDI. Aside from the deltoid, the muscle responses as a function of ANGLE can be explained just as they were in the discussion of the normal patient experiment. The deltoid was more active at 45 degrees for the normal patient trials, while the deltoid was less active at the same angle for the obese patient trials. The normal patient trials required such low force that the primary action of the shoulder was abduction, for which the lateral deltoid is responsible. However, for the obese patient trials, the applied pressure was more than double that of the normal patient experiment, thereby requiring shoulder adduction, for which the deltoid is an antagonist muscle. Therefore, the shoulder adduction was controlled by a different, agonist muscle, likely the latissimus dorsi. The 0 degree angle, on the other hand, did not rely on shoulder adduction, and the deltoid activity was greater.

4.3 Subjective Survey

Subjects indicated their preferred intervention and areas of discomfort associated with each through the completion of a survey following the experiments. These subjective results tended to coincide well with the EMG results. The control, which frequently resulted in the highest activity for many of the muscles of interest, particularly in the obese patient experiment, was ranked the lowest in terms of personal preference. The harness was ranked the highest. The rankings followed the order set in the FDI data, which potentially provided the most significant result from the study. From lowest to highest FDI activity in both the normal and obese patient experiments, the interventions were listed as follows: harness, cover, wide, and control. This was also the order of the interventions in terms of preference, as well as, the order of discomfort ratings from lowest to highest for the hand, which included the thenar and FDI areas. However, the discomfort rankings were very close in value aside from the control, which resulted in hand discomfort more than twice the value of the next worst intervention. Other areas of discomfort noted in the survey were the shoulder (trapezius and deltoid) and the tricep, or upper arm, as seen in other studies (Murphy and Russo, 2000; Muir et al., 2004). These survey findings indicate that the activity of the first dorsal interosseous muscle is directly linked to intervention preference and the level of hand discomfort with a given transducer. As previously discussed, the FDI is critical in the application of the pinch grip, and a significant decrease in its activity shows that the pinch grip was successfully reduced. Decreases in the activity of additional muscles, including the forearm flexors and extensors, are added intervention benefits.

4.4 Design Recommendations

Based on the quantitative and subjective results of this study, it is clear that it is worthwhile to use ergonomic interventions with an ultrasound transducer to reduce upper extremity muscle activity and the risk of musculoskeletal pain or injury. However, the results also indicate that each of the intervention designs, with its strengths and weaknesses, has room for improvement.

While the harness was shown to decrease activity for the most sampled muscles as compared to the other interventions, its use may be the least feasible in its current design because, as it secures the fingers to the transducer, it limits hand movement and the ability to change hand grip. As a result, the wrist and arm would have to move more to compensate for the decreased mobility of the fingers, which was not a factor in the experiment as it was static. Due to the rectangular profile of the transducer, the harness is only useful when the transducer is held in one orientation, across the narrow dimension. The harness cannot easily be switched to the grip across the wider dimension of the transducer. And when the harness is moved to this orientation, the straps across the top have no value as they have no significant surface upon which to pull downward. However, this limited ability to change hand grip with the harness could be remedied if the intervention was coupled with a redesign of the shape of the transducer. A cylindrical handle would allow the harness to rotate more freely around the transducer to change the orientation of the scan head. Because the harness significantly increased the activity of the thenar muscle, perhaps some kind of ledge may be incorporated into the transducer design to better support this thumb muscle. Fabricated from elastic and nylon straps, the harness, while washable, cannot be easily wiped and sanitized between patients like the other interventions. New materials should be considered for the harness such that it can be easily sanitized or disposable. While the use of the harness in its current design has its flaws, it has an advantage over the other interventions in that it eliminates the need to grip and hold the transducer between exertions.

Additional design recommendations can also be made for the wide grip transducer and transducer cover interventions. The wide grip transducer was designed as a separate transducer in this study, but it could also be made as a cover over an existing transducer to avoid the high expense of purchasing a new ultrasound transducer. The cover intervention could be implemented in the field in its current design without the need to buy any new ultrasound equipment. Another recommendation is that the wide grip transducer and transducer cover be integrated into one intervention. The wide transducer has the advantage of creating a more elliptical and comfortable hand grip, and the transducer cover features the ledge for the application of a downward force. The ledge also prevents the slippery gel from reaching the hand of the sonographer. One potential design may even incorporate all three interventions with the use of the harness over a cylindrical handle cover with the diameter of the wide transducer and the support ledge of the transducer cover intervention.

4.5 Study Limitations

There are a number of limitations to this study ranging from the design of the experimental task to the feasibility of the use of the interventions in a real-life application. Sonography is an extremely versatile occupational practice with a plethora of variables to consider. No single sonographer performs ultrasound procedures the exact same way, and every single procedure is as different as the individual patient. As described in the Introduction, scanning is a very dynamic task requiring ever-changing wrist and arm movements and postures. With each motion of the transducer, the angle of the abdomen surface changes. The current study, in an attempt to create a controlled experiment and minimize confounding factors, ignored the dynamic aspects of ultrasound scanning and focused solely on the static postures also inherent in sonography. Because the main goal of the study was to evaluate INTERVENTION, ANGLE was added as an independent variable primarily to better simulate an ultrasound task and to determine whether an interaction existed between the two variables. It would not have been feasible or reasonable to evaluate the interventions at every possible angle.

Sonographers frequently change their hand grips as they manipulate and rotate the transducer to change its orientation. However, participants in this study were told explicitly how to hold each transducer to control variability that would invalidate results. The interventions were designed as modifications for one particular model of ultrasound transducer held in one orientation. It is not known whether these interventions would be suitable for different transducer orientations or for other transducer models. These limitations may be addressed with the design recommendations and further studies.

4.6 Future Research

The current study is unique in its application of design interventions to reduce the risk of upper extremity WMSDs associated with the use of an ultrasound transducer. Many studies have reported survey results of sonographers experiencing pain and discomfort due to work-related tasks, and some studies offer recommendations for improvement, but very few have evaluated the use of interventions. The only sonographer study (Murphey and Milkowski, 2006) found that employed EMG evaluated different sonographer scanning postures with adjustable equipment. Because the current study, focusing on transducer intervention effectiveness, is the first of its kind, there is much room for further research.

