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Use of Vibrotactile Feedback and Stochastic Resonance for Improving Laparoscopic Surgery Performance

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USE OF VIBROTACTILE FEEDBACK AND STOCHASTIC RESONANCE FOR IMPROVING LAPAROSCOPIC SURGERY PERFORMANCE

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Industrial and Human Factors Engineering

Submitted by

Robert Douglas Hoskins,
BS BME, Wright State University, 2000

2014
Wright State University
I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Robert D. Hoskins ENTITLED Use of Vibrotactile Feedback and Stochastic Resonance for Improving Laparoscopic Surgery Performance BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Industrial and Human Factors Engineering

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ABSTRACT


Vibrotactile feedback, used as sensory substitution for loss of haptic feedback, has been utilized to improve performance in manual control, teleoperation and during minimally invasive surgical tasks. Stochastic resonance (SR), introduced into the human control system as white noise at a sub-threshold level, has shown promise to improve the sensitivity of tactile receptors resulting in enhancement of performance for a variety of manual tracking and sensorimotor tasks. The purpose of this study was to determine if SR could improve performance (accuracy, speed) in a simulated laparoscopic palpation task and to compare it to vibrotactile feedback (VIB). It was hypothesized that both VIB and SR feedback would result in better performance over no feedback (Control). Furthermore, SR feedback was expected to lead to the greatest increase in performance by improving subjects' haptic sensitivity to tissue compliance and consistency.

A total of 16 subjects (10 female, 6 male) performed a palpation task using laparoscopic tools to detect the presence of tumors (compacted felt) embedded in simulated tissue samples (silicone gel) in a laparoscopic trainer box. Subjects were randomly assigned to one of three different conditions: (1) Control and SR, (2) Control and VIB, (3) Control and VIB+SR and (4) Control and Control. The control condition was performed before the vibration condition to set a baseline for performance as well as to account for carry-over effects related to vibrotactile
feedback and human performance. The vibrotactile feedback and SR vibrations were administered via two different haptic actuators attached to subjects’ dominant upper and lower arms, respectively. Each subject was presented 36 tissue samples (24 w/tumor, 12 non-tumor) in random order, under the control condition and then presented the same 36 samples in a different random order under the assigned vibration condition (SR, VIB, VIB+SR, Control), for a total of 72 tissue samples (48 w/tumor, 24 non-tumor). A maximum of 30 seconds was allowed for each trial. The dependent variables of accuracy and time to detection were measured.

Results show significant improvement over the control condition in accuracy with the Control-SR group only. A one-way ANOVA was performed on the delta accuracy and delta time values for each subject group and results show that the SR group performed significantly better than the VIB and VIB+SR groups in terms of improved accuracy (See Figure 1). Results for the time variable did not produce any significant effects, suggesting that SR increases accuracy in compliance differentiation, but not in the time needed to make a decision during the process.

The results have implications for the design of instruments and potential methods for increasing accuracy performance in minimally invasive surgical procedures such as in the case of tissue compliance differentiation. This technology could help surgeons better identify tumors located in healthy surrounding tissue.
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Chapter 1 – Introduction

1.1 Motivation

The invention of minimally invasive surgery (MIS), also known as endoscopic surgery, has revolutionized patient care and improved patient safety through higher quality health care delivery (Cuschieri & Buess, 1992). Laparoscopic surgery (LS) is a type of MIS performed by inserting Laparoscopic Instruments (LI) through trocars via small incisions, usually into the abdominal cavity. Since the first laparoscopic cholecystectomy (removal of gall bladder) was performed in the United States in 1988, LS has become the gold standard for cholecystectomy, splenectomy, adrenalectomy, etc. (Zhou, 2010). The primary benefits of LS over conventional open surgery are reduced postoperative pain, shorter postoperative hospital stays, and faster recovery time for the patient (Reddick et al., 1989). Similar mortality rates as compared with open surgical procedures have been reported in LS (Group & others, 2004).

Although the typical LS procedure is beneficial to the patient, it poses many limitations that increase the cognitive and physical load of the surgeons. This increase in cognitive and physical workload can consequently lead to avoidable errors to the detriment of the patient (Xin, Zelek, & Carnahan, 2006). One of the primary limitations is the lack of haptic feedback available during open surgery as well as the distortion of what haptic feedback is available in LS (Picod, Jambon, Vinatier, & Dubois, 2005). One
detriment to this lack of haptic feedback is that higher injury rates for laparoscopy, compared with open surgery, have been documented in the literature (Soper & Strasberg, 1995). A vast majority of these injuries are due to excessive force being applied to organs and tissues due to a lack of haptic force feedback. Lack of haptic feedback also impedes surgeons’ ability to differentiate the consistency or compliance of good tissue versus bad (Way et al., 2003). With experience, laparoscopic surgeons have learned to adapt to the reduced kinesthetic and tactile feedback by relying primarily on visual cues. However, this process of adaptation is time-consuming, error-prone, and costly in terms of patient safety (Perreault & Cao, 2006).

Previous research has focused on providing sensory substitution through the visual and/or haptic channel; however the surgeon’s visual channel is already being tapped through observation of the surgery space on a monitor as well as supervising the surgical team (Xin, Zelek, & Carnahan, 2006). One way of addressing the problem of loss of haptic perception in LS procedures has been through the use of vibrotactile force feedback. Recent studies have shown that force feedback in the form of mechanical vibrations applied to the surgeon's skin using haptic actuators can increase accuracy performance as well as confidence (Schoonmaker & Cao, 2006; Zhou & Cao, 2009). Another potential solution to the haptics problem in LS is to amplify the existing haptic information available to the surgeon's hands as the laparoscopic instruments interact with tissues and organs (Bholat, Haluck, Murray, Gorman, & Krummel, 1999). Research has shown that these existing haptic signals can be used to provide the surgeon with physical
property information about the tissues such as compliance, texture and consistency (Bark et al., 2013; McMahan et al., 2011).

Stochastic resonance (SR), introduced into the human control system as white noise at a sub-sensory level, has shown promise to improve the sensitivity of somatosensory receptors resulting in enhancement of performance for a variety of manual tracking and compliance differentiation tasks. SR is essentially the use of a weak (sub-threshold) noise signal with a broad frequency band to increase the signal to noise ratio (SNR) of a non-linear system such as the human nervous system (Collins, Chow, Imhoff, & others, 1995). SR effects have been shown in a myriad of experiments to enhance human performance from increased sensitivity of tactile stimuli to significantly improved performance on sensorimotor tasks (Liu et al., 2002; Mendez-Balbuena et al., 2012).

There is little evidence in existing literature that investigates the use of SR in more complex human-machine systems such as teleoperation or MIS procedures such as laparoscopy and robotic assisted laparoscopic procedures. The aim of this literature review and subsequent research is to investigate the efficacy of the use of SR for the purpose of improving system and operator performance in the context of MIS using a laparoscopic palpation task. This will be accomplished through use of sensory augmentation techniques (vibrotactile feedback, SR) in the design of a haptic interface to allow enhanced tracking and differentiation performance. Investigation is warranted based on evidence from previous human performance studies (Mendez-Balbuena et al., 2012; Repperger, Phillips, Berlin, Neidhard-Doll, & Haas, 2005) and the documented need for improved accuracy in MIS/LS procedures (Soper & Strasberg, 1995; Way et al., 2003).
1.2 Minimally Invasive Surgery

Conventional open surgery (OS) requires that the surgeon manually reach the organ that is the target of the procedure being performed. To achieve this goal, the relevant body cavity must be incised and laid open, assisted by metal retractors (Cuschieri & Buess, 1992). Palpation becomes critical in open surgery, allowing surgeons to safely move inside the surgical site and manipulate tissues or organs. This makes it relatively easy to gain information concerning the physical properties of the tissues such as compliance, consistency and texture through the haptic channel. The sterile gloves worn by the surgeon, do however present some impediment to important haptic information such as temperature and fine texture by placing a barrier between the mechanoreceptors of the glabrous skin of the palmer aspect of the hand and the tissue being examined. Nonetheless, gloved hands still allow valuable haptic information to be gathered concerning tissue properties. After the procedure, the body cavity must be sutured closed and tissues repaired, which can result in a long postoperative recovery for the patient.

The advent of minimally invasive surgery (MIS), also known as endoscopic surgery, has revolutionized patient care and improved patient safety through higher
quality health care delivery (Cuschieri & Buess, 1992). MIS has become a common medical approach and the preferred alternative to open surgery in many procedures. MIS spans a wide spectrum of existing surgical specialties, which includes laparoscopic, thoracoscopic, endoluminal, perivisceral endoscopic, intra-articular joint surgery, and combined procedures and techniques (Cuschieri & Buess, 1992).

1.3 Laparoscopic Surgery

Laparoscopic surgery (LS) is a type of MIS performed by inserting Laparoscopic Instruments (LIs) through trocars via small incisions into the abdominal cavity. Since the first laparoscopic cholecystectomy or gall bladder removal was performed in the United States in mid-1988 (Reddick et al., 1989), LS has become the standard for cholecystectomy (Soper, Barteau, Clayman, Ashley, & Dunnegan, 1992-A), splenectomy (Friedman, Fallas, Carroll, Hiatt, & Phillips, 1996), adrenalectomy (Smith, Weber, & Amerson, 1999), etc. The primary benefits of LS are reduced postoperative pain, shorter postoperative hospital stays, and faster recovery time for the patient (Reddick et al., 1989; Soper, Barteau, Clayman, Ashley, & Dunnegan, 1992-B). One key factor driving the push for LS is that accumulated trauma on the patient is reduced drastically due to minimal access wounds and avoidance of exposure, cooling, handling and forced retraction of internal organs. Patient recovery and
convalescence are greatly accelerated as a result of the reduction in overall trauma experienced by the patient (Cuschieri & Buess, 1992).

Laparoscopic surgery and other forms of MIS can be viewed as a basic form of teleoperation where the human operator (surgeon) is working in a remote environment (patient’s body) with a communication link. In the case of a laparoscopic procedure, the surgeon has both a physical link (instruments) and a visual communication link via the camera instrument. Similarly, robotic minimally invasive surgery (RMIS) is teleoperation where the surgeon loses the physical link but still has a visual communication link via the control console of the surgical robot. Both MIS and RMIS require a verbal communication link to be present between the surgeon and the rest of the operating team.

Regardless of the scenario, as the distance between the operator and the work environment increases the task being performed via teleoperation becomes more complex due to the communication deficits and the load it puts on the person performing the task. Even though people are adaptable and able to perform under selective sensory deprivation by relying on other sensory channels, there is a limit to the information processing capacity that allows them to compensate in this way and MIS is no exception (Zhou & Cao, 2009). Improving the quality of the information provided and efficiency at which it is utilized by the human sensory channel(s) is a just one of the challenges of working in remote environments.
1.3.1. Challenges in Laparoscopic Surgery

Although the typical LS procedure is beneficial to the patient, the minimal access nature poses many physical and thus perceptual limitations that increase the cognitive and physical workload of the surgeons. This increase workload can consequently lead to avoidable errors that can be a detriment to the patient’s wellbeing (Xin, Zelek, & Carnahan, 2006). The remote workspace and environment for LS is very different from that of open surgery which can pose many access and sensory challenges to surgeons. The remote nature of the surgical manipulations and lack of manual handling and palpation greatly reduce the amount of available information related to physical properties of tissue and organs. Along with the distorted haptic feedback, which is extremely important to the surgeons in the evaluation of the local pathology and orientation, these issues are a detriment to surgeons (Cuschieri & Buess, 1992). In an open abdominal operation, for example, the surgeon simultaneously observes his/her hands, the instruments, and the operative field with normal stereoscopic vision (Xin, Zelek, & Carnahan, 2006). In LS, an image of the operating environment is obtained by inserting an endoscopic camera into the body cavity, which is displayed on a 2-dimensional video monitor. The surgeon views his/her operating environment indirectly and performs the surgical tasks bimanually using instruments extended into the patient’s body cavity through trochars inserted into the initial small incisions (Xin, Zelek, & Carnahan, 2006).
Changes in the laparoscopic image views are typically controlled by an assistant and not the surgeon, which introduces inefficiency in the form of unnecessary verbal communication. If the assistant cannot properly anticipate the surgeon's needs, then some form of information exchange needs to occur which in turn puts unnecessary load on that communication channel.

1.3.2. Perceptual Limitations in Laparoscopic Surgery

The minimal access to the surgical site in LS produces reduced and distorted haptic feedback from the long stemmed instruments (Picod, Jambon, Vinatier, & Dubois, 2005). The distortion of haptic feedback in laparoscopic surgery is due to several factors related to instrumentation. First, the tools are long, placing the surgeons’ hands at a distance from the actual surgical site. The mechanisms that transmit action and reaction are inefficient, allowing slop and dampened interaction forces (Xin, Zelek, & Carnahan, 2006). Second, the instruments are inserted into the body cavity through ports or trochars, which contain friction seals that fit tightly around the instruments to maintain air pressure within the body cavity. These seals distort force feedback and interfere with accurate proprioception of how forcefully a surgeon presses with the instrument (Zhou & Cao, 2009). Third, the small ports constrain the movement of the instruments to only four degrees of freedom (three rotations and in-out translation), as opposed to six (three translations and three rotations about the axes), and levering actions are mostly caused due to the fulcrum effect (Xin, Zelek, & Carnahan, 2006). It is clear that these factors all
contribute to haptic feedback distortion, resulting in degraded performance which can in turn lead to detriments to patient safety.

