Application of Human Factors in Surgery: Studies on Technique, Displays, and Performance

by

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To Mom and Dad

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CHAPTER 1

INTRODUCTION

1.1. Overview

The overall goal of this work is to develop and demonstrate a framework (Figure 1.1) that can be used to describe surgical procedures, measure performance, and identify ergonomic risk factors that may affect surgical outcomes and musculoskeletal stresses (MS stresses). This framework relates the studies presented in this work and is used to understand the impact of findings on surgical procedures and surgeon musculoskeletal health. The rationale and development of the framework will be further described in the following sections.

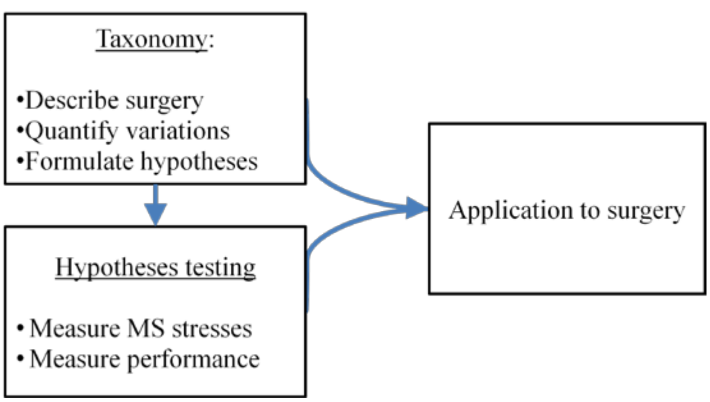

Figure 1.1: Framework for an ergonomics investigation of factors impacting surgery. First, a taxonomy is developed to describe and quantify variations in surgical procedures so that hypotheses of observed variations on outcomes can be formulated. Hypotheses and observations from taxonomy are used to develop laboratory studies that test the impact of

ergonomic factors on surgeon MS stresses and performance. Finally, both laboratory studies and taxonomy are used to discuss the impact of findings to surgical practice.

1.2. Background and Significance

1.2.1. Describing variations in surgical techniques

Since the publication of To Err is Human (Kohn et al. 2000), research has been focused on preventing and reducing medical errors to improve patient outcomes (Leape & Berwick 2005; Hoff et. al 2005). However, factors that may not necessarily be defined as errors, like surgical techniques, can also affect outcomes. Variations in technique commonly exist in surgical procedures and patient outcomes may vary by a factor of two to three among surgeons (Pattani et al. 2010; McCulloch et al. 2002; Gawande 2012). Many different choices, methods, and techniques can be used to complete the same surgical procedure, but some methods may be better than others in terms of surgical performance as measured by clinical outcomes (e.g., tissue failure, re-operations) and systems level outcomes (e.g., time to completion, cost). Surgical outcomes may benefit from understanding how specific methods and techniques impact surgical performance and standardizing surgical procedures based on methods that are associated with best outcomes (Armstrong et al. 2012).

Historical examples showed that the standardization of work can provide a cornerstone for improvements in manufacturing. In the early 20th century, methodologies like motion studies (Gilbreth 1911) and the “one best way” (Taylor 1911) greatly increased the quality and efficiency while minimizing waste and costs. The application of these concepts to surgery can provide similar benefits. Motion studies can improve operation efficiency and surgeon health by identifying work methods that contribute to wasted motions and worker fatigue (Gilbreth 1911). Identifying the “one best way” (Taylor 1911) can improve patient outcomes and facilitate surgeon communication and training.

Several studies in surgery investigated the impact of standardization on improving patient outcomes and communication among medical practitioners (Greenwald et al 2000; Wibe et al. 2005; Attwood et al. 2008; Shrikhande et al. 2008; Kawanaka et al. 2009). These studies proposed surgical standards on the timing of treatment, selection of procedures, and standardized techniques and showed that these efforts led to better patient outcomes (Greenwald et al. 2000; Wibe et al. 2005; Shrikhande et al. 2008; Kawanaka et al. 2009). However, current standards may be limited by subjectivity and the lack of quantitative assessment criteria. Standards were created from “recommended guidelines” that surgeon(s) agreed upon and were based on the subjective experiences of the surgeons (Wibe et al. 2005; Attwood et al 2008; Kawanaka et al 2009). While recommendations based on surgeon experience can be an important step towards standardization, techniques and variations that surgeons disagree amongst may be of particular interest for investigating how variations impact on patient outcomes.

The complexity of surgical work presents a major barrier to systematically describing and linking variations in surgical procedures to surgical outcomes (Lowndes & Hallbeck 2012; Hignett et al. 2013), and these challenges include 1) the large amount of surgical tools and technique that surgeon can choose from, 2) the complex and technical skills performed in surgery, 3) the long length of the procedures, and 4) the variability from patient factors. For example, surgeons have many different vessel suturing techniques (e.g., backwall first, 180°, 120°, end-to-side) and tools (e.g., frame clamp, double clamp) that can be used to complete a microsurgery procedure (Pederson 2010), and a granular description of the surgery is needed to distinguish these variations among cases. Similarly, many tasks in surgery require advanced technical skills and fine-motor control (Pederson 2010) that are difficult to capture and compare using techniques like motion analysis (Gilbreth 1911). Finally, microsurgery tissue transfers were observed to last between 430 to 692 minutes (Ross et al. 2003), thus the length of procedure presents a challenge for detailed description and comparison across a large number of cases. To address these challenges, previous investigators have emphasized the need for new task analysis techniques to better document surgical procedures and analyze surgical events (Hignett et al. 2013).

The descriptive and quantitative tools in human factors, e.g., motion studies and work observation, have potential for addressing current gaps in describing surgical techniques. Several studies explored the application of hand-motion analysis and hierarchical task analysis (HTA) in surgery. For example, Grober et al. (2003) suggested that suturing techniques and surgeon skill can be quantified and compared using hand-motion analysis to measure the number of movements and hand-travel distances. Other studies showed that HTA can be used to decompose surgeries to discrete events and found that HTA provided the flexibility in analyzing lengthy surgical procedures (MacKenzie et al. 2001; Sarker et al. 2008). Although these studies showed that motion studies and HTA can be applied to surgery, current work does not adequately address the technique and patient variations that exist in surgery. *The large amount of variations that exists in surgery must be sufficiently described so that variations in methods can be associated with good or bad outcomes.*

The first aim of this work is to develop a taxonomy that systematically describes surgeries so that technique variations can be quantified among surgeons and cases, and this aim is represented in the framework (Figure 1.1). Observed variations among cases and observed work requirements identified with the taxonomy are used to drive the formation of hypotheses on surgical outcomes, surgeon performance, and surgeon stresses that can be tested to identify best methods (Figure 1.1). Chapter 2 highlights several hypotheses on the impact of surgical techniques on surgical outcomes formed using the taxonomy (Figure 1.1). Common among all observed cases was the need for magnification equipment to perform each technique described by the taxonomy; however, microscope use has been frequently documented to affect surgeon fatigue and musculoskeletal injuries (Park et al. 2010; Capone et al. 2010; Statham et al. 2010; Franken et al. 1995). Specifically, visualization equipment is observed to be critical for surgical tasks described using the taxonomy; however, use of visualization equipment can increase musculoskeletal stresses among surgeons (Nimbarte et al. 2013; Capone et al. 2010). Following the framework (Figure 1.1), laboratory studies are designed to test hypotheses on the impact of various visualization equipments on surgeon performance and musculoskeletal stresses. Studies were designed to simulate 1) microsurgery skills described by the taxonomy, e.g., holding blood vessels during needle drives, moving tissues, and manipulating suture threads, and 2) task conditions observed by the taxonomy, e.g., field of view, workplace constraints (Figure 1.1).

1.2.2. Reducing surgeon's musculoskeletal stresses

The health of the surgeon and his or her ability to perform quality surgeries are concerns (Park et al. 2010; Szeto et al. 2009). Musculoskeletal pain, fatigue, and discomfort can affect the comfort of surgeons and their ability to complete necessary tasks. In addition, biomechanical and physiological factors may also affect how long surgeons continue to practice. However, studies showed that the prevalence of musculoskeletal symptoms was as high as 87% among surveyed surgeons (Park et al. 2010; Szeto et al. 2009). From anecdotal and survey reports, injuries resulted in lengthy time-away-from-work (Liberman et al. 2005), and time-away-from-work may create a void that other surgeons must fill by increasing their workload. In ophthalmic surgeons, Sivak-Callcott (2011) showed that 9% of surgeons stopped operating due to neck pain. Previous work suggested that surgeon postures may have contributed to the prevalence of musculoskeletal injuries (Nimbarte et al. 2013; Capone et al. 2010; Szeto et al. 2009). For example, odds of neck symptoms were twice as high with the presence of physical ergonomic risk factors (Szeto et al. 2009). In addition, posture constraints were postulated to be responsible for the significant associations observed between microscope-use-greater-than-three-hours-per-week with the prevalence of cervical and thoracic pain reported among 339 surveyed plastic surgeons (Capone et al. 2010). Due the high cost of training and impending shortage in the surgical workforce by 2030 (Williams et al. 2009), musculoskeletal disorders disabling surgeons and affecting career longevity can be a costly form of waste to healthcare.

Methodology in human factors and ergonomics has been proposed for reducing musculoskeletal injuries and fatigue in surgery (Lowndes & Hallbeck 2012; Berguer 1999). For example, Patkin (1977) used principles established in manufacturing (Gilbreth 1911; Taylor 1911) and suggested that poor microscope height or table settings during microsurgery may lead to neck fatigue and trapezius strain. Qualitative studies observed that operating microscopes required surgeons to be fixated over optical eyepieces (Franken et al. 1995), constrained the surgeon's eye locations, reduced comfort (Franken et al. 1995), and forced surgeons to be in awkward positions (Ross et al. 2003). Although quantitative studies linking microsurgeon postures with musculoskeletal symptoms are limited, the literature in manufacturing and office ergonomics have shown that constrained postures, sustained muscle exertions without sufficient recovery time, and non-neutral postures may be risk factors for musculoskeletal injuries (Buckle & Devereux 2002; Rempel, Harrison, & Barnhart 1992; Hünting et al. 1981; Harms-Ringdahl and Ekholm 1985). Specifically, ergonomic studies showed that 1) 26-30% of employees using visual display terminals reported that pain limited their head mobility and suggested a casual relationship between pain and postures constrained by visual display terminals (Hünting et al. 1981), 2) muscle exertions with insufficient recovery time were associated with physical discomfort and may be a precursor to chronic muscle, tendon, and nerve disorders (Rempel, Harrison, & Barnhart 1992), and 3) static neck flexion at extreme angles resulted in discomfort or pain within 15 minutes in all subjects in a laboratory setting (Harms-Ringdahl & Ekholm 1985).

The second and third aims of this work focus on measuring the impact of visualization equipment, i.e., microscope, loupes, and video, on musculoskeletal stresses and performance. Laboratory studies were designed using task and conditions described by the taxonomy (Figure 1.1), and the third and fourth chapters of this work presents laboratory studies that measure the impact of visualization displays (i.e., microscope, loupes, and video displays) on postural stresses and on task performance. The final chapter discusses the applications, impact, and limitations of this work to surgical practice by using the taxonomy to link laboratory findings to relevant tasks, task needs, and ergonomics factors described in surgery (Figure 1.1).

1.3. Research Aims

The overall goal of this research is to develop a framework (Figure 1.1) that can be used to describe surgical procedures, measure performance, and identify ergonomic factors that affect surgical outcomes and musculoskeletal stresses. The following specific aims are investigated in this dissertation:

Aim 1: Develop a taxonomy that systematically describe surgical procedures and the variations in surgeon technique in order to form hypotheses on best methods for surgical outcomes, performance, and musculoskeletal health (Chapter 2)

Aim 2: Test hypothesis on microsurgery factors that may affect musculoskeletal stresses in a laboratory setting. Specifically, measure the impact of visualization equipment on postures during simulated microsurgery skills tasks in order to quantify the benefits of alternative video displays to conventional microscope (Chapter 3), and

Aim 3: Test hypothesis on microsurgery equipment and task conditions that may affect surgeon performance. Specifically, determine the impact of microscope, loupes, and video displays on performance during small-amplitude targeting tasks and the application of video displays during microsurgery (Chapter 4).

1.4. Dissertation Organization

This dissertation is presented in five chapters. Chapter one provides an introduction to the problem, rationale, and aims for this work. Chapters two through four are presented as stand-alone manuscripts which describe three studies illustrating the development and application of the framework (Figure 1.1) and addressing one or more of the specific aims proposed in the introduction. Chapter five is an integration and discussion of the findings from the previous chapters and presents overall conclusions and recommendations for future work.