Improvements can be made to the intervention designs, particularly for the harness due to its limitations discussed in the previous section. Additional studies can be conducted to evaluate the interventions in a dynamic task that better simulates an actual ultrasound procedure. When the intervention designs have each been finalized for clinical use, they should be evaluated in the field by trained sonographers using both qualitative (e.g. surveys) and quantitative (e.g. EMG) measures.

5 Conclusion

Sonography is plagued with occupational risk factors for those performing the ultrasound procedures. Over 80% of sonographers experience work-related musculoskeletal symptoms. The gripping of the transducer, particularly with a pinch grip, has been linked to hand and wrist pain and discomfort and symptoms of carpal tunnel syndrome and other musculoskeletal disorders. The objective of this study was to design and fabricate ultrasound transducer interventions and evaluate their effectiveness in reducing the risk of upper extremity musculoskeletal disorders. The interventions were designed with the intent of reducing the pinch grip force. It was hypothesized that the transducer interventions would reduce the activity of the muscles of the upper extremity, primarily those of the hand and forearm as they are most engaged in the pinch grip. It was also expected that the subjects would prefer the interventions to the control transducer and would cite less pain and discomfort associated with their use.

The three transducer interventions and the control transducer were evaluated using electromyography (EMG) to determine their effect on the activity of seven muscles of the upper extremity while the subject was engaged in a simulated ultrasound scanning task. The subjects applied static pressure to an abdomen-like surface set at two different angles to better emulate a real ultrasound scan, where sonographers must manipulate the transducer at varying angles. The experiment was performed in two parts to meet differing conditions to simulate a scan on a normal-sized patient and on an obese patient, because patient size dictates the amount of force to be applied with the transducer. Following the normal and obese experimental trials, subjects completed a survey providing subjective feedback about each of the transducers.

A number of significant results were found in this study. Both independent variables, INTERVENTION and ANGLE, were significant in the normal and obese patient experiments, and there was no interaction effect. As hypothesized, the interventions significantly reduced the activity of several of the sampled muscles. Most notably, each intervention dramatically reduced muscle activity of the first dorsal interosseous (FDI), which provides much of the force in the pinch grip. The transducer harness, transducer cover, and wide grip transducer decreased FDI activity by 74%, 64%, and 50%, respectively, as compared to the control transducer, in the obese patient experiment. This indicates that the interventions effectively reduced the pinch grip force requirement as intended. These results were repeated subjectively in the survey in that the interventions were ranked ahead of the control transducer in this order. Coinciding with these results, subjects reported that the control caused the greatest pain and discomfort in the hand. While each of the interventions showed improvement over the control transducer, the harness may have performed the best, as its use significantly reduced the activity for the FDI (74%), flexor (10%), extensor (3.0%), deltoid (3.1%), and trapezius (3.5%) muscles in the obese patient experiment. However, the use of the harness also resulted in the highest thenar muscle activity and its design has some limitations. The transducer cover performed the best behind the harness as it significantly reduced muscle activity for the FDI and extensor by 64% and 44% in the obese patient experiment. But the wide grip transducer performed better than the cover for the thenar and flexor muscles in both experiments. With each intervention having its own strengths and weaknesses, the optimal transducer design approach may be to integrate different aspects of the three interventions into a new design. This research has demonstrated that ultrasound transducer interventions can effectively reduce upper extremity muscle activity and, thus, reduce the risk of WMSDs when the intervention design decreases the need to utilize a pinch grip.

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Appendices

Appendix A: Informed Consent Form

North Carolina State University
INFORMED CONSENT FORM for RESEARCH

Title of Study: Ergonomic Interventions for Sonographers
Principal Investigator: Kristen Meador Faculty Sponsor: Dr. Gary Mirka

We are asking you to participate in a research study. The purpose of this study is to evaluate how ultrasound transducer interventions affect the biomechanics of the upper extremity.
YOU MUST BE BETWEEN THE AGES OF 18 AND 65 to participate in this study.
Initial here___________ to indicate that you are over 18 and less than 65 years of age.

INFORMATION
If you agree to participate in this study, you will be asked to simulate an ultrasound scan, applying constant pressure with a handheld transducer. The procedure follows: (1) Anthropometric measurements, including weight, will be taken. (2) You will have sensors placed on different muscles of the thumb and hand, and forearm and shoulder. (3) You will be asked to push maximally against stationary surfaces/objects using each of the muscles of interest in order to measure their maximum contractions. (4) The experiment will consist of a short task with many trials and a longer task with only 2 trials. (5) For the short 7-second task, with 10-second rests between trials, you will exert a given pressure with the transducer at a given angle on a simulated abdomen. The trials will be performed at a lower pressure (5 mmHg) representing normal-sized patients and at a higher pressure (12 mmHg) for obese patients. Four transducer systems will be used for the short task; each performed at 2 angles. Each short task trial will be repeated 3 times for a total of 48 trials (4 transducers*2 pressures*2 angles*3 repetitions). (6) You will then perform the long task with the two of the transducer systems, to be randomly assigned. For the long task, you will apply the higher force to the abdomen for 5 minutes, resting for 10 seconds every 20 seconds. At the completion of both the short and the long experiments, you will be asked to fill out a short survey asking your impressions of the transducer systems. You will be videotaped during the tasks, and all videotapes will be destroyed upon completion of the study. None of the data collected will be associated with your identity.
RISKS
The scanning task may cause muscle fatigue and/or discomfort in the muscles of your hand, arm, shoulder, and neck. You should not participate in this experiment if you have any chronic problems or recent injury or pain in your shoulder, neck, arm, or hand. If you do not have any trouble with muscles and joints, please mark your initials here: _____.
There is some risk of skin irritation to people with very sensitive skin, even though all adhesive tapes used in the experiment are hypoallergenic. If you have very sensitive skin, please tell the researchers now. If you do not have such sensitivities, please mark your initials here: _____. Finally, you may experience some shoulder, neck, arm, and/or hand soreness for a couple days after the experiment similar to that felt after a strong workout.
BENEFITS
This experiment could benefit ultrasound technicians and other workers performing similar tasks by reducing the risk of developing upper extremity musculoskeletal disorders. Evaluating the effectiveness of various transducer interventions under different task conditions may lead to new design recommendations for ultrasound equipment.