Another class of perceptual limitations involves the visual channel. One of the most prominent is the reduction in the surgeon’s depth perception. This is mostly due to the loss of stereopsis or a disruption of normal binocular vision which occurs when viewing a 3-dimensional surgical space on a 2-dimensional monitor. Distorted hand-eye coordination due to reduced degrees of freedom of motion can also present perception problems in LS (Cao, MacKenzie, & Payandeh, 1996). The environmental factors associated with LS that contribute to the distortion of hand-eye coordination are; location of the monitor, variable amplification, mirrored movement, and misorientation (Wentink, 2001). The location of the monitor in LS impairs hand-eye coordination because the surgeon cannot see his/her hands and the operative field simultaneously which causes orientation and coordination difficulties (Xin, Zelek, & Carnahan, 2006).

1.3.3. Importance of Haptics working with Vision in Laparoscopic Surgery

In laparoscopic surgery, haptic feedback and vision work together to allow differentiation of tissue properties and sense interaction in surgery (Tholey, Desai, & Castellanos, 2005). Vision can be used to differentiate tissues according to their color, position, and depth, while haptics can be used to differentiate them with respect to their compliance and texture (Tholey, Desai, & Castellanos, 2005). In laparoscopic surgery,
the surgeon may be forced to process all information exclusively through the visual channel (Zhou, 2010). Not only is it inefficient and imprecise to process ordinary haptic information through visual working memory, but the effort to do so may also overload the limited resources for visual and spatial tasks (Baddeley, 1996). Relying on vision could also lead to errors during the surgery. For example, adipose tissue may appear consistent and healthy but in fact may have a cancerous tumor which is identified by an inconsistent compliance. The lack of haptic feedback can cause a surgeon to miss the tissue inconsistency and thus miss the tumor identification because he/she cannot feel its abnormal compliance. The presence of visually obscured but haptically sensed anatomy (i.e., hidden under fatty tissue or other structures) may also provide clues about incorrect positioning or unexpected arteries (Zhou, 2010). Thus, the potential for errors and injuries is increased with a reduction in the quality and availability of haptic feedback.

In a relevant study, Greenwald et al. concluded that participants were significantly more accurate and more efficient at the detection of tumors in simulated tissue samples using their unrestricted finger as compared to using a stick-like surgical tool also unrestricted, and using surgical tool restricted by its insertion through a trocar as in LS. The authors also concluded that participants were also better at detecting harder tumors as compared to softer ones (Greenwald, Cao, & Bushnell, 2012). These results directly identify the core of the “haptics problem” in laparoscopic surgery which is; “how do we provide the surgeon with quality haptic feedback related to tissue properties and which sensory channel do we use to deliver it to the surgeon in a way it can be useful?”
Previous research has focused on providing sensory substitution through the visual and/or haptic channel; however the surgeon’s visual channel is already being tapped through observation of the surgery space on a monitor as well as supervising the surgical team (Xin, Zelek, & Carnahan, 2006). One way of amending the problem of inappropriate force usage and thus errors in LS procedures has been through the use of vibrotactile force feedback. Recent studies have shown that force feedback in the form of mechanical vibrations applied to the surgeon's skin using haptic actuators can increase accuracy performance as well as confidence (Schoonmaker & Cao, 2006; Zhou & Cao, 2009). Another potential solution to the haptics problem in LS is to amplify the existing haptic information available to the surgeon’s hands as the laparoscopic instruments interact with tissues and organs (Bholat, Haluck, Murray, Gorman, & Krummel, 1999). Along the same lines lies another solution which might be to increase the sensitivity of mechanoreceptors in the surgeon’s hands which are responsible for receiving haptic information. Therefore, the weakened mechanical vibrations which are a result of LS tool and tissue interaction can be perceived by the ultra-sensitized receptors. Research has shown that these existing haptic signals can be used to provide the surgeon with physical property information about the tissues such as compliance, texture and consistency (Bark et al., 2013; McMahan et al., 2011). The following literature review will first focus on defining the importance of haptic feedback in LS and then discuss potential methods for increasing the quality of information which can be pushed through the haptic channel to allow surgeons to perform laparoscopic surgery more effectively and efficiently.
Chapter 2 – Literature Review

2.1 Role of Haptic Feedback in Laparoscopic Surgery

The role of haptic feedback in LS is of special interest because it is used in important decision-making scenarios such as the discrimination between healthy tissues and those that are abnormal due to disease as in the case of a tumor. Laparoscopic surgeons must learn, through practical experience, to perceive and manipulate the operative site with tools that have limited dexterity and inability to provide proper haptic feedback related to tissue properties. Haptic feedback permits exploration and detection of disease in structures that cannot be readily visualized (Bholat, Haluck, Murray, Gorman, & Krummel, 1999). Interpretation of haptics permits the surgeon to apply appropriate forces to facilitate dissection and manipulation, while avoiding excessive force that can result in injury. This results in the successful treatment of disease, while avoiding damage to surrounding structures (Bholat, Haluck, Murray, Gorman, & Krummel, 1999).

2.2 The Effect of Reduced Haptic Feedback on Surgical Performance

With experience, surgeons who routinely perform laparoscopic procedures have learned to adapt, to a limited extent, to the reduced kinesthetic and tactile feedback by relying primarily on visual cues (Bholat, Haluck, Murray, Gorman, & Krummel, 1999;
Plinkert, Baumann, Flemming, Loewenheim, & Buess, 1998). The process of empirical adaptation is time-consuming, error-prone, and costly in terms of patient safety. Furthermore, it puts surgeons that are new to laparoscopy at a disadvantage due to a lack of objective methods for obtaining the proper information needed to make decisions in the operating room. One of the major detriments to surgeons is that this type of adaptation requires them to process much of the relevant information through the highly overloaded visual channel which is not ideal for texture and compliance perception (Perreault & Cao, 2006; Klatzky, Lederman, & Reed, 1987). Though surgeons have learned to judge site interactions, tissue properties, and contact pressure in the endoscopic environment largely by visual observation of the tissue, Klatzky et al. indicated that vision cannot entirely substitute for touch (Klatzky, Lederman, & Matula, 1993). In another study, Smyth & Waller showed that the visual modality was the most efficient modality for spatial information, such as shape and size, while the haptic modality was best utilized for force and texture information (Smyth & Waller, 1998).

One detriment to this lack of haptic feedback is that higher injury rates for laparoscopy, compared with open surgery, have been documented in the literature (Soper & Strasberg, 1995). A vast majority of these injuries are due to excessive force being applied to organs and tissues due to a lack of haptic force feedback. Lack of haptic feedback also impedes surgeons’ ability to differentiate the consistency or compliance of good tissue versus bad (Way et al., 2003). In a study that looked at common injuries during laparoscopic cholecystectomy (removal of gall bladder), Way et al. suggest that the misidentification of biliary anatomy in laparoscopic surgeries stems principally from
haptic misperception. Way and colleagues believe that loss of haptic perception is the most significant contributor to such errors, and that the restoration of haptic cues might help guide the surgeon to the cystic duct when it was otherwise difficult to see or identify (Way et al., 2003). Although many researchers have documented injury data related to laparoscopic surgery, a lack of thorough understanding of how haptic perception and feedback affect laparoscopic performance still exists (Zhou, 2010). Furthermore, compared to visual and other perceptual limitation factors, haptics has not been systematically investigated in the context of the laparoscopic remote environment (Zhou, 2010).

2.3 Restoring Haptic Perception in Laparoscopic Surgery

Even though surgeons are adaptable and able to perform under selective sensory deprivation by relying on other sensory channels, there is a limit to the information processing capacity that allows them to compensate in this way (Bholat, Haluck, Murray, Gorman, & Krummel, 1999). Regardless of adaptation, there is still great interest in restoring haptic feedback in LS. In reviewing the existing literature, there emerge four main methods for accomplishing the task of restoring haptic feedback: 1. Mechanical approach, 2. Use of tactile sensors, 3. Master-slave systems / sensorized tools and 4. Sensory substitution.
The earliest attempts to restore haptic feedback in LS were in testing several mechanical efficiency designs that were deflectable endoscopic graspers used to detect contact forces on the grasper using membranes (Jackman et al., 1999; Melzer, Kipfmuller, & Halfar, 1997). The major flaw of these instruments is that their use results in degraded dexterity when compared to conventional laparoscopic graspers (Jackman et al., 1999; Melzer, Kipfmuller, & Halfar, 1997). This mechanical efficiency approach was also applied to the design of laparoscopic instruments with low-friction forces as well as rolling link mechanisms which were designed to transmit movements and forces with a high degree of mechanical efficiency (Herder, Horward, & Sjoerdsma, 1997; van der Pijl & Herder, 2001; Kuntz, 1995). However, the surgeons haptic sensitivity is still reduced compared to bare hands but better than conventional minimally invasive surgery instruments (den Boer et al., 1999).

Several studies also show positive results where the researchers used tactile sensors to restore haptic feedback in laparoscopic surgery. Tactile sensors can be classified as force-torque sensors and array tactile sensors, as well as the tactile sensors that specifically restore capabilities such as palpation, artery detection and compliance detection (Dario, 1991). The literature reveals different designs such as; sensors that record tool-tissue forces and display output as a graphical representation, a piezoelectric sensor that enables hardness differentiation, as well as a polyvinylidene fluoride (PVDF) tactile sensing system with only three sensing elements (Scilingo, De Rossi, Bicchi, & Iacconi, 1997; Omata, Murayama, & Constantinou, 2004; Dargahi, 2000).
Many researchers have attempted to use PHANToM, which is a commercially available personal haptic interface mechanism, in various ways with mixed results (Hu, Castellanos, Tholey, & Desai, 2002; Tholey, Desai, & Castellanos, 2005; Wagner, Stylopoulos, & Howe, 2002). The general objective of these devices is to create the illusion of contact with a rigid virtual object using programmable constraint forces supplied to an end-effector such as a handle or stylus (Brooks, 1990). These applications are usually implemented in minimally invasive robotic surgery with a master-slave system and are typically more bulky and technically complex when compared to other solutions. The main advantage of this system is that it compensates for problematic loss of degrees of freedom in conventional laparoscopic surgery (Gersem, Brussel, & Tendick, 2005).

2.4 Sensory Substitution via the Visual & Haptic Channels Concurrently

Providing sensory substitution feedback through the visual and haptic channels is the fourth way of amending the problem of the absence of valuable haptic cues and thus errors in LS procedures (Bholat, Haluck, Murray, Gorman, & Krummel, 1999). Along these lines a study by Brydges, Carnahan & Dubrowski showed the improved accuracy of subjects in estimating roughness of various objects when presented with both visual and haptic cues (Brydges, Carnahan, & Dubrowski, 2005). This demonstrated that both modalities working in unison provides more usable information than each of them alone and without the other present. In a recent pair of experiments by Ottermo et al. fifteen
subjects were asked to discriminate hardness and size of objects (rubber balls hidden in pig's intestine) using three different palpation methods which were: (1) with gloved fingers, (2) with conventional laparoscopic instruments, and (3) with a laparoscopic instrument with a sensor array attached to its end-effector. When sensory information was available to the sensor array, it was presented visually to the surgeon on a screen. The experiments showed that the gloved fingers are better at differentiating hardness and size compared with conventional laparoscopic instruments and the instrument with sensor, which is not surprising. The researchers also concluded that there was no significant difference between conventional instruments and the instrument with sensor and visual array (Ottermo et al., 2006). This lack of significant difference in performance indicates that visual presentation may not be an ideal way of presenting tactile information. Similar research was conducted by Cao et al. to examine the relative importance of haptic force feedback, visually augmented force feedback, and six degrees of freedom in laparoscopic surgery. Results showed that increased degrees of freedom for manipulation was more important than force feedback; and that visual force augmentation enhanced performance only when haptic force feedback was also available (Cao, Webster, Perreault, Schweitzberg, & Rogers, 2003). A similar conclusion was held by Tavakoli, Patel & Moallem in a study concerning haptic feedback and its augmented substitution in a telemanipulated suturing task (Tavakoli, Patel, & Moallem, 2005a). Seven subjects participated in the suturing experiments on 3 different artificial tissue samples made of foam material but with varied durometers. In each trial of each test and for each tissue sample, the contact forces between the instrument and the tissue were recorded for subsequent analysis. Four different tests were conducted in which, in addition to the
camera vision, subjects received various forms of sensory feedback (visual, haptic, etc.) about the interaction between the instrument and the tissue. Results showed that for a 1-DOF task on soft tissue and for a short period of time, visual force feedback could provide sufficient feedback of an instrument’s contact with tissue. Furthermore, visual force feedback could outperform force feedback only in terms of exerting less force on the tissue, however it was determined that supplying both visual and force feedback at the same time could be better than providing force feedback alone (Tavakoli, Patel, & Moallem, 2005a).