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CHAPTER 2

IDENTIFICATION OF TECHNIQUE VARIATIONS AMONG MICROVASCULAR SURGEONS AND CASES USING HIERARCHICAL TASK ANALYSIS

Abstract: A hierarchical taxonomy was developed for identifying differences among microvascular surgeons and cases and for investigating the impact of those differences on case outcome. Hierarchical task analysis was performed on eight microvascular anastomosis cases. The analyses was simplified by redefining subtasks and elements to only describe actions and adding attributes to describe the work object, method, tool, material, conditions, and ergonomics factors. The resulting taxonomy was applied to 64 cases. Differences were found among cases for the frequency and duration of subtask, elements, attributes, and element sequences. Observed variations were used to formulate hypotheses about the relationship between different methods and outcomes that can be tested in future studies. The taxonomy provides a framework for comparing alternative methods, determining the best methods for given conditions, and for surgical training and retraining.

Keywords: health care ergonomics, ergonomics tools and methods, task analysis, surgical methods, standardization

Practitioner summary: A hierarchical taxonomy, created from a hierarchical task analysis and work attributes, was applied to describe technique variations among microsurgery cases. Variations in time, frequency, and sequence were used to form hypotheses on best methods for standardizing procedures.

2.1. Introduction

This work aims to develop a systematic framework for describing and comparing variability in surgical technique. This framework can be used to: (A) describe surgical procedures with sufficient granularity such that methodological differences among surgeons can be identified, (B) formulate hypotheses about the effects of observed variations on biological outcomes for future testing, and (C) standardize surgeon training, performance assessment, and surgical procedures on best practices.

Since the publication of *To Err is Human* (Kohn, Corrigan, and Donaldson 2000) which estimated that at least 44,000 Americans die annually due to medical errors, research has been focused on preventing and reducing medical errors to improve patient outcomes (Hoff et al. 2004, Lane, Stanton, and Harrison 2006, Bonrath et al. 2013, Hignett et al. 2013). However, factors that may not necessarily be defined as errors, like surgical techniques, can also affect outcomes. Variations in technique commonly exist in surgical procedures, and patient outcomes may vary by a factor of two to three among surgeons (Pattani et al. 2010, McCulloch et al. 2002, Gawande 2012). Many different choices, methods, and techniques can be used to complete the same surgical procedure, but some methods may be better than others in terms of surgical performance (e.g. time to completion, cost). Hignett el al. (2013) identified the need to understand the complexity of surgery and called for the development of a library of well-researched surgical procedures. Understanding how specific methods and techniques impact surgical performance may allow for improved evidence-based surgeon training methods.

Currently, the training of surgeons is largely based on the Halstedian apprenticeship model (Rodriguez-Paz et al. 2009, Temple and Ross 2011); surgical trainees learn from senior surgeons and receive subjective feedback based on their trainers' experiences. Because "every clinician has his or her own way of doing things" (Gawande 2012), there is a lack of universal standards, resulting in subjective assessment of technical skills and competencies. Efforts to categorize and evaluate technical skills have led to many assessment instruments, including global rating scales (Martin et al. 1997), simulations (Cristancho, Moussa, and Dubroski 2011), and procedural checklists (Kalu et al. 2005, Chan, Niranjan, and Ramakrishnan 2010). While these instruments decompose surgical procedures into different skill sets, they are often too general (global rating scales) to assess specific steps or too specific (checklists) to allow for comparisons across different techniques. Furthermore, these instruments are largely developed based on the experience and expectations of expert surgeons rather than direct clinical evidence of a best practice. There is a need to move beyond current assessment paradigms and move towards the standardization of surgical techniques based on best methods (Armstrong et al. 2012).

Standardization of work has been a cornerstone for manufacturing, helping to identify and address abnormal conditions that can adversely affect outcomes. Standardization is similarly important for clinical applications. Kawanaka et al. (2009) reported that standardizing the criteria for splenectomy procedure selection (i.e. purely laparoscopic or hand-assisted), placement of patient and instruments, and steps for dissecting tissues significantly reduced operation time and conversions to open surgery in 159 patients. Shrikhande, Barreto, and Shukla (2008) reported that standardizing the pancreaticoduodenectomy procedure with pancreaticojejunostomy technique reduced pancreatic leaks from 16% to 3.2% in 123 patients. Wibe et al. (2002) reported that standardizing mesorectal tissue excision technique increased four-year survival rates from conventional surgery (73% v. 60%) among 1,395 Norwegian patients who underwent colorectal surgery. Similar benefits of standardizing surgical tools, materials and methods were also reported by Z'Graggen et al. (2002).

While studies have shown that standardizing surgical procedures improves outcomes, these authors acknowledge that there is still much debate about what makes one method better than another and what is the best method for a given conditions (Wibe et al. 2002, Shrikhande, Barreto, and Shukla 2008). This implies that (1) the consistency by which a procedure is performed helps the surgical team work together effectively and (2) standardization provides important benchmarks so that surgeons know when they need to vary a procedure to address variation in patients and conditions.

Standards for surgical procedures have largely relied on the experience and recommendations of surgeons. While acknowledging the value of this, moving beyond expert opinions to best techniques based upon clinical evidence may further improve outcomes. Berguer (1999) describes the application of time and motion study methods to identify and control sources of variability in surgery and traces this method to Taylor and Gilbreth in the early twentieth century (Taylor 1911, Gilbreth 1911). Application of time and motion study to surgical procedures has been limited by the length and complexity of the procedures, which makes them hard to describe using a micro-motion analysis. The time required to describe all the possible motion sequences is a major limitation for performing a detailed motion analysis for a surgical job. Alternatively, hierarchical task analysis (HTA) divides tasks into subtasks, subtasks into elements, and elements into motions as needed to achieve the desired level of detail and to identify possible problems with a particular method (Stanton 2006). HTA has been successfully applied to describe tasks and to identify errors for a number of complex medical procedures including administration of medications, various laparoscopic surgeries, microvascular surgeries, anaesthesia, and medical handovers (Lane, Stanton, and Harrison 2006, Phipps et al. 2008, Raduma-Tomàs et al. 2012, Sarker, Kumar, and Delaney 2010, MacKenzie et al. 2001, Armstrong et al. 2012, Bonrath et al. 2013).

MacKenzie et al. (2001) have proposed that HTA can be a used as a broad framework for surgeon-task-tool analysis and Sarker et al. (2008) have suggested potential applications of HTA for identifying technical skills for surgeon assessment. Additionally, Armstrong et al. (2012) have demonstrated how HTA can be used to describe and identify differences in how suturing is performed. HTA can be used to determine how much a surgeon handles the tissue, how long it takes to complete subtasks or tasks, and how those factors relate to medical outcomes, e.g. repeating key portions of an operation or the entire operation, patient recovery time, development of peri-operative complications, and completeness of recovery.

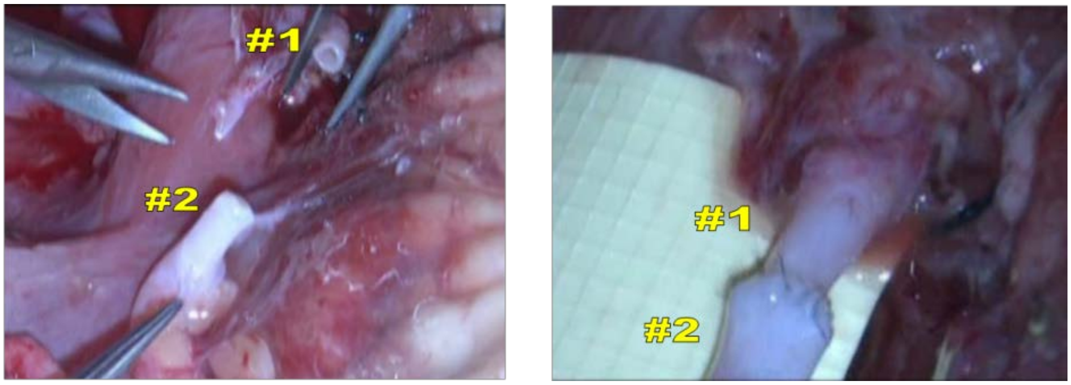
In this work, we develop and demonstrate a hierarchical taxonomy that can be used to describe surgical procedures with sufficient detail to identify differences among techniques used by surgeons. We also formulate a number of hypotheses regarding the sources of those differences and the relationship between this variation in technique and clinically relevant outcomes.

2.2. Development of the surgical taxonomy

This work was divided into three steps: (1) development of initial taxonomy, (2) evaluation and refinement of the taxonomy, and (3) application of the taxonomy. A description of the surgical procedure and of each step is discussed in the following sections.

2.2.1. Microvascular anastomosis

Microvascular anastomosis procedures are used to develop the proposed taxonomy; however, this framework can be adapted to other surgical operations. Microvascular anastomoses procedures join blood vessels from transplanted tissue, typically muscle or skin, (referred to by surgeons as a "flap," #2 in Figure 2.1), with vessels at the recipient site (#1 in Figure 2.1) to re-establish blood flow to the flap. These flap transfers are often performed to repair congenital defects, traumatic injuries or damage following cancer surgery. Blood vessels, one to four mm in diameter, from flap tissue are attached to blood vessels in the recipient tissue in order to re-establish blood flow to the flap tissue in its new location. To isolate and join the blood vessels, a dual-head stereoscopic operating microscope is used by two surgeons to perform the necessary actions (cut, dissect, drive needle, tie suture, etc.). Access to the operating rooms was coordinated by the surgeon co-author. Complications from or failure of flap transfers, often apparent within a week, are recorded for future studies that statistically link methods with outcomes.



a) b)

Figure 2.1: **Microscope view of recipient and flap tissue. Recipient artery (#1) and flap artery (#2) before (a) and after (b) completion of anastomosis**

Microvascular anastomosis was chosen for this study because: 1) it can be decomposed into well-defined steps that are required for all cases, 2) there are many ways of performing each step, 3) surgeons do not agree on the best way to perform each step, 4) outcomes related to various steps are immediately apparent, 5) dissecting microscopes are equipped with cameras that can be used to record the procedures without interference, 6) it is frequently performed at ~160 cases per year in a large teaching hospital, and 7) it provides a good example that can be applied to other procedures, e.g. laparoscopic, endoscopic, dental.

2.2.2. Development of initial taxonomy with HTA (version 1)

2.2.2.1. Data collection

This study was approved by the University Medical School Institutional Review Board (IRBMED:HUM00010638). All attending surgeons from plastic, otolaryngology, and oral specialties that have completed more than 50 microvascular anastomosis procedures were recruited at one university hospital using emails and direct contact. Eight surgeons from plastic and otolaryngology and their patients consented to the recording and studying of their surgeries and surgical outcomes. Surgeons and patients received no compensation for participation. We attempted to record all cases from participating surgeons between August 2010 and August 2011, but only 73 cases (71% of all eligible cases) were recorded due to study team availability and patient consent. Videos were recorded from operating microscopes that typically had a field of view of 6cm-by-10cm with magnification capabilities from 6x-20x, used at the discretion of the surgeon. The recordings captured surgical tools, tool motions, and the surgeon’s view of the patient worksite.

2.2.2.2. Hierarchical task analysis

The methodology for describing surgical procedures was based on hierarchical task analysis (Annett and Stanton 1998, Lane et al. 2006, MacKenzie et al. 2001, Stanton 2006, Sarker et al. 2008). Hierarchical task analysis (HTA) was conducted using video analysis facilitated by software written in Visual Basic for Microsoft Excel that was adapted from Armstrong et al. (2003). The software allowed the user to stop the video, and to play it forwards and backwards. It also allowed the user to input time-stamped annotations that linked directly to the video files. Led by co-author SK who has been a full-time microvascular surgeon in an academic hospital for 15 years, two study team members trained in work observation decomposed the procedure into goals, sub-goals, and additional levels of details following the HTA principles outlined by Stanton (2006). Surgical events corresponding to these goals were annotated in eight full microvascular anastomosis procedures and reviewed by the study team to create the initial taxonomy.

The initial taxonomy contained five levels of detail: Job, Task, Subtask, Element, and Motions levels. The job “microvascular anastomosis” was decomposed into tasks based on the major goals and objectives of the surgery (described previously in Section 2.1). Each task was then decomposed into multiple subtasks by decomposing the goal of each task into smaller more defined sub-goals. Each task was composed of a sequence of subtasks. Subtasks were similarly decomposed into elements by decomposing the subtask goal into more specific sub-goals. Each subtask was composed of a sequence of elements with different subtasks having different elements. Each element corresponds to a sub-task goal and can be further decomposed in motions or "therbligs" as described by Gilbreth (1911) and investigated by Jun et al. (2012). An example element is “Irrigate field,” with requires a sequence of grasp, position, and use motions. Elements could be decomposed into motions if needed (Jun et al. 2012), but that level of detail did not provide sufficient additional information in this study to justify this additional level of decomposition. Additional details of the initial taxonomy can be found in an earlier proceedings publication Yu, Kasten, and Armstrong (2010).