CONFIDENTIALITY
The information in the study records will be kept strictly confidential. Data will be stored securely. You will be represented as a number in the test data that will in no way be linked to your identity. No reference will be made in oral or written reports which could link you to the study.

EMERGENCY MEDICAL TREATMENT
If you need emergency medical treatment during the study session(s), the researcher(s) will contact the University's emergency medical services at 515-3333 for necessary care. There is no provision for free medical care for you if you are injured as a result of this study.

Appendix A: Informed Consent Form

CONTACT
If you have questions at any time about the study or the procedures, you may contact the researcher, Dr. Gary Mirka at 919-515-6399. If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact Dr. David Kaber, Chair of the NCSU IRB for the Use of Human Subjects in Research Committee, Box 7514, NCSU Campus (919/515-3086) or Mr. Matthew Ronning, Assistant Vice Chancellor, Research Administration, Box 7514, NCSU Campus (919/513-2148)

PARTICIPATION
Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time. If you withdraw from the study before data collection is completed your data will be returned to you or destroyed at your request.

CONSENT
“I have read and understand the above information. I have received a copy of this form. I agree to participate in this study with the understanding that I may withdraw at any time.”

Subject's signature_______________________________________ Date _________________

Investigator's signature__________________________________ Date _________________

Appendix B: Subject Survey

Subject #____

Subject Survey

Following completion of the short scanning task trials, rank the interventions and control transducer in order of preference. (1 = most preferred transducer, 4 = least preferred transducer)

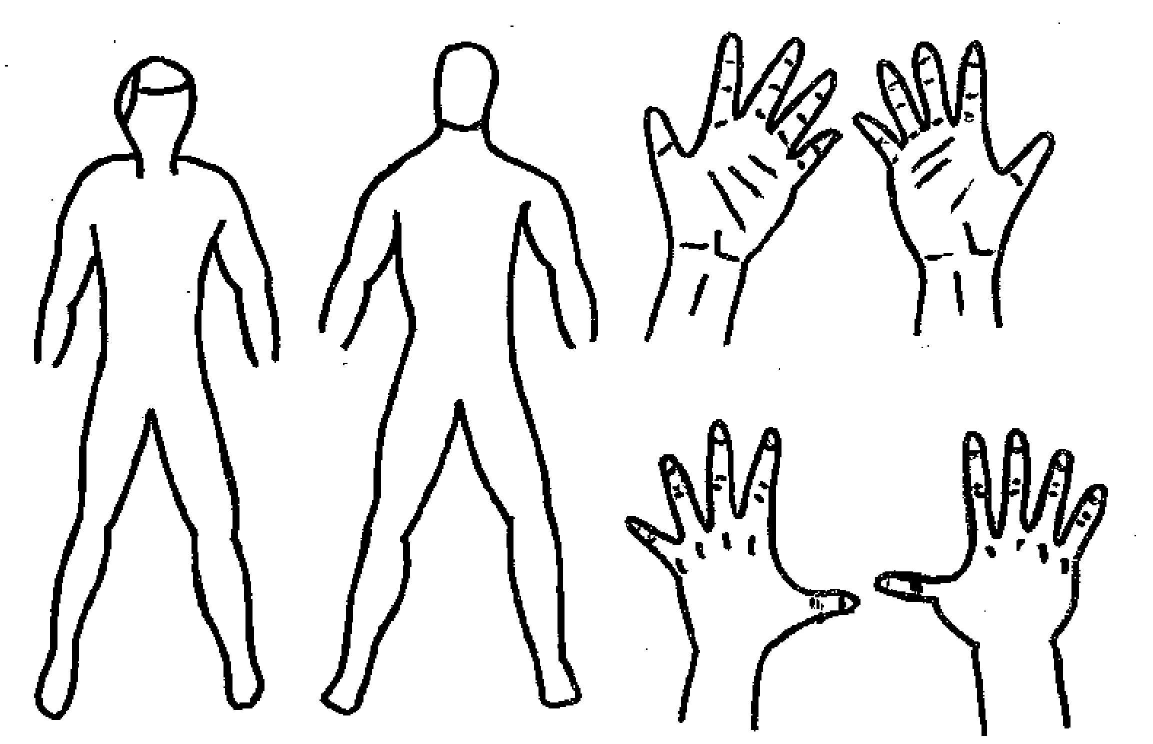
____ Control

____ Intervention 1 (Cover)

____ Intervention 2 (Harness)

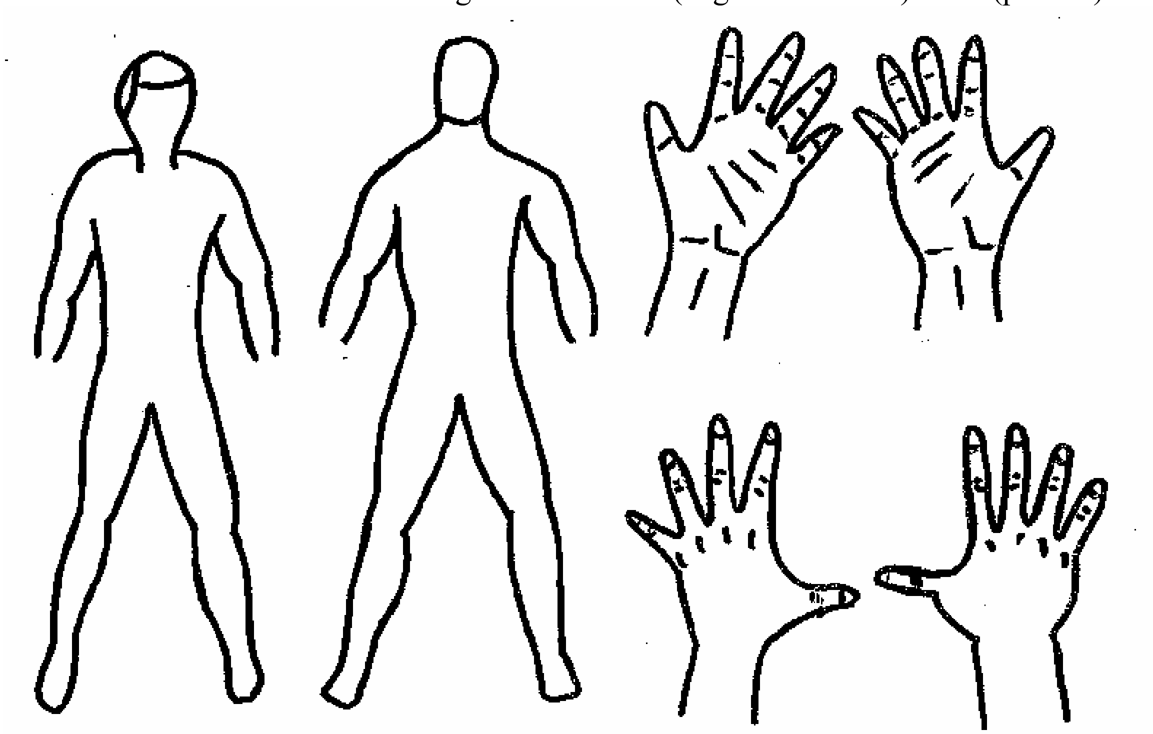
____ Intervention 3 (Wide)