2.5 Sensory Substitution through the Haptic Channel

Several studies conducted in the past twenty years have investigated the use of a vibrotactile sensor as an artificial sense of touch (Plinkert, Baumann, Flemming, Loewenheim, & Buess, 1998; Baumann, 2001; Schoonmaker & Cao, 2006). One study showed that the introduction of this artificial tactile sense to minimally invasive procedures can enable the surgeon to differentiate between critical anatomical structures, as well as normal and pathological tissues (Plinkert, Baumann, Flemming, Loewenheim, & Buess, 1998). Furthermore, the technology has the potential to reduce complication rates in MIS and possibly expand its range of indications (Plinkert, Baumann, Flemming, Loewenheim, & Buess, 1998). In another study Bauman et al. set out to test a prototype electromechanical vibrotactile sensor that was integrated into an oral tissue probe such that the operator receives indirect feedback on the tactile properties of the tissue. The
researchers then examined freshly resected carcinoma of the oropharynx and took ex vivo measurements using the prototype sensor which measured the mechanical impedance of tissue being probed. The impedance magnitude was output to the vibrotactile device by modulating the resonance frequency. The trial demonstrates the possibility of differentiating between carcinoma, healthy mucosa and carcinomatous-infiltrated mucosa. Subsequent in vivo measurements in the oropharynx and oral-cavity regions of 20 human subjects confirmed these results. Bauman concluded that in the oral cavity, tumours of > 1 cm diameter could be distinguished from the surrounding mucosa using vibrotactile feedback (Baumann, 2001).

The literature shows successful use of vibrotactile stimulation to augment an overloaded visual channel or a deficient sensory mode of the human operator in aviation, land navigation, and visual search application areas which warrants investigation into its application in MIS (Lindeman, Yanagida, Sibert, & Lavine, 2003; Van Erp & Van Veen, 2004; Van Veen & Van Erp, 2001). In a 2006 study, Schoonmaker et al. designed a vibrotactile force feedback system and studied its ability to provide useful force information to subjects performing a simulated MIS task when placed against the bottom surface of the foot (Schoonmaker & Cao, 2006). Results show that the system is a viable solution to providing haptic information concerning tissue compliance as it responded as predicted and subjects were able to perceive a linear increase in force as linear increase in vibration amplitude intensity. Furthermore, vibrotactile force information increases one's sensitivity to tissue contact and significantly improves subjects' ability to consistently and accurately differentiate tissue compliance in a simulated MIS task. They concluded that vibrotactile force feedback in MIS appears to have benefits which can lead to a decrease
Another study by Zhou et al. sought to investigate the relative contribution of multiple modulation parameters of a vibrotactile device to haptic augmentation during a laparoscopic palpation task (Zhou & Cao, 2009). A controlled experiment was conducted to explore the potential usefulness of a wearable vibrotactile sensory device capable of delivering force information to surgeons through the modulation of several vibration signal parameters (amplitude, frequency, duty-cycle, or their combinations), for the performance of a palpation task. Results indicate that vibrotactile sensory augmentation results in better performance accuracy, confidence and force applications with each additional signal parameter modulation. However, triple parameter modulation is not better than double parameter modulation which may be due to a redundancy effect (Zhou & Cao, 2009). Zhou's results suggest that palpation can be improved by implementing a vibration device that is capable of multi-dimensional modulation. However, the design of the vibration device should balance the advantage of providing additional information for effective information transmission with that of signal redundancy and complexity (Zhou & Cao, 2009).

2.6 Interpretation of LS Tool Vibrations

Surgeons once believed that the use of minimally invasive techniques eliminated haptics altogether and thus the ability to sense the tactile and kinetic properties of an object (Minnard et al., 1998; Plinkert, Baumann, Flemming, Loewenheim, & Buess,
1998; Scott & Darzi, 1997). Although surgeons cannot directly touch the internal organs and tissues, previous research has shown that some valuable haptic feedback is actually present during LS (Bholat, Haluck, Murray, Gorman, & Krummel, 1999). Research conducted by Bholat et al. was designed to determine whether haptic feedback is present when laparoscopic instruments (LI) are used, and to compare the amount of information available with that which is present during conventional surgery. The researchers hypothesized that both visual and haptic cues give rise to reliable information about physical properties of tissue and that it is unlikely that tasks like delicate dissection, as performed during a laparoscopic procedure, could be performed in the complete absence of haptic information (Bholat, Haluck, Murray, Gorman, & Krummel, 1999). In the experiment, researchers presented several objects with varied physical properties to twenty surgeons who were presented all objects in a random order. The participants were blinded as to the identity of the objects. Inspection by direct palpation, conventional instruments, and laparoscopic instruments was performed on all objects. The results showed that direct palpation was associated with the highest accuracy for shape identification and was superior to both conventional instruments and laparoscopic instruments, which is not surprising considering the conclusions of previous studies into the key differentiators between open and laparoscopic surgery (Cuschieri & Buess, 1992). Results also showed that texture analysis with either a conventional instrument or a laparoscopic instrument was superior to direct palpation. Finally, the three methods of analysis were comparable for consistency analysis (Bholat, Haluck, Murray, Gorman, & Krummel, 1999). Bholat et al. were able to conclude that the data indicates that laparoscopic instruments do, in fact, provide surgeons with haptic feedback and that they
can be useful in the interpretation of the texture, shape, and consistency of objects (Bholat, Haluck, Murray, Gorman, & Krummel, 1999).

In a related study by Brydges et al., twelve naive participants used either their index finger or a laparoscopic instrument to explore sandpaper surfaces of various grits (60, 100, 150 and 220). These movements were generated with either vision or no vision. Participants were asked to estimate the roughness of the surfaces they explored. The normal and tangential forces of either the finger or instrument on the sandpaper surfaces were measured. Results showed that participants were able to judge the roughness of the sandpaper surfaces equally when using both the finger and the LI. They were able to conclude that with the instrument, texture was sensed through vibrations of the instrument in the hand (Brydges, Carnahan, & Dubrowski, 2005).

In another related study, Bark et al. concluded that haptic feedback in laparoscopic surgery also encompasses the high-frequency vibrations that occur during tool-mediated interactions, as when one lightly drags a stick along a rough stone surface (Bark et al., 2013). These vibrations are measured by the skin’s Pacinian corpuscles (fast-adapting type II mechanoreceptors) (Johnson, 2001; Kontarinis & Howe, 1995) which are actually nerve endings in the skin that are responsible for sensing vibration and pressure. Their key function is to enable humans to detect and understand contact between the glabrous skin of the hand and a grasped object (Johansson & Flanagan, 2009). Haptic recreation of these high-frequency vibrations has been shown to increase performance in dexterous manipulation tasks and enhance the perceived realism of robotic teleoperation.
interfaces (Kontarinis & Howe, 1995; McMahan, Romano, Abdul Rahuman, & Kuchenbecker, 2010). Given the importance of these existing tool vibrations, McMahon and Bark developed a system to provide naturalistic high-frequency vibration cues during robotic minimally invasive surgery (RMIS) (Bark et al., 2013; McMahan et al., 2011). Their preliminary work with MIS box-trainers showed that surgeons performing MIS tasks significantly preferred having this feedback and believed that it helped them concentrate on the task (Bark et al., 2013; McMahan et al., 2011).

The research of McMahan et al. and Bark et al. along with Bholat et al. all-together make the argument for measurement and study of LS tool vibrations to characterize tissue properties (compliance, texture, consistency, etc.). It is possible that these existing vibration signals can be augmented or purposed for providing haptic feedback information about tissue properties in MIS. However, most of the existing literature shifts focus towards applying this concept to RMIS for the purpose of restoring tactile cues. It is the opinion of the author that it is worthwhile to apply these concepts to manual LS to increase the amount of information obtainable through the haptic channel and consequently increase performance measures and reduce errors.

2.7 Enhancing Existing Haptic Feedback

Another potential avenue for relieving the overloaded visual channel by increasing the amount of haptically sensed tissue information in laparoscopy is to
augment existing tool vibrations. These are vibrations caused by tool to tissue interaction that were identified by Bholat et al. and later researched by McMahan et al. and Bark et al. for their application in RMIS. In essence, these are signals in the form of mechanical vibrations resulting from the interaction between the end effector of the LI with tissue that is being palpated. In signal processing research, a phenomenon known as “Stochastic Resonance” has been used to enhance or amplify weak aperiodic signals in non-linear systems (Wiesenfeld, Moss, & others, 1995; Collins, Chow, Capela, & Imhoff, 1996; Gluckman et al., 1996). Stochastic resonance (SR) typically occurs in non-linear systems such as the human nervous system and can been used to enhance the signal to noise ratio (SNR) such that weak or borderline sub-threshold signals become supra-threshold. In theory, SR could be used to enhance the mechanical vibrations received from the LI by the surgeon’s hands such that the signal contains information about the tissue being probed that can be utilized haptically. Along the same lines lies another solution which might be to increase the sensitivity of mechanoreceptors in the surgeon’s hands which are responsible for receiving haptic information. Research by Collins, Imhoff & Grigg demonstrates such improvements in human sensory perception (Collins, Imhoff, & Grigg, 1997). In their study the researchers use an optimal level of noise to induce SR and the results show that the ability of an individual to detect a sub-threshold tactile stimulus can be significantly enhanced by introducing a particular level of noise. Similarly, in our MIS application the often weak mechanical vibrations which are a result of LS tool and tissue interaction could potentially be perceived by the ultra-sensitized receptors (Collins, Imhoff, & Grigg, 1997).
2.8 Stochastic Resonance

The term "Stochastic resonance" (SR) is now broadly defined as any phenomenon where the presence of noise in a nonlinear system is better for output signal quality than its absence (McDonnell & Abbott, 2009). That is, the application of noise to the nonlinear system increases the signal to noise ratio (SNR) to allow for a better output signal in terms of quality of information it contains. SR in terms of the human control system or nervous system is the process where a signal that is normally too weak to be detected by the peripheral nervous system (nerves, ganglia, mechanoreceptors, etc), can be boosted by adding a non-zero level of electrical or mechanical noise to the signal, which contains a wide spectrum of frequencies (Kurita, Shinohara, & Ueda, 2011; Mendez-Balbuena et al., 2012). The frequencies in the white noise corresponding to the original signal's frequencies will resonate with each other, amplifying the original signal while not amplifying the rest of the white noise ("Stochastic Resonance," 2014). This action increases the SNR which makes the original signal more prominent. This phenomenon of boosting undetectable signals by resonating with added white noise can be found in many other systems such as biological and physiological (Moss-2004).

2.8.1. SR Background

Since its discovery by Benzi et al. in 1981 (Benzi, Sutera, & Vulpiani, 1981), the SR effect has been observed and applied in numerous nonlinear systems (Gammaitoni,
According to the literature Douglas et al. first described SR effects in the nervous system as occurring in crayfish mechanoreceptors in the early 1990s (Douglass, Wilkens, Pantazelou, & Moss, 1993). This was followed by Levin and Miller's discovery of SR in the cricket cercal sensory system (Levin & Miller, 1996). Collins et al. and Ivey et al. demonstrated SR effects in the rat cutaneous mechanoreceptors, thus showing that SR also plays a role in the mammal nervous system (Collins, Imhoff, & Grigg, 1996; Ivey, Apkarian, & Chialvo, 1998). The first psychophysical studies with human subjects concluded that application of noise increased subjects' sensitivity to sub-threshold tactile stimuli (Collins, Imhoff, & Grigg, 1997). These reports motivated the analysis of SR on tactile evoked potentials in humans and cats (Manjarrez, Rojas-Piloni, Méndez, & Flores, 2003; Martínez, Pérez, Mirasso, & Manjarrez, 2007). SR effects have been shown not only in the somatosensory, but also in visual and auditory systems (Simonotto et al., 1997; Jaramillo & Wiesenfeld, 1998) and in the human cutaneous systems in general (Fallon & Morgan, 2005). Cordo et al. demonstrated that SR improved the afferents sensitivity to Golgi tendon organs and secondary muscle spindles in feline subjects, which was in line with an earlier study on human muscle spindle receptors (Cordo et al., 1996). The science and investigation into SR is relatively new with the majority of the body of existing research occurring within the last twenty years (Benzi, Sutera, & Vulpiani, 1981; Kurita, Shinohara, & Ueda, 2013).
### 2.8.2. Improved Human Sensorimotor Performance

The premise of SR is counterintuitive as conventional logic would reveal noise or any exogenous disturbance as a detriment to system performance. However, it has been shown in the literature that the addition of an optimal level of sub-sensory white noise (mechanical or electrical) to the human control system produces performance advantages (Collins et al., 2003; Repperger, Phillips, Berlin, Neidhard-Doll, & Haas, 2005; Mendez-Balbuena et al., 2012). SR introduced into the human control system as Gaussian white noise at a sub-sensory level, has shown promise to improve the sensitivity of somatosensory receptors and thus improve motor precision in manual tracking and differentiation tasks (Mendez-Balbuena et al., 2012; Repperger, Phillips, Berlin, Neidhard-Doll, & Haas, 2005; Kurita et al., 2011). One possible explanation for this improvement in motor precision is an increase of the peripheral receptors sensitivity and of the internal SR occurring in the central nervous system, resulting in a better sensorimotor integration and an increase in corticomuscular synchronization (Mendez-Balbuena et al., 2012). Regardless of the nature of the stimulus (electrical, mechanical), size of application area as well as location of the applied stimulus, the literature suggests performance enhancement for a variety of tasks when SR effects are induced in the human somatosensory system (Collins et al., 2003; Mulavara et al., 2011; Collins, Blackburn, Olcott, Yu, & Weinhold, 2011; Mulavara et al., 2011).
2.8.3. Methods for Inducing SR in Human Subjects

There are several different methods found in the literature for inducing SR effects in the human nervous system. The sub-sensory stimulus can either be electrical or mechanical in nature and effects can be induced regardless of where the stimulus is introduced (Collins et al., 2003; Mulavara et al., 2011; Collins, Blackburn, Olcott, Yu, & Weinhold, 2011). A majority of the literature reviewed applied sub-sensory mechanical noise via tactors or other actuators by way of embedding them in foot orthotics or another type of platform that interfaced with the plantar surface of the subjects' feet. (Collins, Imhoff, & Grigg, 1997; Cloutier et al., 2009; Priplata, Niemi, Harry, Lipsitz, & Collins, 2003; Zhou et al., 2013). Other studies have utilized a sub-sensory electrical stimulus to the temporal lobe to induce SR in the vestibular system which has been shown to improve balance performance when standing on a force plate (Mulavara et al., 2011).