2.2.3. Evaluation of initial taxonomy

2.2.3.1. Interviews

Five experienced plastic and otolaryngology surgeons were interviewed by the study team, which includes the authors and a focus group specialist. Three of the surgeons were interviewed as a group, while the other two were interviewed individually. In each case, the overall framework and selected sections of the taxonomy were presented, supplemented with corresponding video clips of the operation. Through discussions among the research and clinical investigators, five questions were developed to assess if focus group participants could use the taxonomy, to determine if anything could be eliminated or needed to be added, and to identify other possible improvements. Discussion was focused on five key questions:

Using the descriptive tasks and subtasks of the taxonomy, how well could you instruct another surgeon to perform the procedure exactly how you do it?

- What is missing?
- What is unnecessary?
- How would you organize the taxonomy?
- How else can the taxonomy be improved?

Oral responses from surgeons were video recorded and coded by a study team member experienced in conducting focus groups. Each response was reviewed and discussed within the study team prior to any modification of the taxonomy. Expert surgeon feedback raised five major concerns:

(1) need to clarify the terms used as descriptors in the taxonomy, e.g. surgeons performing these procedures use the terms “recipient” and “flap” rather than “host” and “donor” (original terms proposed in taxonomy);

(2) need to add subtasks and elements in describing a task of the operation to distinguish between similar actions performed on different tissues, e.g. similar actions are performed on veins and arteries, but distinction is needed between actions done on veins and actions done on arteries;

(3) need to re-organize the subtasks and elements for better clarity and granularity, e.g. surgeons interpret the goals of “clean field,” originally an element of “join” subtask, separate from “join” subtask and as a distinct subtask in and of itself;

(4) need to describe more surgical tools; and

(5) need to characterize different ways tools are used, e.g. new elements are needed to describe where surgeons grasp the blood vessels with the forceps.

2.2.4. Refinement of taxonomy and addition of attributes

Additional tasks, subtasks, and elements were needed to document variations in tools, materials, and methods that were not observed in the initial cases. Modification of the taxonomy to incorporate these changes resulted in 33 subtasks and 244 elements to describe this operation of microvascular anastomosis.

It was found that combining similar subtasks and elements then adding attributes to identify the work objects, tools, materials, and methods of those subtasks and elements made the system less cumbersome (Armstrong et al. 2012). This resulted in the taxonomy seen in Figure 2.2. Subtask, selected element, and attribute definitions are shown in Table 2.1. For example, rather than having separate subtasks for “join artery” and “join vein,” the taxonomy has one subtask “join vessel” that could be appended with an attribute (Figure 2.2 and Table 2.1) that specify which type of vessel, e.g. vein or artery.

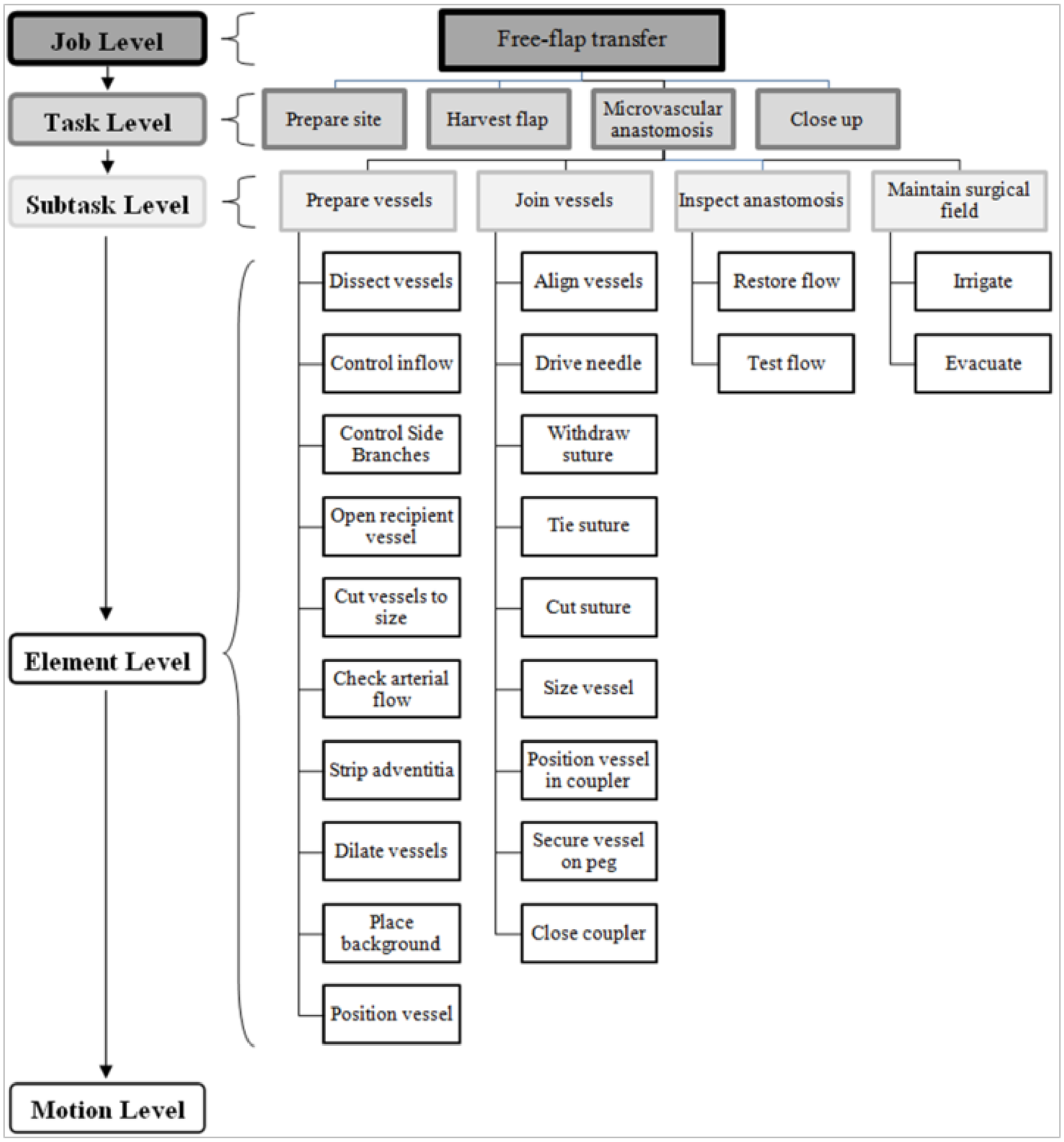


Figure 2.2: Proposed taxonomy contains Job, Task, Subtask, Element, and Motion levels. "Microvascular anastomosis" task decomposes into four subtasks. Each subtask decomposes into 2-10 elements. Motions (i.e. reach, grasp) as prescribed by Gilbreth were not implemented, but this level is included in the graphic for completeness and future use.

Table 2.1: Goals and start and end criteria for (a) subtasks, (b) selected elements used for join vessel subtask (see Figure 2.2), and (c) attribute definitions and examples. Subtask attributes apply to all subtask elements; element attributes may be unique to that element.

(a)

Subtask	Goals and start/end criteria
Prepare vessels	To identify and prepare vessels for joining, by dissecting and removing tissues surrounding the vessels Start: Tissues are in field of view End: Needle driver or coupler is used.
Join vessels	To connect the vessels together using sutures or mechanical coupler Start: Needle driver or coupler is used. End: Suture from the last stitch is cut
Inspect anastomosis	To ensure below flow through the vessels without leaks Start: Suture from last stitch is cut End: Microscope is turned off or when additional stitches are inserted
Maintain surgical field	To remove blood and debris Start: Sponge or irrigation tool enters the field of view End: Sponge or irrigation tool exits the field of view

(b)

Elements	Goals and start/end criteria
Align	To move vessels in alignment Start: Tool moves towards vessel to grasp and move End: Vessel is released from tool after move
Drive needle	To puncture vessel with needle Start: Needle moves towards vessel to pierce End: Needle fully passes the vessel walls or is removed before passing the vessel wall (failed attempt)
Withdraw suture	To pull suture through vessel Start: Suture is pulled through the vessel End: Suture thread is no longer being pulled

Tie suture	To fasten suture thread with knots Start: Suture thread is wrapped around needle driver End: Knots are tightened
Cut suture	To severe excess suture thread from knot Start: Scissors enter field of view to cut End: Suture threads at the ends of the knots are cut

(c)

Attribute	Definition and Examples
Work object	Definition: An object which is being used or transformed Examples: flap, artery, vein, suture, field
Method	Definition: Technique or sequence of actions that are performed to accomplish subtask or element goals Examples: vessel configuration, first stitch location, connection, needle grasp position, needle entry angle, stitch progression, needle extract, # of knots, withdraw
Tools	Definition: Devices, usually held in the hands, used to achieve goals Examples: apposition clamp, forceps, scissors, irrigation, suction
Materials	Definition: Items used to complete goals Example: suture
Ergonomics	Definition: Factors that affect human performance Examples: lumen visualization, posture, fatigue
Conditions	Definition: State of the work object or work site Examples: vessel diameter, stitch number, direction,

Thus, the subtasks and elements are actions that express *What* is done and the corresponding attributes describe *How* and the *Conditions* under which it is performed. Six groups of attributes are proposed: work object, method, tool, material, ergonomics, and condition. Attribute definitions and examples are listed in Table 2.1. The examples are not intended as a definitive list.

2.3. Application of taxonomy

The resulting taxonomy was applied to 64 cases that included 73 arterial and 79 venous anastomoses by three authors. Progress and questions were discussed monthly among all authors. Attributes for the "join vessels" subtask were determined for all cases (n=73 artery, 79 veins) to demonstrate the application of the taxonomy and show the range of variability. Suturing elements and element attributes for the "join vessels" subtask were determined for the 61 arteries and 46 veins (cases that use a mechanical coupling tool rather than suture were excluded) with usable videos at the element level. Element sequences for completing the first suture in seven different cases were determined to demonstrate how sequences can show variability among cases. Finally, observed subtask and element variations were used to develop hypotheses regarding the relationship between methods and outcomes.

The "join vessels" subtask was selected to exemplify this approach for decomposing a surgical task in order to link it to outcomes because: (1) this task involves suturing which is considered to be an important surgical skill, (2) suturing methods may vary significantly from surgeon to surgeon, (3) expert surgeons interviewed opined that elements in the "join" subtask have a high impact on outcomes. Each additional subtask in the HTA can be analysed in a similar manner.

2.3.1. Subtask analysis

Microvascular anastomosis procedures were decomposed into subtasks, following the model shown in Figure 2.2 and annotated with their start and stop times from the video recording as described in Table 2.1. Due to length of the procedure and the number of cases, analysis of all subtasks focused on seven cases. After inspecting all 64 cases, seven cases were selected that 1) contained clear, unobstructed view of all subtasks, and 2) encompassed a range of variations in how the "prepare vessels," "join vessels," "inspect anastomosis," and "maintain surgical field" subtasks were performed. The time required to complete these subtasks for arteries and veins are shown in Table 2.2. Additionally, the times to complete "join vessels" subtask for arteries and veins for all 64 cases are shown in Table 2.2 for comparison purposes.

Table 2.2: Observed time (seconds) to complete microvascular anastomosis subtasks for 7 cases and "join vessels" subtask times for all 64 cases

		Case #								
Subtask		1	2	3	4	5	6	7	Mean±SD (n=7)	Mean±SD (n=64)
Prepare Vessels (s)	artery	386	1,246	809	1,114	923	646	543	810±309	
	vein	648	1132	41	339	441	415	319	476±340	
Join Vessels (s)	artery	830	647	1,255	753	838	1,448	1,263	1,005±309	1,171±463
	vein	1,077	638	1,107	249	328	492	346	605±355	762±456
Inspect Anastomosis (s)	artery	22	11	36	25	25	44	46	30±12	
	vein	7	7	347	13	0	54	37	66±125	
Maintain Surgical Field (s)	artery	101	348	87	368	362	320	348	276±126	
	vein	117	121	37	166	67	74	151	105±47	
Total Time (s)		3,496	4,305	3,985	3,126	3,595	3,669	3,082	3,608±438	

Note: Due to idle time during the case, total time is not expected to equal the sum of all subtask times

The "join vessel" subtask accounted for almost 48% of the microvascular anastomosis time. The time to complete "join vessels" subtask for arteries was similar to veins in cases 1-3, but veins were three times faster for cases 4-7. This time difference may be important because it affects the time that the flap is deprived of blood flow and may jeopardize flap survival (Pattani et al. 2010). Longer anastomosis times also affect the workload and fatigue of the microvascular surgeon. For example, average time required to complete the 64 cases varied significantly (10.6 ± 6.9 hours) with half of the cases requiring more than 10 hours (microvascular anastomosis plus all other portions of the case). In many cases, the nurses and anaesthesiologist frequently transition throughout the operation, but the surgeons are present continuously throughout the entire case. Further analysis of subtask attributes and elements was performed to identify possible reasons that some cases require more time than others.