Place an X on those areas where you felt discomfort while using the ***control*** transducer. For each of these X's rate the feeling on a scale of 1 (slight discomfort) to 10 (painful).

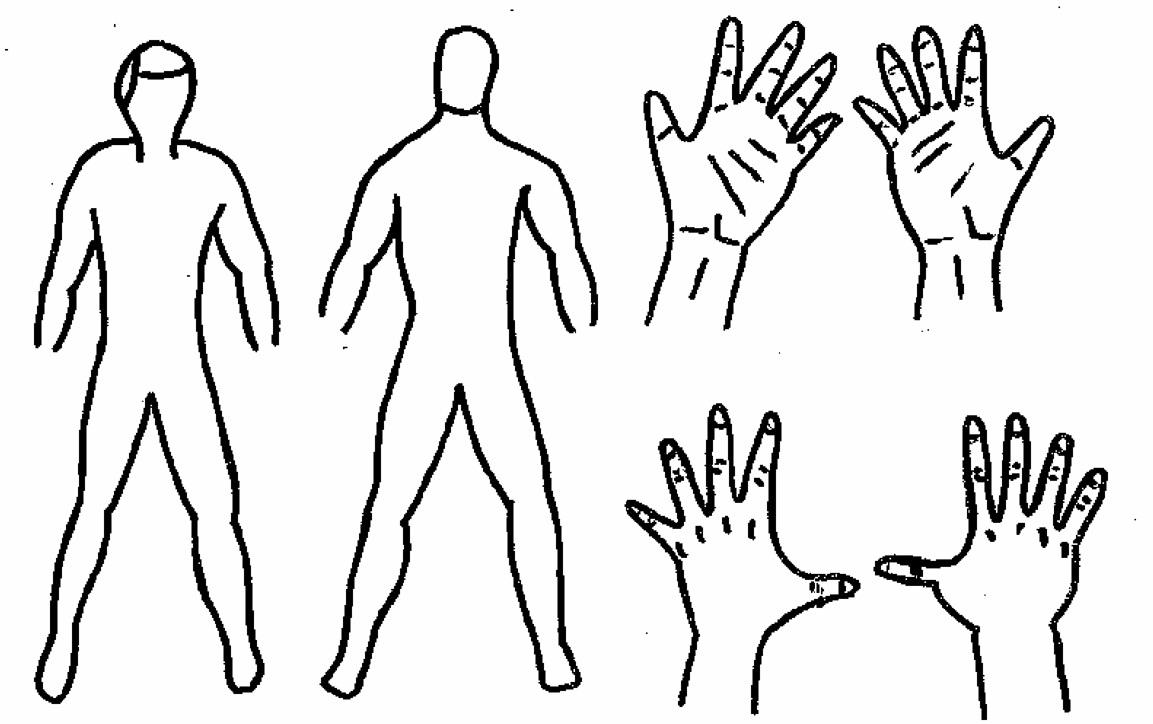


Appendix B: Subject Survey

Place an X on those areas where you felt discomfort while using the transducer with ***cover***. For each of these X's rate the feeling on a scale of 1 (slight discomfort) to 10 (painful).