2.8.4. Tactile Response and Balance Improvement

The majority of human performance studies in the literature investigate the role of SR in increased tactile sensation (Collins, Imhoff, & Grigg, 1997; Cloutier et al., 2009), improved balance control (Priplata, Niemi, Harry, Lipsitz, & Collins, 2003; Mulavara et al., 2010) and joint stability (Collins, Blackburn, Olcott, Yu, & Weinhold, 2011). Many of these human performance studies show significant improvement in subjects afflicted
with neurological disorders such as poly-neuropathy and stroke (Liu et al., 2002; Priplata et al., 2006).

2.8.5. Attenuation of Vibrotactile Adaptation

The findings in the literature suggest that the application of a tactile-proprioceptive noise can improve the stability in sensorimotor performance and potentially attenuate adaptation effects to vibrotactile stimuli via stochastic resonance (Mendez-Balbuena et al., 2012; Liu et al., 2002). In a study involving older subjects, subjects with stroke, and subjects with diabetic neuropathy Liu et al. found that, in general, the magnitude of the noise mediated reduction in detection threshold varied from subject to subject, however the SR-type effect was not attenuated over the course of the trials and there were no apparent learning or adaptation effects to the protocol, the repeated vibration stimuli or the mechanical noise signals (Liu et al., 2002). Results from their research suggest that mechanical noise used to induce SR has the potential to attenuate the adaptation to vibrotactile signals reported in vibrotactile research (Tannan, Simons, Dennis, & Tommerdahl, 2007; Gescheider, Frisina, & Verrillo, 1979).
2.8.6. Tracking Tasks and Target Aiming

In a human performance study involving a tracking task, Repperger et al. concluded that the application of an optimally tuned level of noise to the test apparatus significantly improved performance in human subjects. Based on the findings of Repperger, et al. and other human performance studies (Repperger, Phillips, Berlin, Neidhard-Doll, & Haas, 2005), Mendez-Balbuean et al. conducted experiments with a simplified controlled motor task involving the index finger of human subjects. The findings suggest that the application of a tactile-proprioceptive noise can improve stability in sensorimotor performance via stochastic resonance (Mendez-Balbuena et al., 2012). Kurita et al. conducted five separate experiments with human subjects using a wearable sensory motor enhancement device based on SR principles which delivered sub-sensory mechanical stimuli to the finger tip. The tests included both sensory and motor skills based tasks. The results of the study confirmed that the application of appropriate vibrations enhanced the tactile sensitivity of the fingertip and significantly improved sensorimotor performance (Kurita, Shinohara, & Ueda, 2011; Kurita, Shinohara, & Ueda, 2013).

In a study that used a target aiming task to assess subject performance, Zhou et al. applied SR methods by way of shoe insoles with tactors embedded in them. The results of the study show that application of sub-sensory noise to subjects' feet is beneficial to the complex postural control process during target aiming and that SR significantly improves aiming performance (Zhou et al., 2013).
2.8.7 Cognitive and Neurological Disorders

Research has show SR to be beneficial at inducing these performance enhancing effects in both healthy individuals and those with neurological disorders such as diabetic neuropathy, stroke and Parkinson's (Glass, 2001; Montgomery Jr. & Baker, 2000). Research with respect to Parkinson's has been less consistent than other neurological disorders such as stroke and neuropathy, however some benefit has been reported and studies into that area are in progress (Glass, 2001; Montgomery Jr. & Baker, 2000; Liu et al., 2002; Priplata et al., 2006).

SR has also been studied with respect to inattentive school children diagnosed with ADD and results have shown a significant improvement in attention span (Soderlund, Sikstrom, & Smart, 2007; Soderlund, Sikstrom, Loftesnes, & Sonuga-Barke, 2010). Finally, the literature points out that SR has been successfully applied to human subjects to induce cognitive performance enhancement (Usher & Feingold, 2000; Montgomery Jr. & Baker, 2000).

2.8.8. Surgical Applications

The authors found that the existing literature on SR as used in surgical applications is very scarce. In a pair of studies Kurita and Sueda presented the concept of a medical application of stochastic resonance. The researchers used a piezoelectric
actuator, which generated low-pass filtered white noise, was attached on the grip of the forceps and the appropriate amplitude of the vibration was applied to the subject’s hand via the forceps. The authors each reported statistically significant improvement in performance was observed when appropriate noise is applied. Passive and active sensory tests were conducted to confirm the improvement of tactile sensitivity. The experimental results suggest the usefulness of the application of SR to a medical device (Kurita et al., 2012; Sueda et al., 2013). While this pair of experiments was a first in the application of SR to surgical tooling, it was a tracking task that was only theoretically linked to MIS. There exists a gap in the literature or significant lack of evidence for the use of SR in applied MIS research such as in a differentiation task aimed at improving haptic capability and thus performance in a simulated surgical task.

2.9 Proposed Research and Hypotheses

SR effects have been shown in a myriad of experiments to enhance human performance from increased sensitivity of tactile stimuli to significantly improved performance on sensorimotor tasks. There is little evidence in existing literature that investigates the use of SR in more complex human-machine systems such as teleoperation or even minimally invasive surgical (MIS) procedures such as laparoscopy and robotic assisted laparoscopic procedures. The aim of the proposed research is to investigate the efficacy of the use of SR for the purpose of improving system and operator performance (time, accuracy) in the context of MIS using a laparoscopic palpation task. Furthermore, we will investigate the effect of vibrotactile feedback (VIB)
in the same task as a means of comparison. Previous research has shown vibrotactile force feedback to be beneficial in similar tasks for the purpose of limiting excessive forces and to improve task performance with respect to time, accuracy and confidence. The objectives will be accomplished through use of sensory augmentation techniques (VIB, SR) in the design of a haptic interface to allow enhanced tracking and differentiation performance (Repperger, Phillips, Berlin, Neidhard-Doll, & Haas, 2005) and positively augment task performance. Investigation is warranted based on evidence from previous human performance studies (Mendez-Balbuena et al., 2012; Repperger, Phillips, Berlin, Neidhard-Doll, & Haas, 2005), the documented need for improved attainment and maintenance of surgical skills and previous research into the benefits of haptically enhanced MIS techniques. Finally, further investigation into the use of SR for surgical applications is needed due to the lack of such experiments in the existing literature.

2.9.1 Research Questions

1. Can the application of stochastic resonance to the human control system improve performance (accuracy, time, confidence) in laparoscopic surgery?

2. How does the application of stochastic resonance compare to the use of vibrotactile feedback in terms of potential performance enhancement (time, accuracy)?
3. How does the addition of SR into the human control system affect the simultaneous use of vibrotactile feedback?

2.9.2 Hypotheses

It was hypothesized that both VIB and SR feedback would result in better performance over no feedback. Furthermore, SR feedback was expected to lead to the greatest increase in performance by improving subjects' haptic sensitivity to tissue compliance and consistency.

Chapter 3. Experiment 1

3.1 Introduction - Experiment 1

During the course of the present research three separate experiments were performed. All three experiments involved the same independent variables of the four conditions (SR, VIB, VIB+SR, Control) discussed in the Methods section as well as the same dependent variables of performance accuracy and time. The purpose of all three were to investigate the benefits of a wearable vibrotactile device that provides useful information regarding the forces applied by subjects during a laparoscopic palpation task,
and the relative contributions of the introduction of noise (stochastic resonance) into the system via a second vibrotactile device. We hypothesized that vibrotactile feedback and the addition of stochastic resonance would enhance performance during the laparoscopic probing task and that ultimately SR would result in the greatest increase in performance for both accuracy and time to correctly label the tissue samples. Experiment 1 results led to optimization of two of the four conditions which in turn led to better control over the experiment as a whole. Results of these changes were incorporated into Experiment 2, the results of which were used to build upon the body of knowledge to propose Experiment 3. We will present the methodology and results for Experiments 1 and 2 separately, however the final discussion section will bring together the results from both experiments as well as brand new information which will help us define the scope of Experiment 3.
3.2 Method – Experiment 1

3.2.1 Participants

A total of 10 subjects, 3 female and 7 male ages 23-40 were recruited. All subjects were consenting adults with no known visual, cognitive or motor impairments that would prevent them from taking part in the experiments. No other selection criteria were used.

3.2.2 Apparatus

The vibrotactile feedback system for the task consisted of a force sensor and two vibration devices. The force sensor was responsible for recording tool-tissue interaction force. The laparoscopic tool attached to the force sensor is shown in Figure 3. The force sensor used in the study was the Nano17, a six-axis force-torque (F/T) sensor (ATI Industrial Automation, Apex, NC, USA) which was chosen for its miniaturized design and lightweight construction. The Nano17 F/T sensor was chosen also because the sensing range safely covers the maximum surgical forces and torques that were identified in the literature (Rosen, Hannaford, MacFarlane, & Sinanan, 1999). The sensor is a stainless steel cylinder with a diameter of 1.7 cm and a height of 1.45 cm. The total weight of the sensor is 9 grams. The Nano17 has extremely high strength with maximum allowable single-axis overload values 4.4 to 19.5 times rated capacities. It also possesses
high signal-to-noise ratio with near-zero noise distortion, as well as very fine resolution as low as 0.10 gram.

The force information (voltage) collected by the Nano17 F/T sensor was transferred to the C2 haptic device (tactor) (Engineering Acoustics, Inc., Winter Park, FL, USA) to provide vibrotactile stimulation to the user. The C2 tactor is a miniature vibrotactile device used in a wide range of applications (see Figure 4). The transducer is 3 cm in diameter, 0.8 cm in height, and 17 grams in weight. It is driven by a magnetic actuator, similar in principle to audio speakers. When an electrical signal is applied to the vibrator, the current flowing in its coil pushes a central structure, called a contactor, to oscillate perpendicularly to the skin in a back and forth motion. In the present experiment the voltage from the F/T sensor was used to modulate the frequency and duty cycle parameters of a square sine wave which was applied to the vibration device (tactor). A square sine wave was chosen for the task due to research that suggests that this type of signal is ideal for application with a magnetic based haptic actuator (Okamura, 1998).
The duty cycle and frequency of the signal was modulated proportional to the magnitude of the sensor voltage which in turn was a function of the force applied during the task. The frequency modulation range was 160-250 Hz which was the linear range for the magnetic haptic actuator (C2) and duty cycle was modulated between 20-80%. It has been shown that humans are most sensitive to vibration at 250 Hz (Lynch, 1989). Both the frequency and duty cycle ranges were chosen base off of research conducted by Zhou et al. (Zhou, 2009). When the C2 is placed against the skin the area surrounding the contactor is “shielded” with passive aluminum housing. The contactor is about 0.76 cm in diameter and 0.6 mm in height above the housing and is preloaded against skin to guarantee constant contact. The C2 tactor used in the experiment was driven through a custom-made 0.5 W linear amplifier and a National Instruments PCI DAQ 6036E card, which in turn was controlled with a custom LabVIEW program.

The piezoelectric actuator used in the experiment is part of the HEK-200 SHIVR haptic evaluation kit (Mide Technology Corporation, Medford, MA). The HEK-200 is an evaluation kit purposed to demonstrate the utility and versatility of piezoelectric actuators for haptics application. The kit consists of two main components which are the SHIVR™ SP-21b piezoelectric haptic actuator and a driver board; both are shielded and contained in separate plastic cases. The overall dimensions of the device are: 17 x 5 x 1.5 cm. The actuator housing is 5.7 x 2.5 x 0.8 cm and the driver board housing is 7.5 x 4.5 x 1.5 cm. The SHIVR actuator was used independently of the C2 tactor and force sensor to deliver a constant sub-sensory vibration signal to the subjects forearm. The piezoelectric wafer (SP-21b) is encased in a polyimide film electrical insulation which makes it safe for
direct skin contact. Reference signals in the form of a repeating sine wave (4.5 volts, 100 Hz) were sent to the SHIVR via LabVIEW software. The signal amplitudes were individually determined based on a vibration perception capability test which was performed on each subject prior to the experiment. This procedure involved starting the vibration signal at a supra-threshold level (4.5 V, 100Hz) and then gradually decreasing the amplitude by 0.25 V until the vibration was unperceivable to the subject. Voltages across all subjects were in the range of 2.5-4.5 volts.