2.3.1.1 Subtask attributes

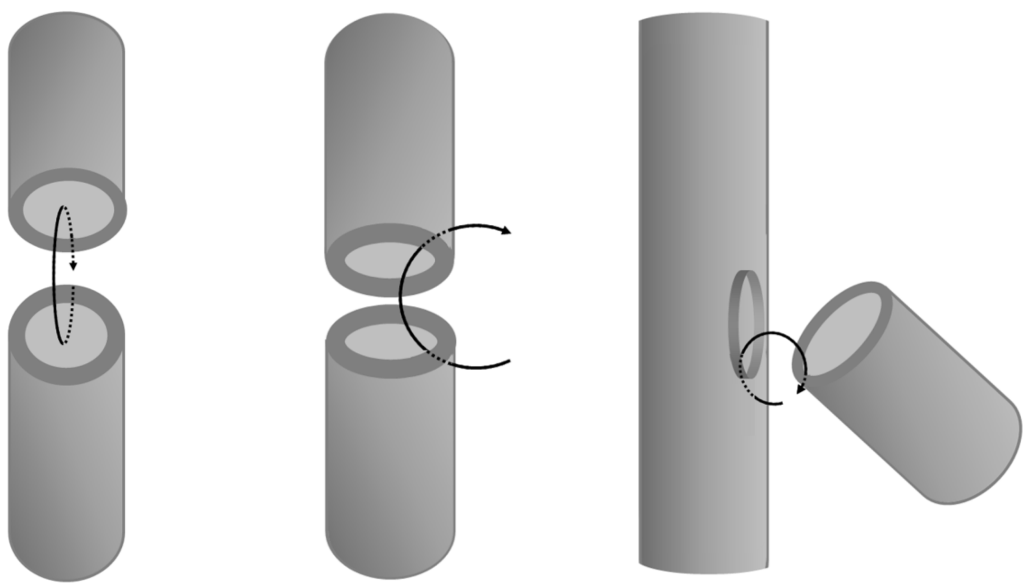
The attributes for the “join vessel” subtask identify the work objects, methods, tools, and conditions (Table 2.1), and subtask attribute frequencies are shown in Table 2.3 for all 64 cases. “Work object” is a direct object of a subtask action. For these cases, work object attributes identify where the flap came from and its composition. The flaps in these cases have distinct shape and composition (e.g. muscle, bone and skin), that affects how the flap is secured and how the vessels are accessed. The work object also indicates if the vessel is an artery or a vein; there may be more than one vein or artery per case. Arteries have thick walls and are well-defined, but they are stiff and can be more difficult to cut and suture than veins. Veins have thin walls and can be hard to manipulate, but can be connected using mechanical couplers or sutures. Thus, the work object may influence the surgeons’ selection of tools, materials, and methods, the required skill, and the required time to complete.

Table 2.3: "Join vessels" subtask attributes as % cases observed in 73 arteries and 79 veins and average "join vessels" subtask times (seconds) ± SD for 64 cases

		Arteries		Veins	
	Attribute	% Observed	Time±SD	% Observed	Time±SD
Work Object: Flap	Skin from anteriolateral thigh	17%	879±473	15%	603±458
	Skin from forearm	40%	1,286±439	47%	867±299
	Skin and bone from fibula	10%	1,377±525	8%	583±288
	Muscle from latissimus dorsi	15%	972±331	14%	1,338±398
	Other	18%	1,189±475	16%	621±526
Method: Configuration	End-to-end	96%	1151±459	66%	726±510
	End-to-side	4%	1346±442	34%	830±332
Method: First stitch location[1]	Back stitch in end-to-end	79%	1,109±418	18%	895±508
	Side stitch in end-to-end	16%	1,358±608	29%	1,340±376
	Side stitch in end-to-side	4%	1,548±469	53%	847±327
Method: Connection	Use mechanical coupler	0%	-	38%	387±144
	Use sutures	100%	1,171±63	62%	989±429
Tool: Apposition	Clamp (Frame or Double)	15%	1,286±655	16%	1,463±399
	Freestyle	85%	1,144±418	46%	831±306
	Coupler	0%	-	38%	387±144
Condition: Vessel diameter[1]	Equal	73%	1,139±458	51%	1,064±378
	One vessel is between 1-2 times larger (noticeable difference)	20%	1,186±463	41%	908±498
	One vessel is >2 times larger	7%	1,296±325	8%	949±348

[1]Note: Vein sample size is 49 because vessel diameters were not measured for coupler cases and first stitch location attribute is not applicable when couplers are used

The “method” attributes identify (1) anastomosis “configuration” – the position of the vessels with respect to one another, i.e. end-to-end or end-to-side, (2) the “first stitch location” – the location of the first stitch and how the vessels are positioned (Figure 2.3), and (3) the “connection” type – sutures or coupler.



a) b) c)

Figure 2.3: Illustrations of joining the vessel described by the “First stitch location” attribute: a) end-to-end with back stitch, b) end-to-end with side stitch, and c) end-to-side with side stitch. Arrows represents the needle’s path through the vessel walls from surgeons’ point of view.

Nearly all of the arteries (96%) were joined end-to-end; 66% of veins were joined end-to-end (Table 2.3). All three “first stitch locations” (illustrated in Figure 2.3) were observed, and frequencies differ between arteries and veins (Table 2.3). The selection of method attributes may be influenced by vessel characteristics, e.g. stiffness, size, length. “First stitch location” may affect the surgeons’ visualization of their work and how much tissue handling is required to complete the anastomosis.

For “connection” method, “use of mechanical coupler” was observed for 38% of veins, but none of the arteries. It was previously observed that “join vessel” subtask completion times for cases 4-7 were three times faster for veins than for arteries (Table 2.2). “Join vessel” subtask times were decomposed by “connection” method to determine if the use of couplers can explain variations observed in subtask times. The average observed time for veins using couplers was 387±144 seconds and for vein using sutures was 989±429 seconds (Table 2.3). These results suggest that the time required to suture veins is only slightly faster (182 seconds) than the time to suture arteries; and the time required to join veins using couplers is much faster (602 seconds) than the time required using sutures. The use of couplers explains the time differences in Table 2.2. These results are consistent with previous studies that showed couplers decrease operative time without increasing complications (Chernichenko et al. 2008, Zhang et al 2012). The fact that coupler use is not ubiquitous may relate to surgeon preferences or training, or to anatomic environmental conditions in certain cases under which the use of the coupler is made difficult due to its size, but this is not certain.

The tool attributes identify devices used to grasp, hold or manipulate a work object. The “apposition” tool attribute indicates if one of two types of clamps was used to hold vessels. Surgeons may elect to use an “apposition” tool to hold the ends of the vessels in position for suturing, e.g. a frame clamp or double clamp (Acland 1972). Clamps were used for only 15% of the arteries and 16% of the veins; in most cases, the vessels were held by hand using forceps. The average observed “join” subtask times for arteries was 1,286 seconds with clamps and 1,144 seconds without clamps; average times for veins was 1,439 seconds with clamps and 831 seconds without clamps. Clamps assist the surgeon by holding the vessels in position while they join the vessel; however, the use of clamps prolonged the join subtask time for both arteries (+142 seconds) and veins (+608 seconds).

The “condition” attribute identifies the relative vessel diameters between the flap and recipient vessels. There was a noticeable difference between diameters for 20% of the observed artery cases (41% for veins) and at least a 2:1 difference for 7% of the artery cases (8% for veins). Mismatch in vessel diameters increases the complexity for end-to-end anastomoses and is expected to increase the time to complete the “join” vessel subtask. The complexity and time to perform an anastomosis when there is a noticeable difference in diameter may be reduced if the vessels are joined end-to-side rather than end-to-end as suggested by Pederson (2010). The average observed times for suturing end-to-side was 17% faster than suturing them end-to-end (839 versus 1,020 seconds) when there was a noticeable diameter difference. The end-to-side cases were even faster -- 32% faster -- than end-to-end cases (855 versus 1,272 seconds) when there was no noticeable diameter difference. There were not enough end-to-side artery cases for a meaningful comparison. Use of the "conditions" attribute allows one to evaluate whether choices made in another attribute – such as the decision to use a clamp in the tool attribute of the "join vessel" subtask, can be explained by varied conditions in the operative environment that dictate such a decision.

Application of the taxonomy demonstrated that there are significant time differences among various subtasks (Table 2.2). Analysis of subtask attributes provided information that helped to explain those time differences and to develop hypotheses about how these differences may be related to skill, to tools, to techniques, to patient factors and how they may influence outcomes. Additional analysis decomposing subtasks into elements (Figure 2.2 and Table 2.1) provide more details about differences from one instance of a subtask to another and about differences in outcomes.

2.3.2. Element analysis

The element analysis was based on the relative stitch number (e.g. first, quarter, final). Because the number of stitches varies among cases, relative stitches are more comparable than an absolute number (e.g. first, second, third). The first stitch is unique because of the attention required to align and hold the vessels while driving the needle. The final stitch is unique because the inside of the vessel is not visible and the needle must pass through both the recipient vessel and the flap vessel in one motion. By contrast, the quarter stitch, which occurs at a location 90° from the first, is of special interest because the vessel is held in alignment by previous stitches, decreasing environmental constraints, and the surgeons have more freedom to choose how they will complete the suture based on their training and habits. Thus, this stitch may most clearly demonstrate a given surgeon's preference. Table

2.4 shows descriptive statistics for the element times observed for the "join vessel" subtask during these stitches in each case.

Table 2.4: Average element times (seconds) per case ± standard deviations for suturing in n=61[1] arteries, 46[1,2] veins for the first, quarter, and final stitches. The pooled time for the first, quarter, and final stitches and results of a multiple linear regression is also shown.

		Average element time (s) per case ± SD			
Element		first	quarter	final	pooled stitches
Align	artery	5.2± 3.2	4.1± 1.9	3.9± 4.6	4.7± 1.9
(to arrange vessels in alignment)	vein	9.3± 24.3	4.4± 3	5.2± 3.4	6.4± 8.1
Drive Needle	artery	8.6± 3	7.3± 3.2	6.1± 4	7.3± 2.1*
(to puncture vessel with needle)	vein	8.0± 3.1	6.6± 4.1	5.8± 3.8	6.6± 2.1
Withdraw	artery	14.5± 9.3	10.3± 8.5	10.2± 7.7	12.2± 4.8
(to pull suture through vessel)	vein	12.0± 9.6	9.3± 6	11.3± 8.7	11.1± 6.0*
Tie	artery	35.9± 20.4	37.0± 23	32.4± 20.1	35.2± 14.0*
(to fasten suture thread)	vein	28.9± 17.8	29.9± 15.4	25.4± 16.1	28.1± 12.3*

*indicates significant relationship between element and subtask times ($p<0.05$) in multiple linear regressions for the pooled stitches
[1]Note: Videos not recorded for 12 arteries and 3 veins.
[2]Elements shown do not apply to the 30 vein coupler cases

The average time to complete an element ranged from 3.9-37.0 seconds, with "tie" elements accounting for the greatest fraction of join vessel time (Table 2.4). The average time to "align" and to "drive needle" consistently decreased from the first to the last stitch for both arteries and veins (Table 2.4). This difference probably reflects the stability of the vessels with increasing numbers of sutures.