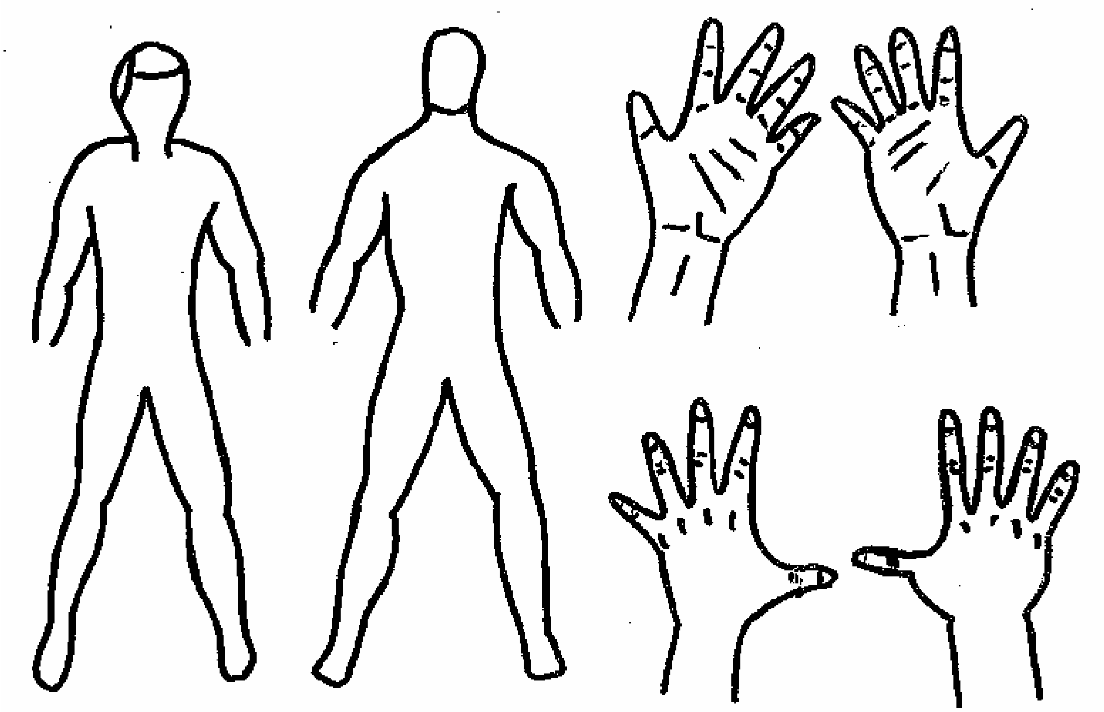


Place an X on those areas where you felt discomfort while using the transducer with ***harness***. For each of these X's rate the feeling on a scale of 1 (slight discomfort) to 10 (painful).



Appendix B: Subject Survey

Place an X on those areas where you felt discomfort while using the ***wide*** grip transducer. For each of these X's rate the feeling on a scale of 1 (slight discomfort) to 10 (painful).



Appendix C: Graphical Test Results of ANOVA Assumptions

Examples of the Test for Normality of Residuals

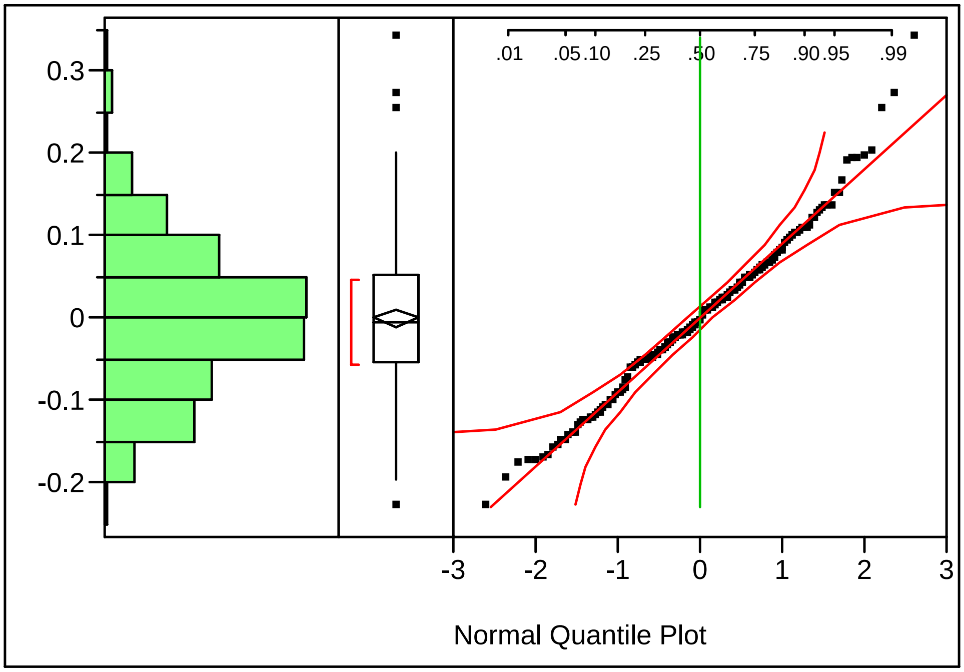


Figure 1. Normal quantile plot for the residuals of the thenar, normal patient experiment.

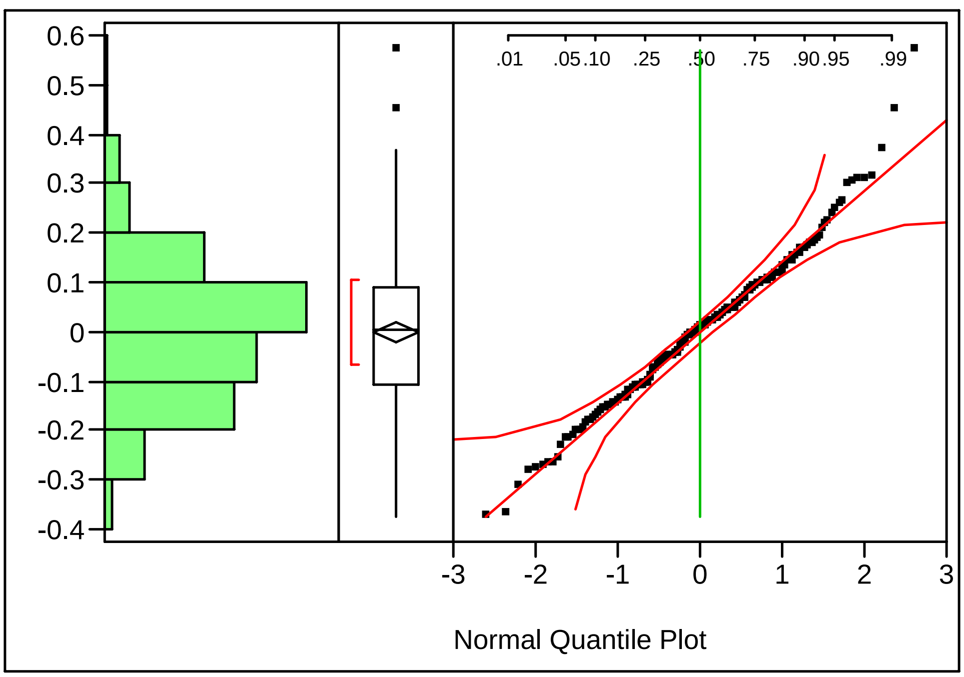


Figure 2. Normal quantile plot for the residuals of the thenar, obese patient experiment.