The experimental setup consists of a modeled surgical workspace consisting of a laparoscopic box trainer (Ethicon Endo-surgery, Cincinnati, OH), monitor, stand, and the laparoscopic probe tool (Figure 3). The top of the box trainer has pre-cut holes to mount a trocar for tool entry into the workspace. A camera was fixed in place to allow a view of the workspace, which was presented on the monitor in front of the subject.

The task of the experiment was for the subject to determine the presence of an embedded “tumor” in mock tissue samples. Tissue samples used in the study were simulated using silicone gel formed from a combination of 87760A and 87760B (Silicone Solutions, Toledo, OH). The ratio of A and B silicone components was 6:4, resulting in a compliance similar to human adipose tissue. Each gel sample was 200 ml in volume, approximately 2.5 cm in height, and 8 cm in diameter (see Figure 3). The embedded tumor was simulated using Heavy Duty Felt Blankets (Home Depot, Atlanta, GA) cut in strips 5 mm in width and 6 cm in length. The dimensions of the tumors were chosen based on previous research by Zhou et al. in which the embedded material was intended
to represent a human bile duct (Zhou, 2010). The same size and shape was chosen for the present research as to not introduce any bias based on size of the embedded structure for means of comparison of results. The simulated tumors were embedded below the surface at two different depths in the tissue samples: superficial (5 mm), medium (10 mm). A thin Nylon stocking was placed over the tissue sample during the testing to prevent subjects from seeing the tumor directly through the transparent tissue sample and to protect the tissue samples from damage.

### 3.2.3 Procedure and Experimental Design

Prior to the start of testing, basic information about each subject was collected. The information collected was: assigned subject ID Number, date of completion, age, gender, occupation, questions aimed at determining experience with playing video games, and whether or not they have experience with laparoscopic tools and/or trainers.

A simulated palpation task with the goal of tumor detection was used. The independent variable was the vibration condition presented to the subjects. The four conditions were: with supra-sensory vibrotactile stimulation (VIB), with sub-sensory stimulation (SR), with both supra-sensory and sub-sensory stimulation (VIB+SR) and with no stimulation (Control). The experiment was a one-factor within-subjects design. The dependent variables examined for the experiment were performance accuracy and time to task completion.
Subjects were asked to probe the tissue sample using the laparoscopic tool, and to judge the presence of an embedded tumor. The task was completed under each of the four following conditions: with vibrotactile stimulation (supra-threshold) through the C2 tactor [VIB], with sub-sensory vibrotactile stimulation through the SHIVR haptic device [SR], with both sensory and sub-sensory modes [VIB+SR] as well as without any stimulation [Control]. Subjects performed 9 trials in each condition. The 9 samples consisted of 6 targets (3 superficial, 3 deep) and 3 non-targets. The order of the conditions and the tissue samples were randomly presented. Once the judgment was made, subjects were asked to withdraw the instrument immediately. The interaction force between the tool tip and the tissue sample was delivered to the subjects through the C2 tactor. The C2 was attached to the dorsal aspect subjects’ upper arm and the SHIVR piezo actuator was attached to the ventral aspect of the subject’s forearm, both using an elastic arm band or similar to hold the haptic device. A 30-second per trial time limit was imposed on all subjects to limit the session duration. Prior to the testing, each subject was allowed two practice trials with and without vibrotactile feedback. The two tissue samples used during the practice trials were: 1) with tumor embedded superficial, and 2) no tumor embedded.
3.3 Results

Overall, 10 subjects performed a total of 360 trials of the palpation task, data from two of the subjects was excluded due to knowledge that they were guessing and did not clearly understand the experimental procedure. Therefore, 8 subjects performed a total of 288 trials of which 192 were with samples containing an embedded tumor. Of the 288 trials, subjects made a wrong judgment in 73 trials. The key dependent variables which this report focuses on are performance accuracy and time to completion of each trial.

3.3.1 Accuracy

The results for the one-way ANOVA on the mean accuracy are seen in Figure 5. The results indicate that there appears to be a significant difference in the means for SR condition with respect to the VIB and VIB+SR conditions, but not significant with respect to the Control condition. A Tukey-Kramer HSD test was performed (Figure 6) to further investigate the apparent differences in condition means and the result of the LSD Threshold Matrix shows that there is not a significant relationship between any of the condition pairs.
3.3.2 Time

The results for the one-way ANOVA on the mean time to task completion are seen in Figure 7. The results indicate that there appears to be a significant difference in the means for SR condition with respect to the VIB+SR conditions, but not significant with respect to the Control and VIB conditions. There also appears to be a significant difference for the VIB condition with respect to VIB+SR, but not significant with respect to the Control and SR conditions. A Tukey-Kramer HSD test was performed (Figure 8) to further investigate the apparent differences in condition means and the result of the LSD
Threshold Matrix shows that there is only a significant relationship between the SR x VIB+SR pair.

3.4 Discussion

With the results of the experiment failing to show meaningful significant interaction between the independent (vibration condition) and dependent (accuracy, time)
variables, a more thorough investigation was needed on previous and referenced similar research studies in an attempt to make sense of the results and for future research direction.

In a 2006 study Schoonmaker and Cao used a vibrotactile device attached to the plantar surface of subjects’ feet to provide haptic force feedback information in a simulated laparoscopic needle driving task. The task required subjects to locate and penetrate a small target in a double layer silicone gel mass consisting of a soft upper layer and harder lower layer, until they perceived the harder layer. The soft layer was equivalent to fatty tissue, while the harder layer was equivalent to human liver in compliance. Results showed that the system responded as predicted against the bottom surface of the foot, and that subjects were able to perceive a linear increase in force as linear increase in vibration intensity. Furthermore, vibrotactile force information increased one’s sensitivity to tissue contact (1.3 N maximum force – no vibration, 1.0 N maximum force– fine step vibration feedback; p<0.001) and improved one’s ability to consistently and accurately differentiate tissue softness in a simulated MIS task. The researchers concluded that vibrotactile force feedback in MIS appears to have benefits which can lead to a decrease in trauma to tissue and adverse events (Schoonmaker & Cao, 2006).

In another related study, Zhou and Cao reported on a controlled experiment similar to the present experiment that was conducted using a wearable vibrotactile device that responded with various levels of vibration signal parameters (i.e., amplitude,
frequency and duty-cycle) as a function of applied force during a palpation task. Results showed that subjects were able to perform more accurately and more confidently, applying lower peak forces and smaller force ranges to make a judgment regarding the presence of an embedded structure, with vibrotactile augmentation than without. In addition, as more parameters of the vibration signal were modulated (up to three), the vibrotactile augmentation tended to be more effective with two parameters being optimal and three parameters being redundant. The results suggested that palpation can be improved by implementing a vibration device that is capable of multi-dimensional modulation. However, the design of the vibration device should balance the advantage of providing additional information for effective information transmission with that of signal redundancy and complexity (Zhou & Cao, 2009).

Given this information and results of the present study, researchers when back and evaluated the design of the experiment and related conditions. We found that there were two fundamental issues that could possibly be a detriment to results and explain our lack of significant findings. First, the frequency response range of the C2 vibration device that was used in the VIB and VIB+SR conditions of the present experiment was defined at 0-250 Hz since that was the operating range provided by the specifications sheet from the manufacturer. However, in a previous related study, Zhou and Cao plotted the frequency response of the C2 tactor and it was observed that the vibrator was a linear system throughout the frequency range of about 160 Hz to 250 Hz that was the highest frequency of interest in this experiment (Zhou & Cao, 2009). Therefore, this range was chosen as the working frequency range in their experiment. This discrepancy could
potentially account for the difference in results between our experiment and that of Zhou and Cao. The second fundamental issue concerns the design of the SR condition. It was discovered that the signal used to drive the SHIVR haptic actuator used in the SR condition had a frequency of only 100Hz. Previous research into the sensorimotor benefits of stochastic resonance shows that a signal with a frequency of at least 300 Hz is used (Kurita, Shinohara, & Ueda, 2011; Mendez-Balbuena et al., 2012). A frequency of 300 Hz was used in these studies due to the frequency response characteristics of the tactile mechanoreceptors which are: Meissner corpuscles, Pacinian corpuscles, Merkel cells, and Ruffini endings. Each are classified as either rapid adapting (RA) or slow adapting (SA) and are optimally sensitive at distinct frequency ranges. Pacinian corpuscles are extremely sensitive at the optimal vibration frequency of 250 Hz in young adults (Bolanowski Jr, Gescheider, Verrillo, & Checkosky, 1988; Freeman & Johnson, 1982).

3.5 Conclusion

Given the aforementioned issues in the design of the VIB, VIB+SR and SR conditions, the researchers were confident that one or a combination of the deficits in the design likely introduced bias into the experiment. Furthermore, this bias was likely the cause of the lack in significant interaction between the independent and dependent variables in the experiment. It was determined that a second experiment (Experiment 2)
would need to be performed to further investigate the benefits of vibrotactile feedback and stochastic resonance for the laparoscopic palpation task.

Chapter 4 - Experiment #2

4.1 Methods - Experiment 2

4.1.1 Participants

A total of 8 subjects, 2 female and 6 male ages 22-26 years old were recruited. All subjects were consenting adults with no known visual, cognitive or motor impairments that would prevent them from taking part in the experiments. No other selection criteria were used.

4.1.2 Apparatus

The vibrotactile feedback system for the task consisted again of a force sensor and two vibration devices. The force sensor was responsible for recording tool-tissue interaction force. The laparoscopic tool attached to the force sensor is shown in Figure 3. The force sensor used in the study was the Nano17, a six-axis force-torque (F/T) sensor (ATI Industrial Automation, Apex, NC, USA) which was chosen for its miniaturized
design and lightweight construction. The Nano17 F/T sensor was chosen also because the sensing range safely covers the maximum surgical forces and torques that were identified in the literature (Rosen, Hannaford, MacFarlane, & Sinanan, 1999). The sensor is a stainless steel cylinder with a diameter of 1.7 cm and a height of 1.45 cm. The total weight of the sensor is 9 grams. The sensor has extremely high strength with maximum allowable single-axis overload values 4.4 to 19.5 times rated capacities. It also possesses high signal-to-noise ratio with near-zero noise distortion, as well as very fine resolution as low as 0.10 gram.

The force information (voltage) collected by the Nano17 F/T sensor was transferred to the C2 haptic device (tactor) (Engineering Acoustics, Inc., Winter Park, FL, USA) to provide vibrotactile stimulation to the user. The C2 tactor is a miniature vibrotactile device used in a wide range of applications (see Figure 4). The transducer is 3 cm in diameter, 0.8 cm in height, and 17 grams in weight. It is driven by a magnetic actuator, similar in principle to audio speakers. When an electrical signal is applied to the vibrator, the current flowing in its coil pushes a central structure, called a contactor, to
oscillate perpendicularly to the skin in a back and forth motion. In the present experiment the voltage from the F/T sensor was used to proportionally modulate the frequency and duty cycle parameters of a square sine wave which was applied as a reference signal to the vibration device (tactor). A square sine wave was chosen for the task due to research that suggests that this type of signal is ideal for application with a magnetic based haptic actuator (Okamura, 1998). The duty cycle and frequency of the signal was modulated proportional to the magnitude of the sensor voltage which in turn was a function of the force applied during the task. The frequency modulation range was 160-250 Hz which was the linear range for the magnetic haptic actuator (C2) and duty cycle was modulated between 20-80%. It has been shown that humans are most sensitive to vibration at 250 Hz (Lynch, 1989). Both the frequency and duty cycle ranges were chosen base off of research conducted by Zhou et al. (Zhou, 2009). When the C2 is placed against the skin the area surrounding the contactor is “shielded” with passive aluminum housing. The contactor is about 0.76 cm in diameter and 0.6 mm in height above the housing and is preloaded against skin to guarantee constant contact. The C2 tactor used in the experiment was driven through a custom-made 0.5 W linear amplifier and a National Instruments PCI DAQ 6036E card, which in turn was controlled with a custom LabVIEW program.