A regression analysis (Equation 1) was performed to examine the relationship between the total time it takes to "join vessels" (i.e. artery, vein) and the average time (seconds) surgeons take to "align vessels," "drive needle," "withdraw suture," and "tie suture" (Figure 2.2) during the first, quarter, and final stitches (Table 2.4).

$$Time_{Join} = \beta_0 + \beta_{Align} * x_{Align} + \beta_{Drive} * x_{Drive} + \beta_{Withdraw} * x_{Withdraw} + \beta_{Tie} * x_{Tie} + \varepsilon \quad (1)$$

This analysis was conducted using the pooled times for the first, quarter, and final stitches (Table 2.4). Differences in element times accounted for 23% of the variance in join artery times (adj-R^2=.23, $F(4,57)=5.4$, $p<0.05$) and 49% of the variance in join vein times (adj-R^2=.49, $F(4,39)=11.2$, $p<0.001$). For joining arteries, only the time it takes to perform "drive needle" (β_{Drive}=76) and "tie suture" (β_{Tie}=10) elements was significant in the regression model. For joining veins, only "withdraw suture" ($\beta_{Withdraw}$=28) and "tie" (β_{Tie}=16) elements was significant. Although the average time the surgeon takes to perform "align" (β_{Align}= -7.8) elements on veins was not significant (p=.23), it is interesting to note that the coefficient is negative and may suggest that increased time spent aligning vessels reduces total subtask time.

2.3.2.1 Element attributes

Attribute (Table 2.1) frequencies for the first stitch, quarter stitch, and final stitch for 61 arterial and 46 venous (excludes venous anastomoses performed with coupler) anastomoses with usable videos at the element level are shown in Table 2.5. Some attributes apply to all elements, e.g. work object, and are shown in the first row while other attributes shown in subsequent rows apply only to specific elements. In some cases, the <u>number of elements</u> for which a given attribute is observed per case is an important metric of handling, trauma, and skill (e.g. work objects, condition: stitch number, method: support vessel). In other cases, the <u>percentage of elements</u> for which a given attribute is observed is an important metric because they indicate the frequency an attribute is observed over alternatives (e.g. ergonomics: lumen visualization).

Table 2.5: Attribute frequencies (average number of elements with a given attribute per case ± standard deviation and percent of elements with that attribute) for 61[1] arterial and 46[1, 2] venous join vessel subtasks by element for the first, quarter, and final stitch

Element	Attribute		ARTERIES (n=61) Average number of elements with attribute per case ± SD	ARTERIES %	VEINS (n=46) Average number of elements with attribute per case ± SD	VEINS %
All Elements (pooled)	Work Objects	Recipient artery	21.8±7.1	40%	0±0	0%
		Flap artery	23.0±7.4	42%	0±0.1	0%
		Suture	10.0±2.0	18%	9.7±2.3	21%
		Field	0.3±0.7	1%	0.2±0.7	1%
		Recipient vein	0.0±0.0	0%	18.8±9.1	40%
		Flap vein	0.0±0.0	0%	17.8±6.2	38%
	Tool: Forceps	Jewelers	34.4±11.5	57%	31±13.1	59%
		Pierce	0.1±0.5	0%	0.3±1.9	1%
		Dilator	2.0±7.7	3%	1.5±4.4	3%
		Pickups	0.0±0.0	0%	0±0	0%
		Unidentified	0.0±0.2	0%	0.2±0.6	0%
		Needle driver	23.7±5.7	39%	19.3±4.5	37%
	Tool: Scissor	Straight	3.1±0.8	95%	2.8±1.4	91%
		Curved	0.1±0.3	2%	0.1±0.5	4%
		Tenotomy	0.0±0.0	0%	0±0	0%
		Unidentified	0.1±0.3	3%	0.2±0.4	5%
	Tool: Irrigation	Catheter	0.2±0.5	78%	0.2±0.9	92%
		Olive tip	0.1±0.3	22%	0.02±0.1	8%
		Bulb	0.0±0.0	0%	0±0	0%
	Materials: Suture	Size 9	18.4±9.3	83%	16.3±8.5	85%
		Unidentified	3.7±8.4	17%	2.8±5.6	15%
	Condition: Stitch Number	First	14.3±8.0	40%	12.6±4.5	36%
		Quarter	12.6±5.6	35%	11.3±2.9	32%
		Final	8.9±4.7	25%	11.2±11.3	32%
Align	Methods: Manipulate	Hold adventitia	12.0±6.9	82%	10.7±8.2	79%
		Hold edge of vessel	0.2±0.6	1%	0.4±1.1	3%
		Without hold	2.5±3.0	17%	2.5±2.9	18%
Drive Needle	Methods: Support vessel	Hold suture	0.7±1.9	4%	1.1±2.1	9%
		Hold adventitia	11.9±4.6	77%	7.8±3.5	66%
		Hold vessel edge	0.2±0.8	1%	0.4±0.8	3%
		Hold inside lumen	1.6±2.2	11%	1.2±1.7	10%
		Hold outside lumen	1.0±1.3	6%	1.1±1.3	9%
		Move vessel over needle	0.1±0.4	1%	0.2±0.6	2%
	Methods: # of	One	4.4±3.3	37%	3±2.1	44%

	Bites	Two	7.4±4.6	63%	3.8±2.4	56%
	Methods: Needle Grasp	< ½ (tip to center)	0.0±0.0	0%	0±0	0%
		1/2-2/3 from tip	1.8±2.3	16%	1.7±2.6	20%
		> 2/3 from tip	9.8±4.6	84%	6.9±3	80%
	Methods: Needle Entry Angle	< 90°	1.5±2.4	15%	1.6±2.2	21%
		90°	8.5±4.4	84%	6.2±2.2	79%
		> 90°	0.1±0.5	1%	0±0.1	0%
	Method: Stitch Progression	Interrupted	5.3±3.3	80%	4.8±2.6	94%
		Running	1.3±2.0	20%	0.3±1.1	6%
	Method: Needle Extract	Follow curve	0.7±0.9	16%	1±1.3	18%
		Don't follow curve	3.7±1.5	84%	4.3±1.7	81%
	Condition: Direction	Out to in	6.9±3.5	58%	4.8±2.3	54%
		In to out	5.0±2.2	42%	4.1±1.9	46%
	Ergonomics	Lumen visualized	9.5±4.2	80%	5.4±3.1	62%
		Lumen not visualized	2.3±2.4	20%	3.3±2.5	38%
Tie	Method: # of Knots	< 3 Knots	0.0±0.0	0%	0±0.2	1%
		3 Knots	3.0±0.8	95%	3±0.5	98%
		> 3 Knots	0.1±0.4	5%	0±0.1	1%
With-draw	Method: Withdraw	Continuous	3.0±1.5	73%	3.4±1.3	79%
		Hand-over-hand	1.1±1.1	27%	0.9±0.9	22%
Evacuate	Tool: Evacuate	Suction	0.0±0.2	2%	0.1±0.5	22%
		Weck-cel	1.6±2.3	97%	0.3±1	52%
		Sponge unidentified	0.0±0.1	1%	0.1±0.7	26%

[1]Note: Missing video data from 12 arteries and 3 veins.
[2]Elements shown do not apply to the 30 vein coupler cases

The “work objects” attribute is particularly important for some elements, such as “align” and “drive needle,” because it indicates the number of times a vessel is grasped or poked, which may cause injury. An average of 44.8 elements per case during suturing involved arteries and 36.6 elements involved veins (Table 2.5). The “stitch number” attribute helps identify the number elements needed to complete the first, quarter, and final stitches. The number of elements per stitch decreases from “first” to “quarter” to “final” for arteries and from the “first” to “quarter” stitch for veins (Table 2.5). The times needed to complete the stitch decrease in a similar fashion for arteries (153±109 seconds, 107±53 seconds, and 79±39 seconds) and for veins (111±56 seconds, 80±33 seconds, and 89±78 seconds). These results suggest that the first stitch is more complex and requires more steps and time than the subsequent stitches. The large variances observed for each stitch may be due to variations in methods or in surgeon skill.

“Support vessel” method attribute indicates how surgeons hold the vessels during the “drive needle” element. “Hold adventitia” describes the method where the connective tissue surrounding the artery and vein is grasped with forceps to hold the vessel and is the most commonly observed method (Table 2.5). Studies have suggested that holding the adventitia reduces trauma to the vessel walls, edge of the vessels, and vessel lining, which may prevent clots and anastomosis failure (Pederson 2010, Acland 1972, Squifflet et al. 1983). However, whether this technique provides sufficient support to drive the needle through the vessel wall can be tested by linking this technique with the requirement of additional elements or time to complete the suture. Occasionally, surgeons were observed to “hold inside lumen” (inserting their forceps inside the vessel) to stabilize the vessels (Table 2.5). Some believe that inserting the forceps into the vessel may cause injury to the lining of the blood vessel, leading to clotting and adversely affecting the outcome of the anastomosis (Pederson 2010, Acland 1972); however, others *recommend* inserting forceps into the vessel to provide counter-pressure (Yonekawa et al. 1999). To move beyond opinion-based practices, hypotheses on “support vessel” methods can be tested with outcomes using our HTA approach.

“Lumen visualized” attribute indicates if the surgeon can see the “lumen of the vessel” (the inside) while driving the needle through the vessel of each stitch – currently defined as a best practice by expert surgeons. Table 2.5 shows that surgeons were able to see the lumen of the artery 80% of the time (62% for veins) while performing “drive needle” elements. The literature emphasizes the importance of seeing the lumen during suturing to prevent accidentally injuring the artery or inadvertently capturing the back wall with the suture and sewing the anastomosis closed (Pederson 2010). Suturing patterns have been developed to increase visibility when performing a microvascular anastomosis (Harris, Finseth, and Buncke 1981, Şimşek et al. 2006). However, the lumen was not visualized in 20% of the “drive” elements for arteries and 38% for veins (Table 2.5). Using our HTA, we can again test the hypothesis of whether failure to visualize the lumen during the creation of an anastomosis leads to increase rate of anastomotic failure or adverse outcomes.

2.3.2.2 Element sequence

Subtasks and subtask attributes impose constraints on the sequence in which elements occur and on element attributes. Still, there are many ways to complete a given subtask. It can be hypothesized that the best methods are those that require the fewest steps and minimize the time required to complete the subtask or number of times that the tissues are grasped, cut or poked. Defining a minimum set of elements for completion of a given subtask provides a framework for comparing alternative methods. For example, a minimum set of elements and attributes required to complete a suture is as shown in Table 2.6.

Table 2.6: Hypothesized minimum set of elements and attributes required to complete suture. Not all methods attributes are included.

Element	Work Object	Methods	Tools	Materials	Ergo-nomics	Condi-tions
1. Align vessels	Flap: Vein (or artery)	Manipulate Method: Hold adventitia	Forceps: Jewelers			Stitch Number
2. Drive needle	Flap: Vein (or artery)	Support Method: Hold adventitia	Forceps: Jewelers; Needle; Needle Driver	Suture Size: 9/0	Lumen Visibility: visualized	Stitch Number
3. Align vessels	Recipient: Vein (or artery)	Manipulate Method: Hold adventitia	Forceps: Jewelers			Stitch Number
4. Drive needle	Recipient: Vein (or artery)	Support Method: Hold adventitia	Forceps: Jewelers; Needle; Needle Driver	Suture Size: 9/0	Lumen Visibility: visualized	Stitch Number
5. Withdraw suture	Suture	Withdraw Method: Continuous	Forceps: Jewelers; Needle Driver	Suture Size: 9/0		Stitch Number
6. Tie suture	Suture	Tie: 3 throws	Forceps: Jewelers; Needle Driver	Suture Size: 9/0		Stitch Number
7. Cut suture	Suture		Forceps: Jewelers; Needle Driver; Scissors: Straight	Suture Size: 9/0		Stitch Number

The first stitch elements and times for the arteries in the seven representative cases described above (Table 2.2) are shown in Table 2.7 and the veins are shown in Table 2.8. As many as nine "drive needle" elements were needed to complete the first stitch, and the number of failed "drive needle" elements ranged from zero to seven for these cases. Under ideal conditions a skilled surgeon should require only two "align vessel" and two "drive needle” elements (Table 2.6). Early studies on needle types showed that the needle perforations tear the intima (lining) of the blood vessel (Pagnanelli et al. 1983) and needle perforations increased the number of clots in rats (Gu et al. 1991). Failed drive needle elements may be related to patient factors or surgeon skill and may affect case outcomes.

Table 2.7: Element sequences for the 1st suture in seven arterial anastomoses (time in seconds). The number of instances of “drive needle” elements is indicative of the number of attempts needed before successfully completing the goal of “drive needle.” “# failed drives are “Drive Needle” element attempts that were not successful. “Evacuate” are elements for removing blood and other fluids from the work site.