Appendix C: Graphical Test Results of ANOVA Assumptions

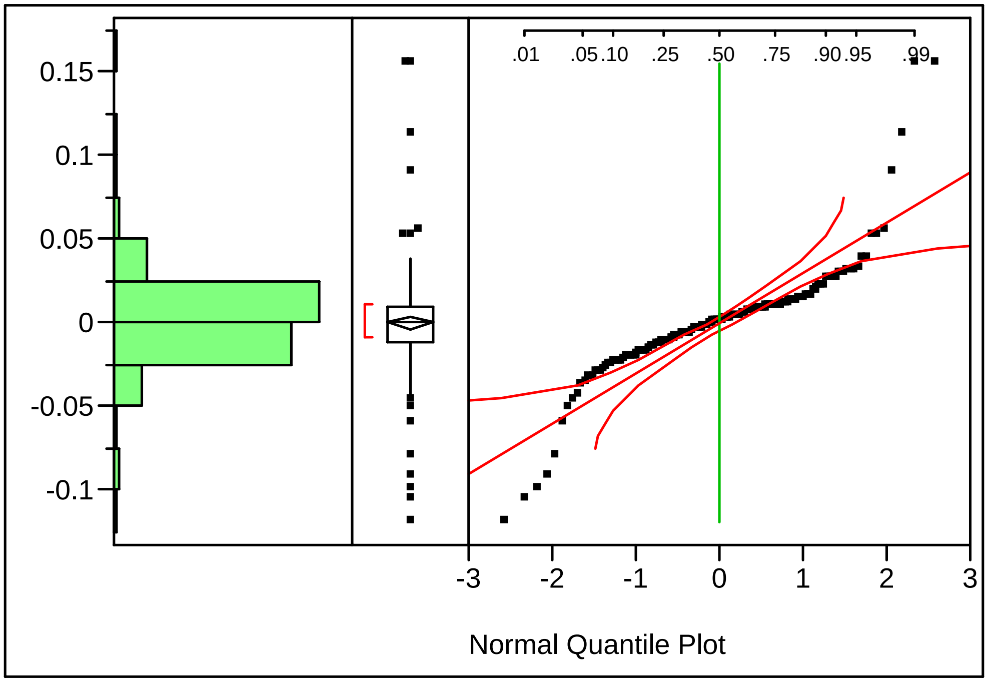


Figure 3. Normal quantile plot for the residuals of the tricep, obese patient experiment.

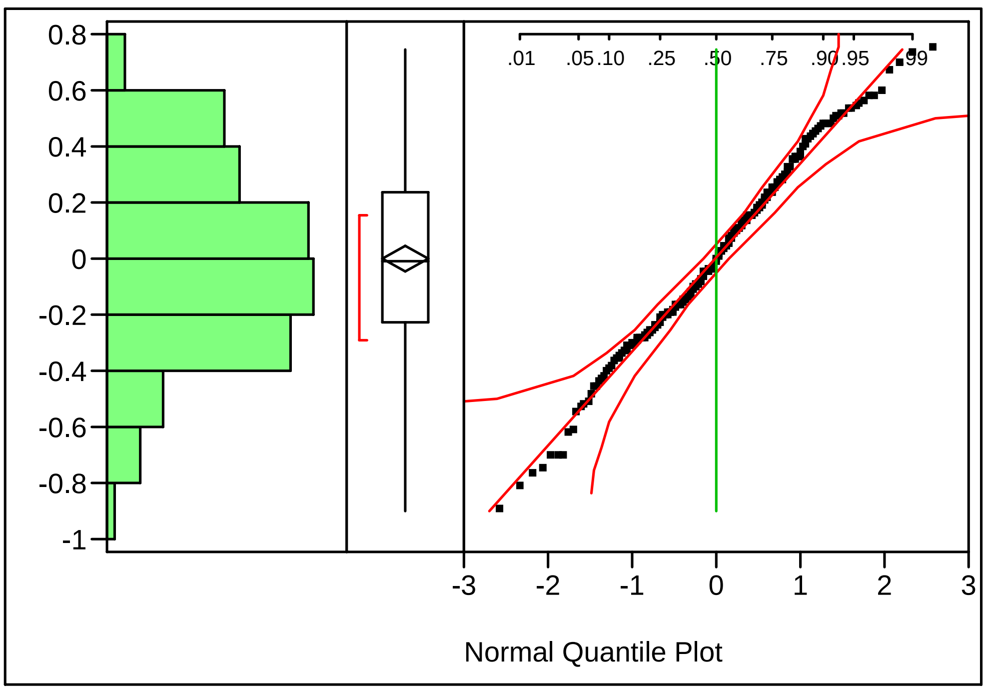


Figure 4. Normal quantile plot for the residuals of the tricep using the log transformation values, obese patient experiment.