The piezoelectric actuator used again in the experiment is part of the HEK-200 SHIVR haptic evaluation kit (Mide Technology Corporation, Medford, MA). The HEK-200 is an evaluation kit purposed to demonstrate the utility and versatility of piezoelectric actuators for haptics application. The kit consists of two main components which are the
SHIVR™ SP-21b piezoelectric haptic actuator and a driver board; both are shielded and contained in separate plastic cases. The overall dimensions of the device are: 17 x 5 x 1.5 cm. The actuator housing is 5.7 x 2.5 x 0.8 cm and the driver board housing is 7.5 x 4.5 x 1.5 cm. The SHIVR actuator was used independently of the C2 tactor and force sensor to deliver a constant sub-sensory vibration signal to the subjects forearm. The piezoelectric wafer (SP-21b) is encased in a polyimide film electrical insulation which makes it safe for direct skin contact. A reference signal in the form of a repeating sine wave (4.5 volts) with a sweeping frequency (0-300 Hz) was sent to the SHIVR via LabVIEW software (Kurita, Shinohara, & Ueda, 2011; Mendez-Balbuena et al., 2012). A frequency range of 0-300 Hz was chosen in consideration of lack of significant results in Experiment 1 and the frequency response characteristics of the tactile mechanoreceptors which are: Meissner corpuscles, Pacinian corpuscles, Merkel cells, and Ruffini endings. Each are classified as either rapid adapting (RA) or slow adapting (SA) and are optimally sensitive at distinct frequency ranges. Pacinian corpuscles are extremely sensitive at the optimal vibration frequency of 250 Hz in young adults (Bolanowski Jr, Gescheider, Verrillo, & Checkosky, 1988; Freeman & Johnson, 1982).

Considering the range of sensitivity for all types of mechanoreceptors and to ensure that all four main types were activated, a vibration signal with a cut-off frequency of 300 Hz was used in the study. The signal amplitudes were individually determined based on a vibration perception capability test which was performed on each subject prior to the experiment. This procedure involved starting the vibration signal at a supra-threshold level (4.5 V, 300Hz) and then gradually decreasing the amplitude by 0.25 V.
until the vibration was unperceivable to the subject. Voltages across all subjects were in the range of 2.5-4.5 volts.

The experimental setup is shown in Figure 3. It consists of a modeled surgical workspace consisting of a laparoscopic box trainer (Ethicon Endo-surgery, Cincinnati, OH), monitor, stand, and the laparoscopic probe tool. The top of the box trainer has pre-cut holes to mount a trocar for tool entry into the workspace. A camera was fixed in place to allow a view of the workspace, which was presented on the monitor in front of the subject.

The task of the experiment was for the subject to determine the presence of an embedded “tumor” in mock tissue samples. Tissue samples used in the study were simulated using silicone gel formed from a combination of 87760A and 87760B (Silicone Solutions, Toledo, OH). The ratio of A and B silicone components was 6:4, resulting in a compliance similar to human adipose tissue. Each gel sample was 200 ml in volume, approximately 2.5 cm in height, and 8 cm in diameter (see Figure 3). The embedded tumor was simulated using Heavy Duty Felt Blankets (Home Depot, Atlanta, GA) cut in strips 5 mm in diameter and 6 cm in length. The dimensions of the tumors were chosen based on previous research by Zhou et al. (Zhou & Cao, 2009). The “tumors” were embedded below the surface at two different depths in the tissue samples: superficial (5 mm), medium (10 mm). A thin Nylon stocking was placed over the tissue sample during the testing to prevent subjects from seeing the tumor directly through the transparent tissue sample and to protect the tissue samples from damage.
4.1.3 Procedure and Experimental Design

Prior to the start of testing, basic information about each subject was collected. The information collected was: assigned subject ID Number, date of completion, age, gender, occupation, questions aimed at determining experience with playing video games, and whether or not they have experience with laparoscopic tools and/or trainers.

A simulated palpation task with the goal of tumor detection was used. The independent variable was the vibration condition presented to the subjects. The four conditions were: with supra-sensory vibrotactile stimulation (VIB), with sub-sensory stimulation (SR), with both sensory and sub-sensory stimulation (VIB+SR) and with no stimulation (Control). The experiment was a one-factor within-subjects design. The dependent variables examined for the experiment were accuracy and time to task completion.

Subjects were asked to probe the tissue sample using the laparoscopic tool, and to judge the presence of an embedded tumor. The task was completed under each of the four following conditions: with vibrotactile stimulation (supra-sensory) through the C2 tactor, with sub-sensory vibrotactile stimulation through the SHIVR haptic device, with both supra-sensory and sub-sensory modes and without any stimulation (Control). Subjects completed four sets of counterbalanced conditions in which they were presented 6 samples for each of the four conditions in the set, see Table 1. Each subject was therefore presented with 96 total samples in the experiment. The six samples presented
during each condition were always a combination of four targets (2 deep, 2 superficial) and two non-targets and were randomly presented. Each trial began as soon as the tool tip touched the sample and once the judgment was made, subjects were asked to withdraw the instrument immediately so that an exact trial time could be extracted from the force profiles. The interaction force between the tool tip and the tissue sample was delivered to the subjects through the C2 tactor. The C2 was attached to the dorsal aspect subjects’ upper arm and the SHIVR piezo actuator was attached to the ventral aspect of the subject’s forearm with the actuator placed as close as possible to the subject’s palm, both using an elastic arm band or similar to hold the haptic device. A 30-second per trial time limit was imposed on all subjects to limit the session duration. Prior to the testing, each subject was allowed two practice trials with and without vibrotactile feedback. The two tissue samples used during the practice trials were: 1) with tumor embedded superficial, and 2) with tumor embedded deep in the sample.

<table>
<thead>
<tr>
<th>Matrix</th>
<th>Block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>SR</td>
</tr>
<tr>
<td>SR</td>
<td>Vib</td>
</tr>
<tr>
<td>Vib</td>
<td>Vib-SR</td>
</tr>
<tr>
<td>Vib-SR</td>
<td>Control</td>
</tr>
<tr>
<td>Vib-SR</td>
<td>Control</td>
</tr>
<tr>
<td>Control</td>
<td>SR</td>
</tr>
<tr>
<td>SR</td>
<td>Vib</td>
</tr>
<tr>
<td>Vib</td>
<td>Vib-SR</td>
</tr>
<tr>
<td>SR</td>
<td>Vib</td>
</tr>
<tr>
<td>Vib-SR</td>
<td>Control</td>
</tr>
<tr>
<td>Control</td>
<td>SR</td>
</tr>
</tbody>
</table>

Table 1: Condition order and blocks presented
4.2 Results

Overall, eight subjects performed a total of 768 trials of the palpation task, of which 512 were with samples containing an embedded tumor. Of the 768 trials, subjects made a wrong judgment in 106 trials (13.8%). The key dependent variables which this report focuses on are: accuracy at correctly identify targets from non-targets and time to task completion.

4.2.1 Accuracy

The results on the ANOVA for mean accuracy are summarized in Figure 9. The results indicate that there was not a significant difference between any of the conditions. Furthermore, the accuracy rate for all conditions was between 81.3 to 86.7%.

![Figure 9: ANOVA for Mean Accuracy for each of the four conditions](image-url)
4.2.2 Time

The results on the ANOVA for mean time to completion are summarized in Figure 10. The results indicate that there was not a significant difference between any of the conditions. Furthermore, the standard deviation of the times for all conditions ranged from approximately 5 to 25 seconds.

![Figure 10: ANOVA for mean Time to Completion for each of the four conditions](image)

4.3 Discussion

The authors found it intriguing that the independent variable of vibration condition (VIB, SR, SR-VIB, Control) did not yield any significant difference in either of the dependent variables (Accuracy, Time). Furthermore, the mean accuracy for each condition was between 81.3-86.7% and the mean time for each condition between 14.8
and 15.9 seconds. It was unexpected that the means for all conditions for each feature would even out like they did. Previous research involving vibrotactile feedback in a laparoscopic surgery task by Schoonmaker and Cao has shown that force information in the form of vibrotactile feedback increased subject’s sensitivity to tissue contact and improved their ability to consistently and accurately differentiate tissue softness or compliance (Schoonmaker & Cao, 2006). This would suggest that there should have at least been some significant difference between the Control and VIB conditions. Also, the results from the study by Zhou and Cao showed that subjects were able to perform more accurately and more confidently, applying lower peak forces and smaller force ranges to make a judgment regarding the presence of an embedded structure, with vibrotactile augmentation than without (Zhou & Cao, 2009). Researchers from the present experiment duplicated Zhou’s experimental design and set up for the VIB condition with the changes made to the response frequency, duty cycle modulation and amplitude. This suggests that we should have at least seen some significant interaction between the VIB and Control conditions with respect to accuracy and time.

The authors noticed that there appeared to be a significant improvement in the accuracy (See Figure 11) and time (See Figure 12) dependent variables between the first and second experiments. In general, it appeared that the subjects had improved in both accuracy and time to complete the task with the second experiment. Learning effects were ruled out due to the fact that none of the subjects from experiment 1 participated in experiment 2. Furthermore the experimental conditions remained the same between experiments except for the improvements to the VIB and SR conditions reported earlier.
To test whether there was significant interaction between conditions from Experiment 1 and Experiment 2 a paired Student’s t-test was run on each pair of conditions for both the accuracy and time features. To clarify, the student’s t-test was run
on the Control condition from Experiment 1 for accuracy (Control-E1-Acc) versus the Control condition from Experiment 2 for accuracy feature (Control-E2-Acc). This test was run on each condition pair (Control, SR, VIB, VIB+SR) for both dependent variables. Tables 2a and 2b show the results from the Paired Student’s t-tests.

<table>
<thead>
<tr>
<th>Condition Pair - Accuracy</th>
<th>P-value</th>
<th>Significant?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control E1 – Control E2</td>
<td>0.0245</td>
<td>Yes</td>
</tr>
<tr>
<td>SR E1 – SR E2</td>
<td>0.0053</td>
<td>Yes</td>
</tr>
<tr>
<td>VIB E1 – VIB E2</td>
<td>0.0201</td>
<td>Yes</td>
</tr>
<tr>
<td>VIB+SR E1 – VIB+SR E2</td>
<td>0.0167</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 2a – Results for paired Student’s t-tests for Accuracy

<table>
<thead>
<tr>
<th>Condition Pair - Time</th>
<th>P-value</th>
<th>Significant?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control E1 – Control E2</td>
<td>0.0165</td>
<td>Yes</td>
</tr>
<tr>
<td>SR E1 – SR E2</td>
<td>0.5937</td>
<td>No</td>
</tr>
<tr>
<td>VIB E1 – VIB E2</td>
<td>0.2627</td>
<td>No</td>
</tr>
<tr>
<td>VIB+SR E1 – VIB+SR E2</td>
<td>0.0475</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 2b – Results for paired Student’s t-tests for Time
4.4 Discussion – Experiment 1 vs. Experiment 2

Based on the results of the paired Student’s t-test, the authors were confident that changes made to the SR and VIB conditions had a significant effect on subject’s performance in terms of accuracy and time to find the embedded tumors in the target samples. However, the fact that there were no significant differences or interactions between conditions in Experiment 2 was still perplexing. To help determine the cause of these phenomena the authors went back to the literature concerning stochastic resonance (SR) and sensorimotor performance. Two findings stood out as the problem was researched. The first was a “carryover effect” found in the literature (Conrad, Scheidt, & Schmit, 2011; Duclos, Roll, Kavounoudias, Roll, & Forget, 2007; Hur, Wan, & Seo, 2014) and the second finding was “cross modal stochastic resonance” (Ai, Liu, & Liu, 2009).

The carry-over effect described by several studies is where both supra- and sub-threshold vibrotactile signals were found to induce sensorimotor performance enhancement both while the vibration was being administered as well as for a period ranging from 3-180 minutes after the vibration treatment was removed (Conrad, Scheidt, & Schmit, 2011; Duclos, Roll, Kavounoudias, Roll, & Forget, 2007). A study by Conrad et al. used a supra-threshold vibration to the wrist tendon of Stroke (S) and Non-Stroke (NS) subjects to improved performance in a tracking task for the (S) subjects. They also noted that there were post vibratory effects to the 30 second vibration condition and that effects can last 3-180 minutes. They reported that just a short (30s) vibration can produce
contractions in the targeted muscle for several minutes after it is removed (Conrad, Scheidt, & Schmit, 2011). In another study, Duclos et al. used a 30 second sub-threshold unilateral vibration to induce weight shift towards the vibration in amputee and able-bodied subjects. Center of pressure (CP) position during stance was recorded prior to and up to 13 minutes after the 30 s unilateral vibration. A CP displacement (shift), without an increase in CP velocity was noted in both groups of participants over the 13-minute post-vibration period (Duclos, Roll, Kavounoudias, Roll, & Forget, 2007). The findings of both of these studies suggest that both the VIB and SR conditions used in the present study could have significant carry-over effects and introduce bias into the experiment for all conditions that were presented following the initial VIB and/or SR condition (Conrad, Scheidt, & Schmit, 2011; Duclos, Roll, Kavounoudias, Roll, & Forget, 2007). The maximum time for a one-condition trial in the present experiment was 180 seconds (6 samples at 30 s each) with only 60 seconds of rest between conditions. Thus, each subsequent condition following a SR, VIB or even VIB+SR condition was well within the carry-over window as reported by the previous studies (Conrad, Scheidt, & Schmit, 2011; Duclos, Roll, Kavounoudias, Roll, & Forget, 2007).