Time (seconds)	Case 1 Surgeon 1	Case 2 Surgeon 1	Case 3 Surgeon 1	Case 4 Surgeon 2	Case 5 Surgeon 2	Case 6 Surgeon 3	Case 7 Surgeon 3
0	Align Drive needle Drive needle Withdraw suture Align Align Drive needle	Align Drive needle Align Drive needle Drive needle Drive needle Align Drive needle Align Align Drive needle	Align Drive needle Drive needle Drive needle Evacuate Align Align Drive needle Drive needle Drive needle Withdraw suture	Align Drive needle Drive needle Drive needle Drive needle Align Drive needle	Align Drive needle Evacuate Drive needle Evacuate Align Align Align Align Drive needle	Align Evacuate Drive needle Align Drive needle Withdraw suture	Align Drive needle Drive needle Evacuate Evacuate Align Drive needle Drive needle Align Drive needle Drive needle Drive needle
75	Withdraw suture Tie suture Cut suture	Withdraw suture Tie suture Cut suture	Tie suture Cut suture	Withdraw suture Tie suture Cut suture	Withdraw suture Withdraw suture Tie suture Cut suture	Tie suture Cut suture	Drive needle Align Evacuate Align Evacuate Align Drive needle Withdraw suture Tie suture
150+						Cut suture Cut suture	Tie suture Cut suture
# Drive needle	3	6	6	5	3	2	9
# Failed Drive	1	4	4	3	1	0	7
# Evacuate	0	0	1	0	2	1	4
Total Time	143.4	96.8	81.7	129.4	124.8	158.7	171

Table 2.8: Element sequences for the 1st suture in seven different vein anastomoses (time in sec). Veins may also be coupled together instead of being sutured.

Time (seconds)	Case 1 Surgeon 1	Case 2 Surgeon 1	Case 3 Surgeon 1	Case 4 Surgeon 2	Case 5 Surgeon 2	Case 6 Surgeon 3	Case 7 Surgeon 3
0	Align vessels	Align vessels	Align vessels	Coupler	Coupler	Coupler	Coupler
	Drive needle	Drive needle	Drive needle				
			Drive needle				
	Align vessels	Align vessels	Align vessels				
	Align vessels	Drive needle	Align vessels				
			Align vessels				
	Drive needle	Withdraw suture	Drive needle				
	Withdraw suture	Tie suture	Withdraw suture				
	Tie suture	Cut suture	Tie suture				
75+	Cut suture		Cut suture				
# Drive needle	2	2	3	n/a	n/a	n/a	n/a
# Failed Drive	0	0	1	n/a	n/a	n/a	n/a
# Evacuate	0	0	0	n/a	n/a	n/a	n/a
Total Time	97.99	56.79	91.41	217	304	491	364

2.4. Discussion

Previous applications of HTA in healthcare have demonstrated how HTA can be used to systematically describe tasks and investigate errors (MacKenzie et al. 2001, Lane, Stanton, and Harrison 2006, Phipps et al. 2008, Raduma-Tomàs et al. 2012, Bonrath et al. 2013). This paper demonstrates how HTA can (A) describe procedures such that methodological differences among cases can be compared, (B) formulate hypotheses that can be used to determine best methods, and (C) be used to assess performance.

2.4.1. Overview of taxonomy

A hierarchical taxonomy was developed for describing microvascular anastomosis with four levels (job, tasks, subtasks and elements) that can be used to identify differences among surgeons and cases (Figure 2.2). The initial taxonomy construction resulted in a complex system with many categories at multiple levels; however, this work demonstrates how the taxonomy can be simplified through the use of subtask and element attributes.

Attributes can be used to simplify existing surgical taxonomies created by previous investigators. For example, Mackenzie et al. (2001) used 89 categories with five levels to describe Nissen Fundoplication surgery. The size of Mackenzie's (2001) taxonomy can be reduced by implementing work objects and tool attributes to avoid the repetition of similar elements (e.g. reduce the nine "cut" elements into one element with attributes).

The frequency and sequences of subtasks and elements provide details on performance variations, and the subtask and element attributes can be used to explore the sources of variation, e.g. patient factors, equipment used, techniques used, and skill. Attributes augment the descriptive ability of the taxonomy and can be applied to existing taxonomies (Sarker et al. 2006, 2008). For example, adding method and tool attributes can provide information about the types of knots and needle size used for Sarker's (2006) "suture port sites" element.

Hignett et al. (2013) highlighted that a key goal for human factors in surgical safety is to develop methodology for analyzing the complexity of surgery to provide evidence-based change. Systematically describing and comparing variability in surgical technique with an objective taxonomy provides a framework for identifying the optimal technique within a specific condition or circumstance. This ability to identify and clearly describe an optimal technique then provides a foundation on which surgical procedures can be standardized – at least for critical steps that impact clinical outcomes. This approach may therefore be a means by which variation can be reduced in surgical technique as called for by Pattani et al. (2010), McCulloch et al. (2002), and Gawande (2012).

2.4.2. Use of the taxonomy to determine the best methods

The best methods can be defined as those that provide the best outcomes. Studies of best methods and outcomes should be based on clear hypotheses about what makes one method better than another. The proposed taxonomy is a powerful tool for determining the qualities of best methods, describing them and characterizing how cases are performed. For example, although no statistical significance was found, the multiple linear regression data suggests that extra time spent aligning the vessels may reduce the overall time required to join the vessels. This relationship is plausible and merits further study. In another example, variations were observed in “support vessel” methods, and it can be argued that it is better to support arteries and veins by grasping the adventitia rather than inserting a tool into the lumen of the vessel. The taxonomy provides a framework for capturing this difference and testing this hypothesis. Table 2.5 shows that objects were inserted into the lumen for 10-11% of the drive needle elements. This analysis can be used to study the relationship between how the vessel is stabilized and case outcomes. In a preliminary study, Frischknecht et al. (2012) showed a significant relationship between the frequency with which arteries were supported by inserting a tool inside lumen and the frequency with which the anastomosis had to be redone. Further studies are needed to determine why the surgeon chose to support the artery one way or the other.

Surgery is a complex job that demands great skill. A best method does not imply that all surgeons should use exactly the same procedures and techniques under all conditions. It does mean that there are common features and steps for each procedure. Clearly defining and describing these steps can help determine when and how it is appropriate to alter a procedure due to the unique features of a patient or under a particular condition. It also implies that some tools and methods are better than others. For example, couplers may be the fastest way to complete a venous anastomosis with the fewest complications. It may be possible to design a new tool to hold and stabilize arteries so that it is not necessary to use the “hold inside lumen” method to drive the needle.

Given the complexity of most surgical procedures, it is not feasible to conduct controlled studies to evaluate all possible variations; however, standardization of procedures will make it possible to conduct comparisons of some procedures to identify both good and bad features. Even if a “best” technique is not identified in analysis of the taxonomy, it has been shown that the simple act of standardizing procedures – even if the procedures have not been shown to be the best – leads to improved outcomes (Shrikhande, Barreto, and Shukla 2008). The proposed taxonomy provides a means by which a procedure can be standardized by creating a shared mental model and clear identification of the steps involved in performing the procedure at a very granular level. Given the taxonomy’s ability to create a framework to standardize a procedure in this way, as well as the ability to then link specific methods to outcomes, we propose that the taxonomy tool will enable surgeons to identify and describe various optimal techniques for a given surgical procedure so that best methods can be evaluated and taught.

2.4.3. Assessment of performance

Current systems for assessing microsurgical skill focus on checklists and global rating scales (Kalu et al. 2005) or creating training modules of selected elements, such as “tie” knot (Temple and Ross 2011); however, these systems only provide scores (1-5) on generic skills like steadiness and tissue or instrument handling (Temple and Ross 2011, Chan, Niranjan, and Ramakrishnan 2010), which are important aspects of technical performance but fail to give specific feedback that can be incorporated in a measurable way. Quantitative feedback from automated motion assessment has also been proposed, but has only been feasibly applied in a simple skills task environment (Jun et al. 2012). The taxonomy can be used to describe critical details that can be measured to assess surgical performance during surgical procedures (Table 2.2-Table 2.8). The taxonomy can also be used to describe a minimum set of elements required for a skilled surgeon to complete a subtask under ideal conditions (Table 2.6). Deviations from the minimum set of elements can be studied to determine if they are an appropriate response to abnormal patient conditions or conversely due to a lack of knowledge or skill. For example, based on preliminary analysis of our data (Frischknecht et al. 2012), inserting forceps in the lumen is not a recommended method for stabilizing the vessel while driving the needle, as it is associated with worse outcomes. However under constrained anatomic conditions where grasping the outside of the vessel wall is difficult, it may indeed represent the least traumatic method of support. The taxonomy and these results can be used to evaluate surgeon skill and performances as suggested by Sarker, Kumar, and Delaney (2010) and Cristancho, Moussa, and Dubrowski (2011) after further studies linking technique differences described by the taxonomy to patient outcomes.

2.5. Limitations

The taxonomy is based on 73 arterial and 79 venous anastomoses by eight surgeons at one institution. We anticipate that analysis of additional surgeons at other institutions will demonstrate more variation and may require additional elements and element attributes to be added to the taxonomy.

This work demonstrates how the taxonomy can be used to develop insights into factors and mechanisms that affect performance and outcomes. While these insights can be useful, they also can be misleading. As stated at the outset, they should be regarded as observational data which can then drive the development of hypotheses which can be tested prospectively to ensure that the relationships identified are predictive and not merely correlative. The purpose of this work was development of a tool that can be used to objectively describe variation in surgical technique at a sufficiently granular level that the impact of variation in surgical technique can be objectively assessed in the context of actual operations that are subject to varying conditions. The taxonomy provides the tool to describe this variation and to evaluate its impact on proximate and future outcomes. Specific hypotheses were formed by linking observed variations in subtask completion times, element sequences, and attributes with potential biological impacts, e.g. tissue trauma, ischemia time, and with potential impacts on task performance, e.g. visualization. Further work will be required to test the hypotheses that this work generated.

2.6. Conclusions

This work shows how hierarchical task analysis can be used to describe a surgical procedure using tasks, subtasks, and elements. It also shows how the taxonomy can be simplified by using attributes to describe work objects, methods, tools, materials, conditions, patient factors, and ergonomics. The proposed taxonomy has sufficient detail to describe differences among cases and to formulate hypotheses about why one way of doing a procedure may be better than another. These hypotheses can then be tested using case outcomes to identify the best methods. We believe that the proposed taxonomy will facilitate standardization on the best methods and will facilitate surgeon training and assessment. Furthermore, we believe that the proposed taxonomy can be enhanced and applied to other surgical procedures.

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CHAPTER 3

EFFECT OF ALTERNATIVE VIDEO DISPLAYS ON NECK AND UPPER EXTREMITY POSTURES, PERCEIVED EFFORTS, AND PERFORMANCE DURING MICROSURGERY SKILL TASKS

Abstract: Musculoskeletal pain has been reported to be prevalent among 72.5-81.5% of surgeons who frequently use optical magnification. Physical work demands and posture constraint from the operating microscope may adversely affect surgeon health and performance. Thus, alternative video displays were developed to reduce posture constraints, and their effect on postures, perceived efforts, and performance were compared with the operating microscope. Sixteen participants performed simulated microsurgery tasks using stereoscopic and non-stereoscopic video displays and operating microscopes. Mean neck angles were 9-13° more erect on video displays than microscope, and participants spent more time in neck extension using video displays than microscope (30% vs. 17%). Neck movements were 3.2x more frequent on the video displays than microscopes. No significant differences were found in perceived efforts. Task completion times on the video displays were 66-110% slower than microscopes. Biomechanical analysis of the results predicted that the increased neck flexion angles and lower prevalence of neck extensions observed using the microscope led to increased joint loads and muscle exertion in the neck than when using video displays. Although improved postures and posture patterns were observed on video displays, further research is needed to identify the impact of display location and improve task performance on video displays.

3.1. Introduction

3.1.1. Significance

Work-related musculoskeletal pain, fatigue, and discomfort can affect both the comfort of surgeons and their ability to complete surgical tasks; yet, the reported prevalence of musculoskeletal symptoms in the neck, back, and shoulders is as high as 87% among surveyed laparoscopic, ophthalmic, and general surgeons (Park et al. 2010; Szeto et al. 2009; Wauben et al. 2006; Sivak-Callcott et al. 2011; Capone et al. 2010). Furthermore, a survey of 130 ophthalmic surgeons found that 9.2% of surgeons stopped operating due to neck pain (Sivak-Callcott et al. 2011).