Appendix C: Graphical Test Results of ANOVA Assumptions

Examples of the Test for Independence

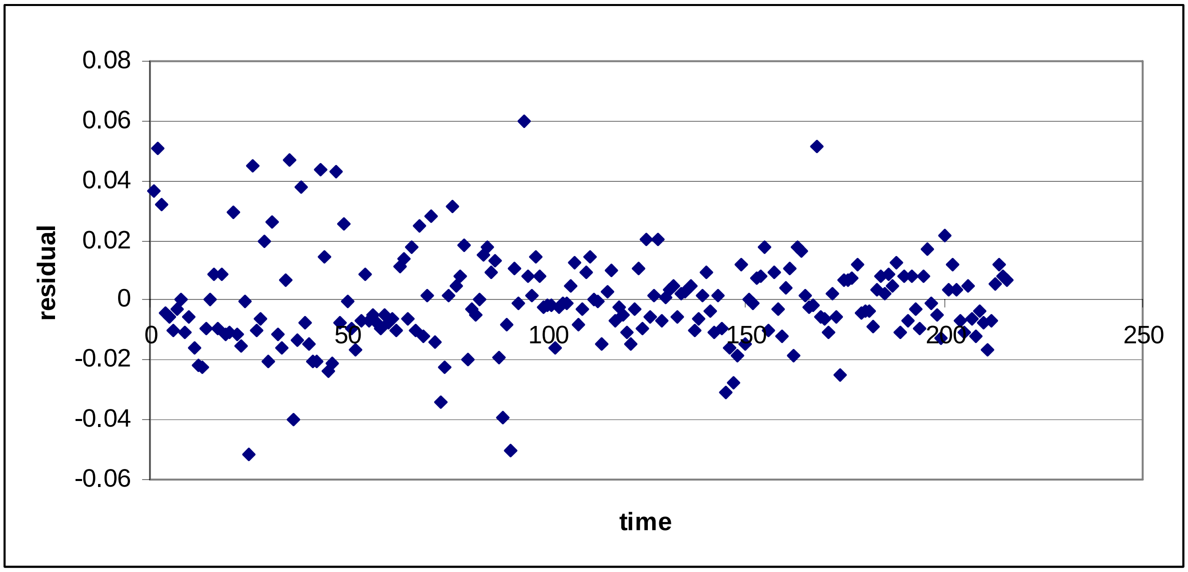


Figure 5. Scatter plot of the residuals for the deltoid as a function of time, normal patient experiment.

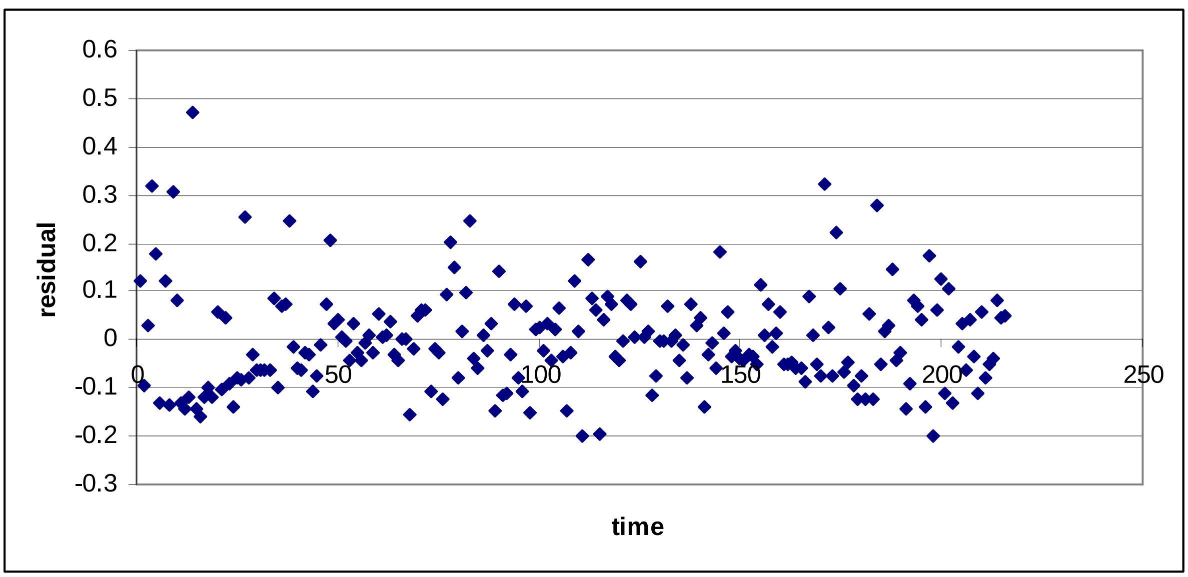


Figure 6. Scatter plot of the residuals for the FDI as a function of time, obese patient experiment.

Appendix C: Graphical Test Results of ANOVA Assumptions

Examples of the Test for Homogeneity of Variances

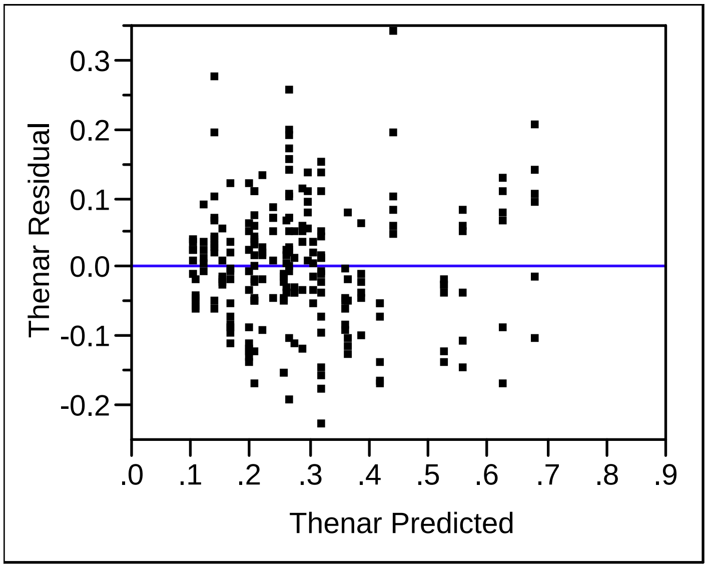


Figure 7. Scatter plot of the residuals as a function of the predicted values for the thenar, normal patient experiment.

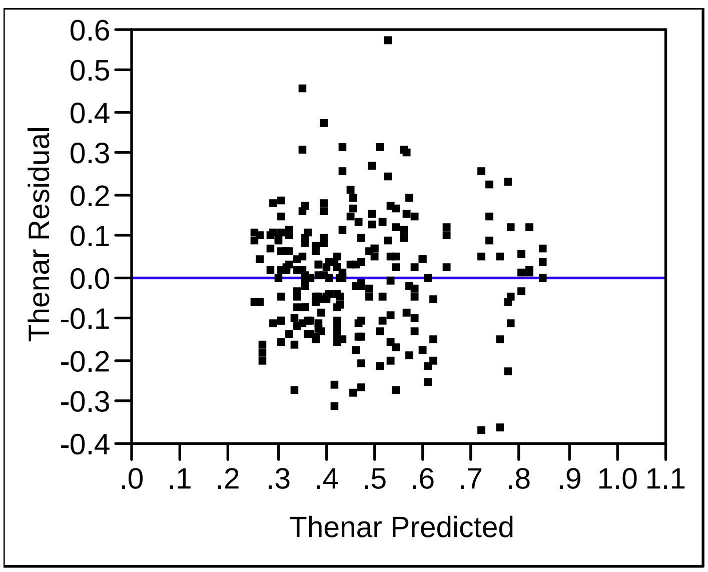


Figure 8. Scatter plot of the residuals as a function of the predicted values for the thenar, obese patient experiment.