The second interesting finding resulting from our research was that of cross-modal stochastic resonance (CMSR). CMSR is defined as the influence of noise on the response of one sensory modality elicited by stimuli in another modality (Ai, Liu, & Liu, 2009). When the researchers went back and analyzed the administration of both Experiment 1 and Experiment 2, it was noted that one of the environmental conditions that existed was auditory noise produced by fume hoods in the testing laboratory. The
fume hoods were constantly running and could not be shut-off; however the researchers did not consider isolating subjects from the exogenous source of noise. Of great interest was a study by Ai et al. which looked at how different magnitudes of auditory noise can induce CMSR resulting in increased sensorimotor performance during a peg transfer task (Ai, Liu, & Liu, 2009). Researchers found that optimal auditory noise can largely improve the fine-motor performance of subjects performing the peg transfer task. The optimal level of noise across the subjects in this particular study was approximately 68 (+/- 2) dB SPL (Ai, Liu, & Liu, 2009). The researchers from the present study went back and performed SPL measurements at and around the testing area with two different calibrated dosimeters and found that the average reading at the experimental set-up was 66.5 dB SPL. This measurement is within the range of “optimal noise” level described by Ai et al. and thus was determined to be a bias introduced into the experiment which could have significantly altered the results obtained (Ai, Liu, & Liu, 2009).

4.5 Conclusion

The results from Experiment 1 when compared to similar studies warranted a second look at the design of the experimental conditions. The literature was used to guide the authors towards redesigning the experimental procedures and these changes were incorporated into the design of Experiment 2. Although results for Experiment 2 were significantly improved over Experiment 1, there still exist potential experimental design issues which warrant consideration in designing a third experiment. It is suggested by the
authors that the design of “Experiment 3” take into account the carry-over effect and cross-modal stochastic resonance and that a more controlled environment be created to ameliorate these two issues.

Chapter 5 - Experiment #3

5.1 Methods - Experiment 3

5.1.1 Participants

A total of 16 subjects, 10 female and 6 male ages 20-31 years old were recruited. All subjects were consenting adults with no known visual, cognitive or motor impairments that would prevent them from taking part in the experiments. No other selection criteria were used.

5.1.2 Apparatus

The experimental set-up remained unchanged from Experiments 1 & 2 except for the adjustments made to address the two sources of bias that were identified in Experiment 2. The entire experiment was moved to a quiet, private location as to not introduce bias via cross-modal SR. The experimental room had a SPL of 47 dB which is
similar to the average sound in your home (50 dB) and below that of normal conversation in a room (60 dB). The possibility of carry-over effect was addressed by only presenting each subject one treatment condition along with the control (Control-SR or Control-VIB or Control-VIB+SR) and by always starting with the control presentation such that it was not biased by the VIB and/or SR treatment. A fourth group of subjects which was presented a Control-Control pair of conditions was created to serve to represent the increase in performance based purely on learning effects. Therefore the four groups of subjects were: 1. Control-SR, 2. Control-VIB, 3. Control-VIB+SR and 4. Control-Control.

5.1.3 Procedure and Experimental Design

Prior to the start of testing, basic information about each subject was collected. The information collected was: assigned subject ID Number, date of completion, age, gender, occupation, questions aimed at determining experience with playing video games, and whether or not they have experience with laparoscopic tools and/or trainers.

Experiment 3 employed the same simulated palpation task that was used in Experiments 1 & 2. Experiment 3 was a between-subjects design which attempted to isolate each experimental condition (SR, VIB, VIB+SR) with the control condition (No Stim). Therefore, there were three different groups of subjects: (1) Control and SR, (2) Control and VIB, and (3) Control and VIB+SR. Each subject was presented 36 tissue
samples (24 w/tumor, 12 non-tumor) in random order, under the control condition and then presented the same 36 samples in a different random order under the assigned vibration condition (SR, VIB, VIB+SR), for a total of 72 tissue samples (48 w/tumor, 24 non-tumor).

The six samples presented during each condition were always a combination of four targets (2 deep, 2 superficial) and two non-targets and were randomly presented. Each trial began as soon as the tool tip touched the sample and once the judgment was made, subjects were asked to withdraw the instrument immediately so that an exact trial time could be extracted from the force profiles. The interaction force between the tool tip and the tissue sample was delivered to the subjects through the C2 tactor. The C2 was attached to the dorsal aspect subjects’ upper arm and the SHIVR piezoelectric actuator was attached to the ventral aspect of the subject’s forearm with the actuator placed as close as possible to the subjects palm, both using an elastic arm band or similar to hold the haptic device. A 30-second per trial time limit was imposed on all subjects to limit the session duration. Prior to testing and data collection, each subject was allowed one untimed practice session as in previous experiments. However, for Experiment 3 no vibration or stimulation from either haptic actuator was used during the practice trial. This was in an attempt to control for the possibility of carry-over effect identified in the previous experiment.
5.2 Results

Overall, 16 subjects performed a total of 1152 trials of the palpation task, of which 768 were with samples containing an embedded tumor. The number of samples presented to each of the four groups was 288, of which 192 contained an embedded tumor. Of the 1152 trials, subjects made a wrong judgment in 258 trials (22.4%). The key dependent variables which this report focuses on are: accuracy at correctly identify targets from non-targets and time to task completion.

5.2.1 Accuracy

The mean increase in accuracy for each of the condition groups (Control-Control, Control-SR, Control-VIB, Control-VIB+SR) is reported in Figure 13. Results from the ANOVA for the main effects of mean increase in accuracy between the control condition and respective treatment condition as well as the ANOVA and Tukey-Kramer HSD on the mean increase in accuracy for each group are summarized in Table 3. The accuracy results indicate significant improvement over the control condition in accuracy with the Control-SR group only suggesting that the addition of SR allowed the Control-SR group participants to perform significantly more accurate. The results of the ANOVA on mean increase in accuracy show that the SR group performed significantly better than the Control, VIB and VIB+SR groups in terms of improved accuracy (Table 3).
Table 3 – Results of ANOVA on Accuracy and Time Data
5.2.2 Time

The mean decrease in time to task completion for each of the condition groups (Control-Control, Control-SR, Control-VIB, Control-VIB+SR) is reported in Figure 15. Results from the ANOVA for the main effects of mean decrease in time between the control condition and respective treatment condition as well as the ANOVA performed on the mean decrease for each group are summarized in Table 3.

The results indicate that there was not a significant difference between any of the conditions. Furthermore, the standard deviation of the times for all conditions ranged from approximately 5 to 30 seconds without any significant correlation. These results suggest that none of the treatment conditions (SR, VIB, VIB+SR) produced any significant differences in the time needed to make a decision during the process.

Figure 15 – Mean Decrease in Time
5.2.3 Signal Detection Theory

The data from each group was also analyzed using Signal Detection Theory (SDT). The results for each group are reported below with emphasis on the sensitivity ($d'$) and selection bias ($\beta$) and how the vibration condition affected each value when compared with the control condition or no vibration. The values for $d'$ and $\beta$ were calculated using the following equations:

\[ d' = Z(H) - Z(FA) \]
\[ C = -\frac{1}{2} [Z(H) + Z(FA)] \]
\[ \ln \beta = d' \times C \]

<table>
<thead>
<tr>
<th><strong>Control Trial 1: C-C Group</strong></th>
<th>Signal:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>d' = 1.63  B = 1.47</td>
<td>Present (1)</td>
<td>Absent (0)</td>
<td></td>
</tr>
<tr>
<td>Decision: Present (1)</td>
<td>Hit - 69 (0.719)</td>
<td>FA - 7 (0.146)</td>
<td></td>
</tr>
<tr>
<td>Absent (0)</td>
<td>Miss - 27</td>
<td>CR - 41</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Control Trial 2: C-C Group</strong></th>
<th>Signal:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>d' = 1.55  B = 0.946</td>
<td>Present (1)</td>
<td>Absent (0)</td>
<td></td>
</tr>
<tr>
<td>Decision: Present (1)</td>
<td>Hit - 76 (0.792)</td>
<td>FA - 11 (0.229)</td>
<td></td>
</tr>
<tr>
<td>Absent (0)</td>
<td>Miss - 20</td>
<td>CR - 37</td>
<td></td>
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</table>

Table 4 – SDT for Control - Control Group
<table>
<thead>
<tr>
<th>Control Trial: C-SR Group</th>
<th>Signal:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present (1)</td>
</tr>
<tr>
<td></td>
<td>Absent (0)</td>
</tr>
<tr>
<td>( d' = 1.28 ) \ B = 0.660</td>
<td>Hit 80 (0.833)</td>
</tr>
<tr>
<td>Decision:</td>
<td>Present (1)</td>
</tr>
<tr>
<td></td>
<td>Absent (0)</td>
</tr>
<tr>
<td></td>
<td>Hit 16 (0.833)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SR Trial: C-SR Group</th>
<th>Signal:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present (1)</td>
</tr>
<tr>
<td></td>
<td>Absent (0)</td>
</tr>
<tr>
<td>( d' = 2.23 ) \ B = 0.722</td>
<td>Hit 86 (0.896)</td>
</tr>
<tr>
<td>Decision:</td>
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<tr>
<td></td>
<td>Absent (0)</td>
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<tr>
<td></td>
<td>Hit 8 (0.833)</td>
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</table>

Table 5 – SDT for Control - SR Group

<table>
<thead>
<tr>
<th>Control Trial: C-VIB Group</th>
<th>Signal:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present (1)</td>
</tr>
<tr>
<td></td>
<td>Absent (0)</td>
</tr>
<tr>
<td>( d' = 1.39 ) \ B = 0.892</td>
<td>Hit 75 (0.781)</td>
</tr>
<tr>
<td>Decision:</td>
<td>Present (1)</td>
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<tr>
<td></td>
<td>Absent (0)</td>
</tr>
<tr>
<td></td>
<td>Hit 21 (0.781)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VIB Trial: C-VIB Group</th>
<th>Signal:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present (1)</td>
</tr>
<tr>
<td></td>
<td>Absent (0)</td>
</tr>
<tr>
<td>( d' = 1.08 ) \ B = 0.744</td>
<td>Hit 76 (0.792)</td>
</tr>
<tr>
<td>Decision:</td>
<td>Present (1)</td>
</tr>
<tr>
<td></td>
<td>Absent (0)</td>
</tr>
<tr>
<td></td>
<td>Hit 12 (0.792)</td>
</tr>
</tbody>
</table>

Table 6 – SDT for Control - VIB Group
Results from the SDT breakdown of the data for each of the four condition groups shows that the discriminability index or sensitivity (d') was improved from the control trial to the vibration treatment trial in only the Control-SR and Control-VIB+SR groups. This means that the addition of SR and SR+VIB in these groups of subjects produced an effect that allowed for the increase of sensitivity performance of the system. 

In the other two groups of subjects (Control-Control and Control-VIB) did not show any improvement in sensitivity from the control to the vibration treatment trial.

The results of the SDT analysis of the study data also shows that the Control-SR group was the only group to both improve in sensitivity (d') and decision bias (β) from the control trial to the vibration treatment trial. The increase in decision bias (β) from the first to second trial indicates that the SR vibration allowed for the subjects in this group to improve their ability to determine targets from non-targets.

Table 7 – SDT for Control-VIB+SR Group

<table>
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<tr>
<th>Control Trial: C-VIB+SR Group</th>
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</thead>
<tbody>
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<td></td>
<td>Present (1)</td>
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<tr>
<td><strong>d’</strong></td>
<td>1.65</td>
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<tr>
<td>Decision:</td>
<td>Present (1)</td>
</tr>
<tr>
<td></td>
<td>Absent (0)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VIB+SR Trial: C-VIB+SR Group</th>
<th>Signal:</th>
</tr>
</thead>
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<td>Present (1)</td>
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<tr>
<td><strong>d’</strong></td>
<td>2.07</td>
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<tr>
<td>Decision:</td>
<td>Present (1)</td>
</tr>
<tr>
<td></td>
<td>Absent (0)</td>
</tr>
</tbody>
</table>
5.3 Discussion

In the existing literature there emerge two theories of how/why SR improves human performance in various tasks. The more established theory is explained in the context of general signal processing and applies to non-linear systems. The generally accepted theory is that the addition of noise into the system increases the SNR and thus the performance of the closed loop tracking tasks is improved via less subjectivity of whether the signal exists or not (Collins, 1995; Repperger, 2005). Tracking tasks in human behavioral experiments are essentially closed loop control systems where the human controller uses the feedback loop to adjust the system parameters to achieve a desired output (Adams, 1971; Adams, 1961). When SR is entered into the control system it allows the SNR of the feedback signal to increase and thus removes some of the ambiguity out of the system or in terms of signal detection theory, the noise in the system is reduced or sensitivity is increased. Many of the early studies involving SR explore its effect on the mechanism of human balance control. One of the earliest examples was research carried out by Collins et. al in which the addition of SR via mechanical vibrations to the soles of the feet was shown to improve the standing balance of human subjects. The researchers tracked the COP trajectories of human subjects via stabilograms to show that the addition of SR removed variability and thus improved subjects’ balance control (Collins, 2002; Priplata, 2006). Results of this study were in line with their earlier balance studies, not involving SR intervention, which were based on the assumption that the act of maintaining an erect posture could be viewed, in part, as a stochastic process (Collins, De Luca, Burrows, & Lipsitz, 1995; Collins & De Luca, 1993). The pair of
studies used posturographic analyses of human subjects to demonstrate that COP trajectories could be modelled as fractional Brownian motion and that at least two control systems - a short term mechanism and a long-term mechanism – were operating during quiet standing. Results from the two studies suggest that over short-term intervals open-loop control schemes are utilized by the postural control system, whereas over long-term intervals closed loop control mechanisms, which are subject to SR intervention, are called into play (Collins, 1993; Collins, 1995).