3.1.2. Background

Although the mechanisms of musculoskeletal injuries are not fully understood (Garg & Kapellusch 2011), several theories and conceptual models (National Research Council 2001; Kumar 2001; Armstrong et al. 1993) are used to explain the associations between postures with musculoskeletal pain and fatigue observed in both laboratory and workplace settings (Ferguson et al. 2013; Villanueva et al. 1997; Szeto et al. 2012; Grieco et al. 1998; Buckle and Devereux 2002; Looze, Bosch, & van Dieen 2009; Reenen et al. 2006; Ariens et al. 2000; Ariens et al. 2001; Hünting, Laubli, & Grandjean 1981; Sauter, Schleifer, & Knutson 1991; Kilbom, Persson, & Jonsson 1986; Harms-Ringdahl & Ekholm 1985). Specifically, the National Institute for Occupational Safety and Health (Bernard 1997) and Buckle & Devereux (2002) found sufficient and strong evidence for causal relationship between postures and musculoskeletal disorders (MSDs) in the neck and shoulders.

Figure 3.1 illustrates a possible relationship between posture risk factors with musculoskeletal discomfort and fatigue based on findings of previous literature (Burgess-Limerick et al. 2000; Snijders et al. 1991; Villanueva et al. 1997; Harms-Ringdahl et al. 1986; Frey-law & Avin 2010). Biomechanical models have shown that non-neutral postures and time spent in these postures increase joint moments, reduce strength capability, and increase muscle activity levels (Burgess-Limerick et al. 2000; Straker et al. 2009; Villanueva et al. 1997; Snijders et al. 1991; Harms-Ringdahl et al. 1986). Furthermore, physiological and psychophysical studies have shown that the high levels and sustained durations of muscle exertions lead to localized fatigue, discomfort, perceived exertion, pain, and reduced performance (Ferguson et al. 2013; Hanvold et al. 2013; Looft 2012; Potvin 2011; Frey-law & Avin 2010; de Looze et al. 2009; Bystrom & Fransson-Hall 1994; Harms-Ringdahl & Ekholm 1985; Rohmert 1960). For example, Harms-Ringdahl and Ekholm (1985) observed that 1) load moments during extreme neck flexion were 3.6 times higher than during neutral position, 2) static neck flexion at extreme angles resulted in discomfort or pain within 15 minutes in all subjects, and 3) neck pain reoccurred within four days for 90% of subjects.

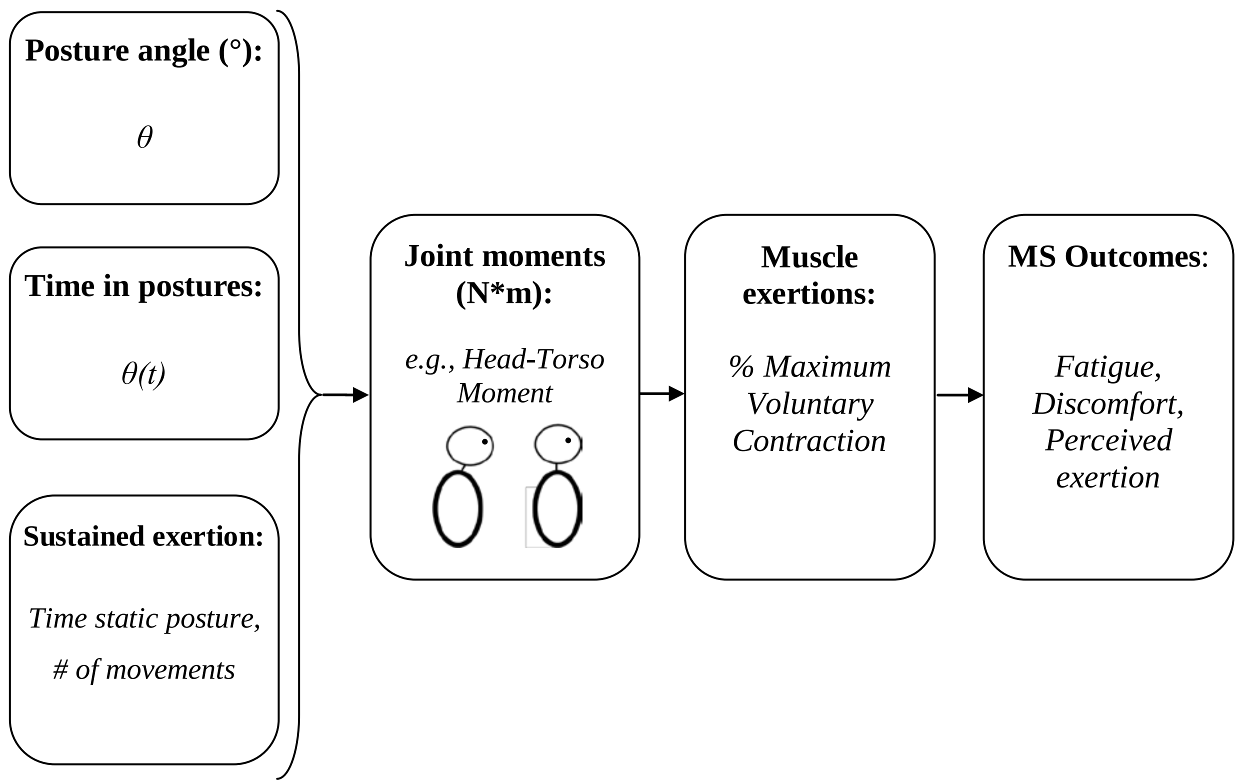


Figure 3.1: **Possible relationship on how variations in posture patterns (i.e., angles, duration, sustained muscle exertions) can affect musculoskeletal (MS) fatigue, discomfort, and perceived exertions, based on published biomechanical, biological, psychophysical, and epidemiological literature.**

Surgeons who perform microsurgery (Figure 3.2-Figure 3.3) may be at additional risk for musculoskeletal symptoms. Investigators observed that operating microscopes required surgeons to be fixated over optical eyepieces (Franken et al. 1995, Yu et al. 2012), constrained the surgeon's eye locations (Figure 3.2-Figure 3.3), reduced comfort (Franken et al. 1995), and forced surgeons to be in awkward positions (Ross et al. 2003). Additionally, the small work site, assisting surgeon's position (i.e., two surgeons were observed for microvascular surgery by Yu et al. 2014), operating room (OR) table, and microscope working distance (Figure 3.2-Figure 3.3) can constrain surgeon head and hand locations and limit the range of postures the surgeon can choose. These posture constraints were postulated to be responsible for the significant associations observed between microscope-use-greater-than-three-hours-per-week with the prevalence of cervical and thoracic pain reported among 339 surveyed plastic surgeons (Capone et al. 2010). Due to the high cost of training and impending shortage in the surgical workforce (Williams et al. 2009), time away from work and reduced career longevity due to musculoskeletal pain can be a costly form of waste in the healthcare system.

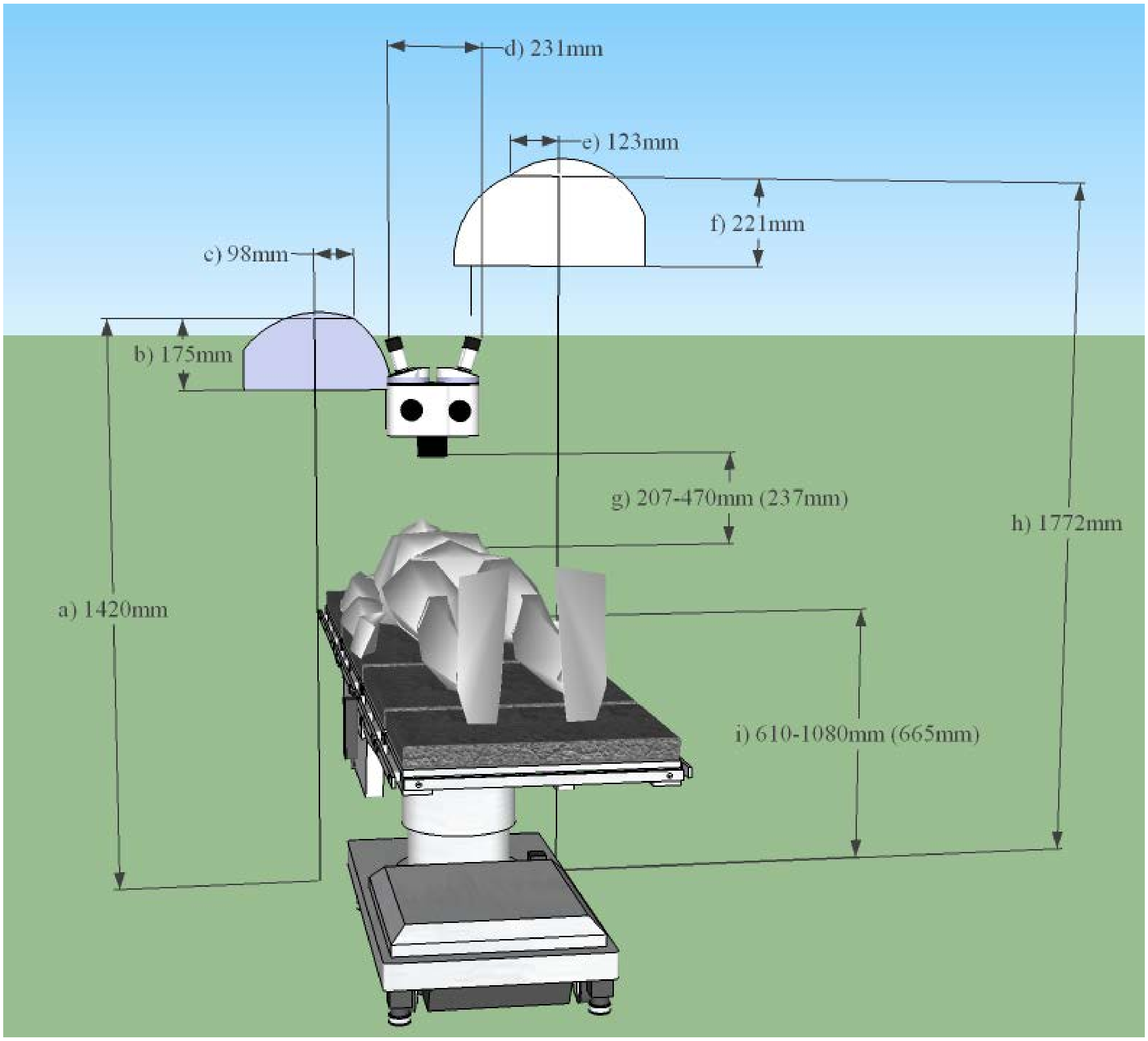
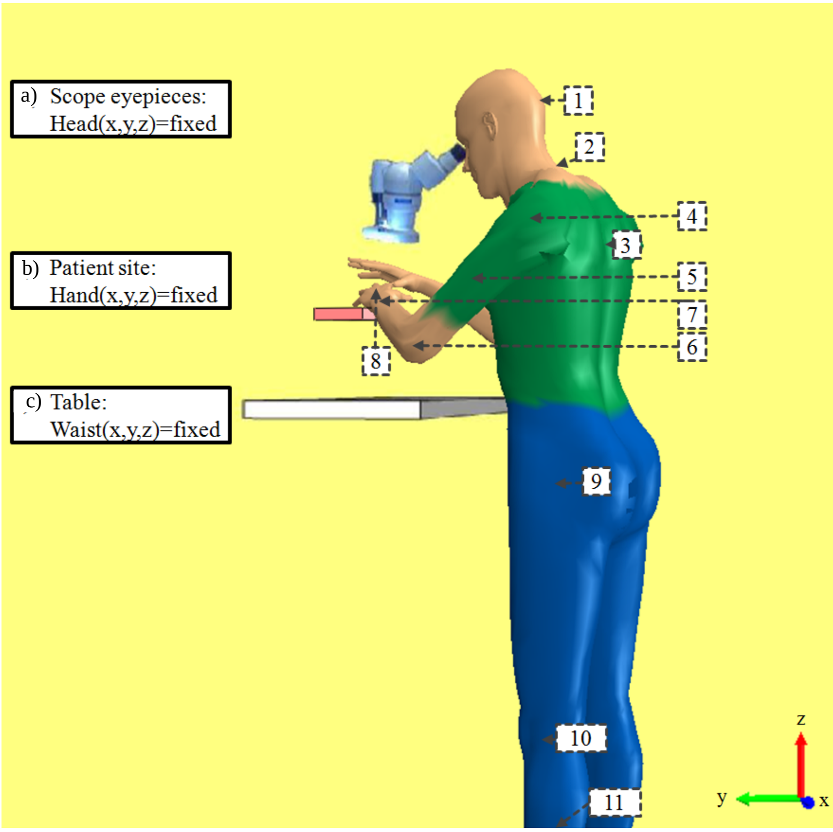