Appendix C: Graphical Test Results of ANOVA Assumptions

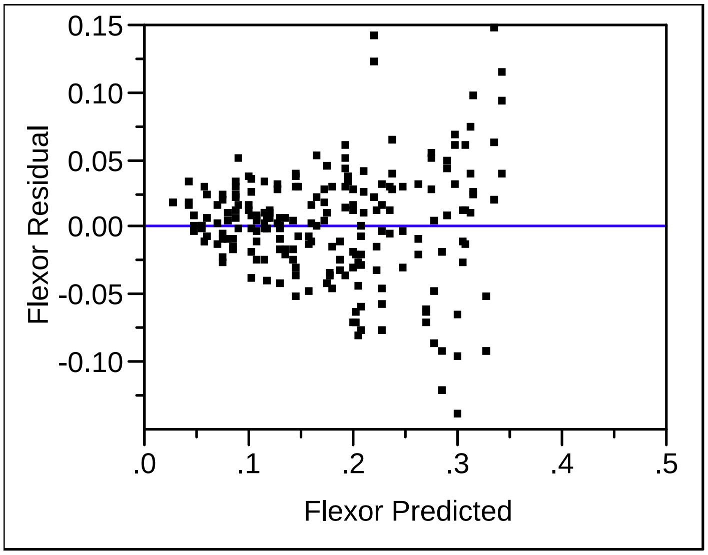


Figure 9. Scatter plot of the residuals as a function of the predicted values for the flexor, normal patient experiment.

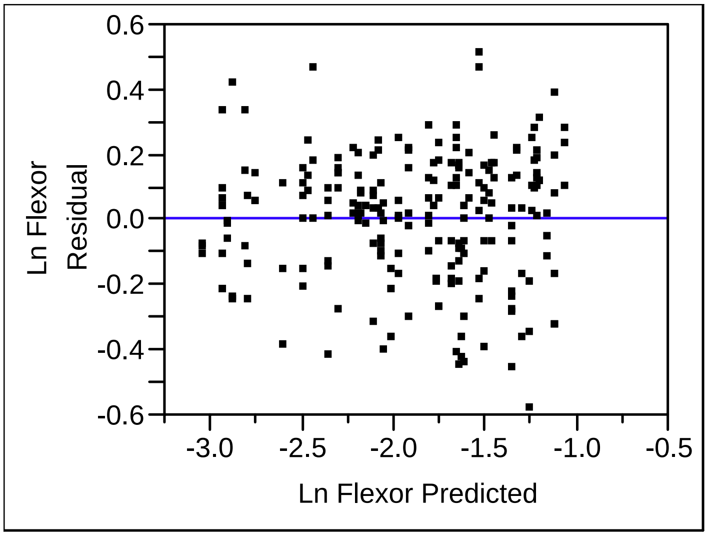


Figure 10. Scatter plot of the residuals as a function of the predicted values for the flexor using the log transformation values, normal patient experiment.

Appendix C: Graphical Test Results of ANOVA Assumptions

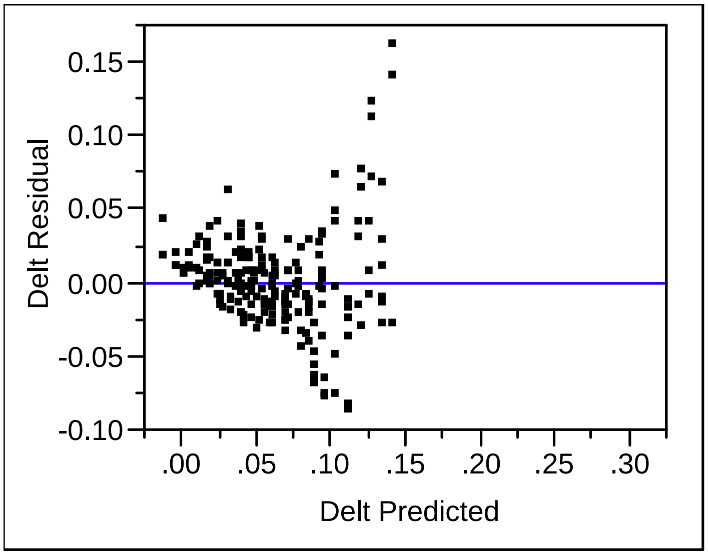


Figure 11. Scatter plot of the residuals as a function of the predicted values for the deltoid, obese patient experiment.

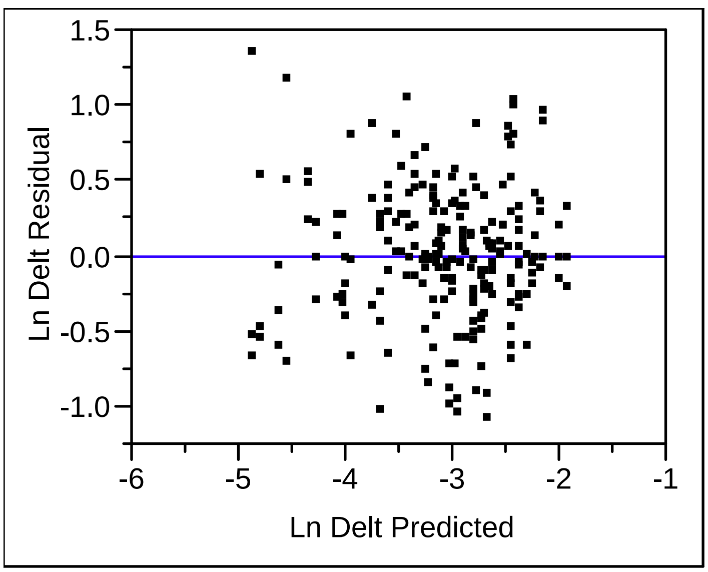


Figure 12. Scatter plot of the residuals as a function of the predicted values for the deltoid using the log transformation values, normal patient experiment.