The second and more recent theory that emerges is that SR enhances the sensitivity of cutaneous mechanoreceptors and of proprioceptors, increasing the internal SR of the human control system (Mendez-Balbuena et al., 2012). This in turn increases the neuronal synchronization between motor areas and muscles and thus improves motor control by increasing the stability of the performance (Mendez-Balbuena et al., 2012). A possible neuronal mechanism underlying such an effect involves mechanical noise producing small changes in strain on the receptor membrane that translates to small fluctuations in receptor transmembrane potentials through changes in ion permeability (Priplata et al., 2006; Priplata et al., 2002). As the membrane partially depolarizes, the potential of the neuron is brought closer to the threshold for firing an action potential in the presence of a weak signal (Mendez-Balbuena, 2012; Repperger, 2005). It effectively becomes predisposed to fire or sensitized to additional mechanical stimulation or input. Therefore, a mechanism is provided by which normally sub-threshold mechanical stimuli (i.e. weak haptic signals from laparoscopic tooling) become detectable in the presence of mechanical noise (Priplata et al., 2006; Priplata et al., 2002; Liu, 2002; Kurita, 2011).
Our results are more in line with this sub-set of previous studies involving the proposed sensitization of mechanoreceptors and other physiological structures that make up the human somatosensory system. The results of the present study are likely to be less related to the studies involving the use of SR to improve balance control, tracking tasks and other closed-loop control systems (Collins, 2002; Repperger, Phillips, Berlin, Neidhard-Doll, & Haas, 2005).

These results from earlier studies and those from the present research suggest that SR may in-fact operate on several mechanisms which are task based. Tracking tasks such as balance control and target aiming are affected via one mechanism and tasks such as texture and compliance differentiation are affected via a different mechanism. However, more study into this theory is needed in order to make a definitive conclusion.

In the case of the laparoscopic palpation task that was used in this experiment, an increase in accuracy or task completion time can be directly correlated to a subjects ability to differentiate between soft tissue (silicon) and a harder mass (tumor) located within the soft tissue. The ability to correctly differentiate between different tissue compliances is similar to the differentiation tasks found in the literature involving sand paper and objects with varied surface textures (Brydges, Carnahan, & Dubrowski, 2005; Kurita, 2011). Performance during such differentiation tasks can be directly linked to sensorimotor abilities and sensitivity of the mechanoreceptors in the palmer region of the hand used to grasp the tool (Darian-Smith, 1984; Johansson & Westling, 1984). Therefore, accuracy rate for the task can be directly linked to a performance measure
associated with laparoscopic palpation skill level when differentiation between tissues of differing compliance. The time variable is inherently more difficult to directly relate to performance in the palpation task used. The time variable is a challenge due to confounding factors that could not easily be controlled during the experiment such as subjects' varied decision making strategies and the importance they placed in the time-accuracy tradeoff of the task.

The results of the data analysis and ANOVA show significant improvement in accuracy over the control condition with the Control-SR group only. This indicates that of the four groups (Control-Control, Control-SR, Control-VIB and Control-VIB+SR) only those given the SR stimulus improved in accuracy from the control to the stimulus trial. Furthermore, lack of significant accuracy improvement in the Control-Control group allows the researchers to conclude that the learning effect associated with the task from the first to the second trial was not a significant factor in determining accuracy. When the same analyses were performed on the time variable data, no evidence was found to suggest that SR or any of the other independent variables have a significant effect on the time it takes for subjects to make a determination. Data analysis was also performed on the mean increase in accuracy for each subject group. Although each group showed improvement from the first trial (Control) to the second trial (SR, VIB, VIB+SR, or Control), a one-way ANOVA and Tukey-Kramer HSD shows that the Control-SR group performed significantly better than the Control-VIB and Control-Control groups in terms of improved accuracy. This indicates that although some accuracy improvement was seen with the other three stimuli treatments, that only the SR stimulus resulted in a significant
improvement in accuracy rate. The lack of significant improvement over the Control-VIB+SR group may be due to the fact that the SR signal was present, but the effect was degraded by the presence of the VIB condition at the same time. For the time variable, a one-way ANOVA was also performed on the mean decrease/increase in time to task completion for each group from the control trial to the stimulus trial. The results indicate that there was not a significant difference between any of the conditions. Furthermore, the range of the times for all conditions ranged from approximately 5 to 30 seconds without any significant correlation. These results suggest that none of the treatment conditions (SR, VIB, VIB+SR) or Control produced any significant change in the time needed to make a decision during the process. As a whole, results for the accuracy and time variables suggest that SR affects the accuracy associated with compliance differentiation, but not the time needed to make a decision during the process.

The force profiles recorded for each of the 1152 trials were not analyzed for the accuracy variable because the author did not feel they were of great use in determining the accuracy rate. Since each of the samples were numbered and delivered in a random order which was known only to the researchers, the accuracy could objectively be determined by comparing the subjects’ answers to the know answers of whether the sample was a target or non-target. The force profiles could be used if the author wanted to determine if there was a significant correlation between accuracy rate and average force applied to the tissue samples. While this would be interesting information and potentially useful for future experiments, the author set out to determine if vibration
condition had an effect on accuracy and time to make a determination of “target” or “non-target.”

The research of McMahan et al. and Bark et al. along with Bholat all together make the argument for measurement and study of LS tool vibrations to characterize tissue properties (compliance, texture, consistency, etc.). Given the results of the present experiment, one possible explanation for the increase in accuracy seen in the SR group is that the mechanical vibrations resulting from the interaction between the end effector of the LI and tissue sample being palpated were enhanced by the addition of the noise contained within the SR signal. The weak, sub-threshold tool vibrations combined with the sub-threshold noise signal resulted in the resonance of the tool vibrations with similar frequencies, thus boosting the SNR to a point where they were pushed above the sensory threshold where they were read by the mechanoreceptors of the somatosensory system and interpreted by the central nervous system.

Another potential explanation for the increase in accuracy performance seen with the SR group is that the mechanoreceptors themselves were affected by the SR and their sensitivity was increased. There are several studies found in the literature where even elderly subjects with neurological disorders such as peripheral neuropathy experienced increased tactile sensitivity when SR was applied to that specific body part (Liu et al., 2002; Priplata et al., 2006). In a study involving older subjects, subjects with stroke, and subjects with diabetic neuropathy Liu et al. tested subjects' sensitivity on the plantar aspect of their feet with a standard Weinstein monofilament exam. Results from the study
show that SR significantly increased subject's sensitivity to the tactile stimulus delivered by the Weinstein test. The results are also concurrent with more recent research into the ability of SR to enhance tactile sensitivity. Kurita et al. describe research of a SR based, wearable sensorimotor enhancement device for the finger. They used a battery of evaluative tasks including the Weinstein monofilament test, sensitivity tests, texture differentiation as well as a grasping test to show that the device did in fact significantly improve subjects' sensorimotor performance when an optimum level of SR was applied (Kurita, Shinohara, & Ueda, 2011). These results were later applied to a surgical application when the same SR device was attached to a pair of grasping forceps commonly used in MIS. Experimental results again confirmed that the application of appropriate vibrations enhanced the tactile sensitivity even when using the forceps. These results support past studies that investigated the SR effect on the improvement of tactile sensation (Gescheider, Bolanowski, Pope, & Verrillo, 2002; Harada & Griffin, 1991; Kurita, Shinohara, & Ueda, 2011). The experimental results imply that the proposed forceps can be used in practical surgical situations where a high sensitivity of touch is required. The results of the aforementioned studies and those of the present research suggest that SR could also improve sensorimotor capabilities and thus performance in laparoscopic surgical applications.

The authors again found it intriguing that the vibrotactile feedback treatment condition (VIB) did not yield any significant improvement over the Control condition for either the accuracy or time variables. Previous research involving vibrotactile feedback in a laparoscopic surgery task has shown that force information in the form of vibrotactile
feedback increased subject’s sensitivity to tissue contact and improved their ability to consistently and accurately differentiate tissue softness or compliance (Schoonmaker & Cao, 2006). This would suggest that there should have at least been some significant difference between the Control and VIB conditions. Also, the results from the study by Zhou and Cao showed that subjects were able to perform more accurately, quickly and with more confidently, applying lower peak forces and smaller force ranges to make a judgment regarding the presence of an embedded structure, with vibrotactile augmentation than without (Zhou & Cao, 2009). The present experiment sought to duplicate Zhou’s experimental design and set up for the VIB and Control conditions utilizing the same tissue samples, equipment and modulation parameters. It is puzzling and intriguing why the VIB condition failed to yield improvement in at least one of the performance measures studied (time, accuracy). The literature clearly points to the benefits of vibrotactile feedback in an MIS probing/palpation task beginning with Plinkert et al. who concluded that the introduction of artificial tactile sense to minimally invasive procedures would enable the surgeon to differentiate between critical anatomical structures, as well as normal and pathological tissues. Furthermore, the technology had the potential to reduce complication rates in MIS and possibly expand its range of indications (Plinkert, Baumann, Flemming, Loewenheim, & Buess, 1998). In terms of application and real-world efficacy, the experiment by Baumann showed success in using vibrotactile feedback in tumor identification in an oral surgery application (Baumann, 2001). These early studies along with the results from the aforementioned works by Schoonmaker and Cao and later by Zhou and Cao strongly suggest that the addition of vibrotactile feedback in MIS applications provides valuable information concerning force
feedback and tissue compliance that is capable of significantly improving surgical task performance (Schoonmaker & Cao, 2006; Zhou & Cao, 2009; Zhou, 2010).

A possible explanation for the conflicting results between the present research and Zhou’s research is that there was a difference in the voltage applied to the linear amplifier which was used to drive the C2 tactor. Previous research, including Zhou, 2010, did not discuss how much voltage was applied via the power source to the linear amplifier used in the experiment. Therefore the researcher used the manufacturer’s specifications which suggested to use a bipolar, linear amplifier at 2V rms, and 0.5 A rms (EAI C2 Tactor Spec. Sheet). In each experiment performed the power supply was set at 2 V to power the linear amplifier that the square sine wave signal was output to via the custom LabVIEW program. During the set-up of the experiment, the researcher did at times increase the voltage which would drive the amplifier and C2 tactor harder, however this could potentially lead to an overload on the amplifier and tactor. It is possible that the experiment run by Zhou was carried out using a higher voltage supplied to the amplifier and C2 tactor that made up the vibrotactile feedback system. It is also possible that the power requirements for the linear amplifier were misconstrued by the researcher of the present study. It is the opinion of the author that a failure in the VIB condition does not affect the conclusion that the Control-SR group performed more accurately than the Control-Control group suggesting performance enhancement via SR. However, it does affect the conclusion that Control-SR performed more accurately than the Control-VIB group as well as Control-VIB+SR group. In order to verify any conclusions involving
the VIB condition, the experiment would need to be repeated for those groups containing the VIB independent variable.

5.4 Conclusions

Although further investigation is necessary to determine the mechanism of SR in improvement of surgical skills, the application of SR to a laparoscopic instrument or directly to the surgeon is a promising route to assist surgeons in a minimally invasive surgery. The results of this study have implications for the design of instruments and potential methods for increasing accuracy performance in minimally invasive surgical skills such as tissue compliance differentiation. Technology that delivers a SR signal to the surgeon via tooling or direct application could help surgeons better identify tumors located in healthy surrounding tissue and further improve outcomes and patient safety in surgical procedures.

5.5 Limitations and Future Direction

The results of the present experiment add to the growing body of evidence that exists for use of SR in sensorimotor enhancement. Although the results suggest that SR can be used to increase accuracy performance in a laparoscopic palpation task, there is still an overwhelming lack of evidence for its use in MIS. The authors were only able to
find one other study which investigated the potential benefits of SR in a MIS application. Combined with our results the existing literature only suggests that performance enhancement is possible. More investigation into the mechanism that allows SR to enhance performance is needed. Two of these potential avenues are discussed in this paper in the possible amplification of existing haptic signals and the sensitization of mechanoreceptors theories. It is suggested that further research into this topic include exploring different locations for the application of the SR signal to include the instrument itself as well as on the palmer region of the hand in which the highest density of mechanoreceptors exists. It is also suggested that the magnitude of the SR signal just below the sensory threshold (T) be determined for each individual subject and that different magnitude levels of this signal (-0.25T, -0.5T, 0.25T, 0.5T) be evaluated to determine if an optimum level of noise exists that produces maximum benefit in terms of performance enhancement during the palpation task.
BIBLIOGRAPHY