Figure 3.2: **Schematic of key dimensions in the operating room during microsurgery performed by a 5th %tile female and a 95th%tile male operating on a 50th%tile male. Also shown are the range of eye locations for a 5th%tile female (gray area) and a 95th%tile male (white area) throughout the neck range of motion. Key dimensions are: a) floor to Tragion of 5th %tile female, b) neck to tragion of 5th %tile female, c) tragion to nasion of 5th %tile female, d) width of typical dual-head microscope, e) tragion to nasion of 95th %tile male, f) neck to tragion of 95th %tile male, g) range of working distance or focal length of typical surgical microscope (237mm as shown in figure), h) floor to tragion of 95th %tile male, and i) range of heights for typical operating room table (665mm as shown in figure).**



Marker Abbr.	Marker Location
1. He*	Back of head
2. C7	7th cervical vertebrae
3. Ba*	Midpoint of scapulas
4. L/R Sh	Acromion
5. L/R UA*	Upper Arm
6. L/R El	Lateral epicondyles
7. L/R Wr*	Distal radioulnar articulation
8. L/R Ha	3rd metacarpal
9. L/R Hip	Greater trochanter
10. L/R Kn	Lateral condlye
11. L/R Ll	Lateral lower leg, superior to ankle

* indicates use of Rigid Body structure which contains three markers.
L/R denotes Left or Right

Figure 3.3: **Illustration showing how a) microscope eyepieces, b) small patient site, and c) operating table fix posture locations. Numbers refer to locations where motion tracking markers where placed.**

Despite associations between non-neutral postures and sustained muscle exertions (with insufficient recovery time) with musculoskeletal symptoms and fatigue (Figure 3.1), these risk factors are still commonly observed in surgeries requiring optical magnification. When using loupes magnification, neck flexion was estimated to be 20-60° during thyroid surgeries (Davidson et al. 2009) and neck postures were non-neutral for 85% of the time during ophthalmic surgeries (Nimbarte et al. 2013). Another study rated postures of laryngologists performing microsurgery and measured rapid upper limb assessment (RULA) scores of 4-5, indicating poor posture and potential risk for injuries (Statham et al. 2010; Mctamney & Corlett 1993).

Alternative video displays to traditional loupes and operating microscopes have been proposed to 1) reduce physical demands of microsurgery, 2) allow surgeons to select comfortable postures, and 3) improve team communication (Chen et al. 2012; Nissen et al. 2011; Gorman et al. 2001; Franken et al. 1995). Although performance times were longer using video displays (Nissen et al. 2013; Cheng et al. 2012), these studies showed that 1) video displays were successfully used in live microsurgery and 2) majority of surgeons (50-75%) were positive regarding the improved comfort and education potential of video displays (Gorman et al. 2001; Franken et al. 1995). However, posture benefits from alternative displays were merely speculated by these previous studies. In addition, previous studies used 2D video displays (Nissen et al. 2011; Gorman et al. 2001), and recent study suggest that stereoscopic displays may reduce the observed performance gap between video and conventional microsurgery (Jianfeng et al. 2014). However, performance benefits of stereoscopic video systems over non-stereoscopic systems in surgery is still currently debated and warrants further investigation (Hofmeister et al. 2001; Kong et al. 2010; Gurasamy, Sahay, & Davidson 2011; Munz et al. 2004; Bilgen et al. 2013). Quantitative and controlled studies on the effect of stereo and non-stereoscope alternative displays on posture stresses (Figure 3.1) and perceived effort are needed to assess the potential musculoskeletal health and performance benefits of implementing alternative video displays over traditional microscopes.

3.1.3. Study aims

The purpose of this study is to quantify the effect of stereoscopic video displays in reducing physical risk factors that may contribute to musculoskeletal fatigue and injuries (Figure 3.1) during simulated microsurgery skills tasks. In contrast to conventional operating microscopes, it is hypothesized that video displays will allow users to:

1) assume more neutral and less static postures (Figure 3.2-Figure 3.1),

2) reduce perceived efforts, and

3) improve task performance, i.e., completion time and errors.

Findings from this study can provide quantitative measurements on the impact of video systems on postural demands for microsurgery and other jobs that require optical magnification.

3.2. Methods

A laboratory study was conducted to determine how posture patterns, discomfort, and performance were influenced by different magnification displays.

3.2.1. Subjects

The study was approved by the university's institutional review board and written informed consent was obtained from 16 university students with no prior surgical experience. Mean age of the participants was 22 ± 2 years old. Mean BMI was 22±3.6, and mean height was 170cm ± 10cm. All subjects were right-handed, 50% were males, 63% wore corrective lenses, 81% had experience with microscopes, and 44% had experience with 3D displays.

3.2.2. Displays

Four displays were tested in this experiment (Figure 3.4): 1) monocular microscope (Micro2D), 2) binocular microscope (Micro3D), 3) monoscopic video display (Video2D), and 4) stereoscopic video display (Video3D). To simulate the monocular microscope (Micro2D), participants wore a concave eye patch that occluded vision of one eye while using a binocular microscope (Scienscope™ Model XTL-V). The 3D video system streamed real-time interlaced video, at <100ms lag, to a 101.3cm 3D high-definition television (Samsung UN40C7000WF) from two synchronized microscope eyepiece cameras (Premiere Microscope MA87N) mounted on the binocular microscope. Multiple users were able to view the video in 3D, using Samsung wireless shutter glasses. The 2D video system was created using the tele-macro video stream from a video camera (Sony DCR-SX83) positioned 64cm above work site that was viewed on the flat-panel without 3D glasses.

Field of view for all displays was calibrated to 38mm x 38cm and was within the field of views range (16.5mm-180mm in diameter) of commercial surgical microscopes (Leica™). The optical microscope and the 3D video system were positioned, as shown in Figure 3.4. The table height was adjusted so that the microscope eyepieces were between the tip of the participant's nose and eyes. The distance to the flat panel display was 100 cm in front for all subjects. Subjects were instructed to position the flat-panel display (height, distance, and lateral location) and microscope (height) according to their preferences, but selected locations were not recorded.

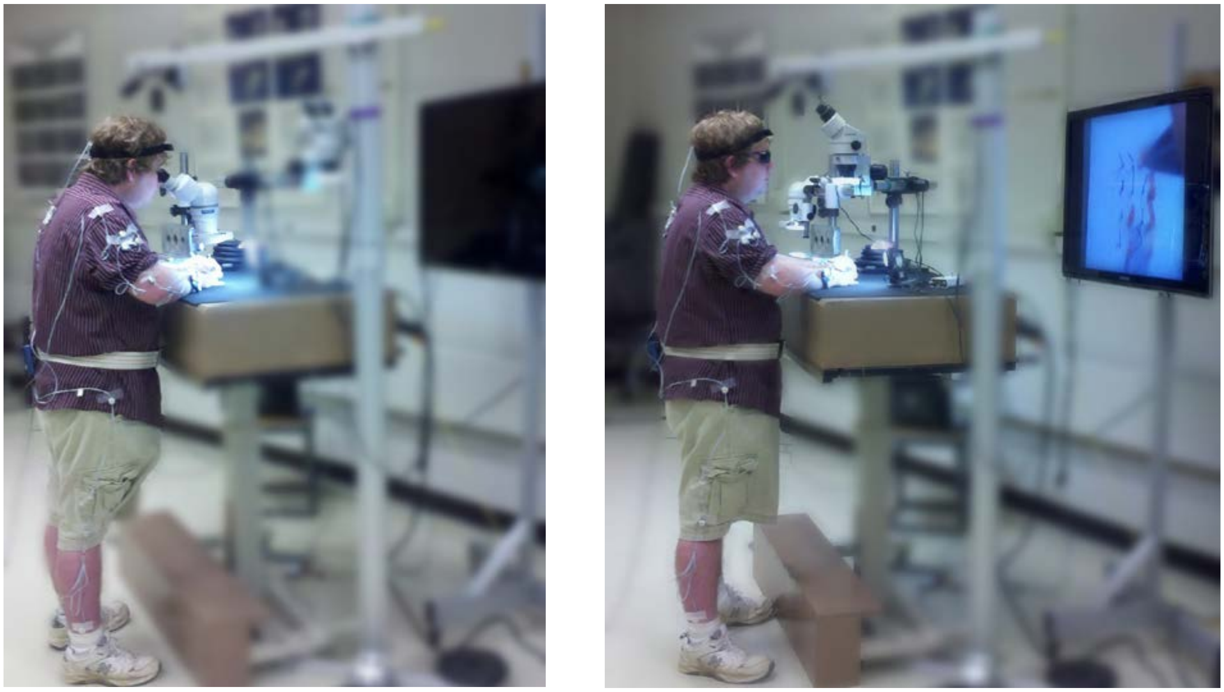


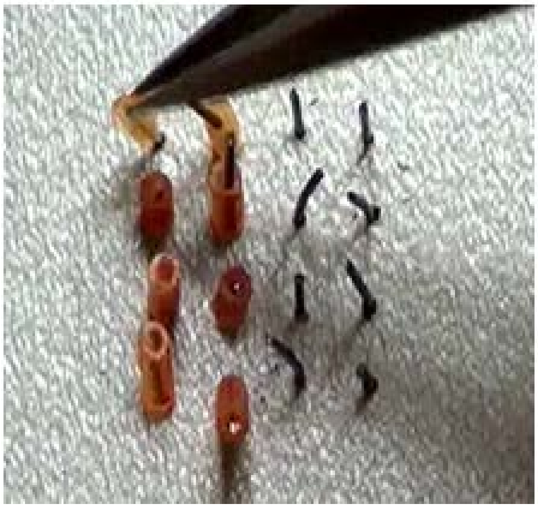
Figure 3.4: **Subject performing tasks using microscope (Left) and Video 3D display (Right). Note that the set up for Video 2D display is similar to Video 3D but without the shutter glasses.**

3.2.3. Experimental tasks

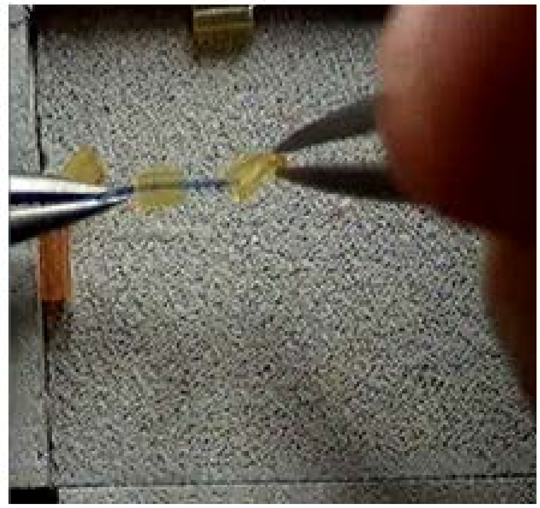
During this study, subjects performed two microsurgery skill tasks adapted from standardized laparoscopic skills tasks (Rosser et al. 1997) or designed with microsurgeons' input to reflect microsurgery skills:

1. Pegboard Transfer (Figure 3.5a): This task was adapted from laparoscopic skill task (Rosser et al. 1997). Subjects transferred eight silicon tubes (Silastic Laboratory Tubing, 1.5mm length and 1.2mm outer diameter) from the one side of the pegboard to the opposite side then back to their original position using microsurgery forceps (KLS Martin forceps, 12-412-11). The pegboard was adapted to have 16 pegs either short (0.5mm) or tall (1mm) in length with five orientations (Figure 3.5a). These adaptations increased task length and complexity. Participants held the pegboard with the non-dominant hand and used the dominant hand to transfer each tube to the corresponding tube on the opposite side of the board from top to bottom and outermost to innermost.

2. Tube Transfer (Figure 3.5b): This task was created to simulate how surgeons grasp and manipulate blood vessels and suture threads during microsurgery identified (Yu et al. 2014). Subjects held forceps with both hands to thread a monofilament thread (0.16 mm diameter) through eight silicon tubes. Subjects were instructed to complete the tasks as quickly as possible while maintaining accuracy.



a)



b)

Figure 3.5: Peg board transfer task (a) and the tube threading task (b).

Completion time and number of handling errors (i.e. grasp and release errors) were quantified using recorded videos. Grasp errors were defined as the number of failed grasp attempts, where subjects attempted to grasp the tube, but does not succeed (e.g. forceps misses tube or tube slips out of forceps). Release errors were defined as the number of failed attempts to place tube at its destination, e.g. peg for task 1 or thread for task 2.

3.2.4. Experimental design

Each of the four displays, i.e., Micro2D, Micro3D, Video2D, Video3D, was repeated three times. For the first two repetitions, subjects had 12 minutes to complete each task twice on each display. For the third repetition, subjects performed each task continuously for six minutes. Five minute breaks were taken between displays for changeover and 10 minute breaks were taken between the three repetitions. Total time each subject spent performing the skill tasks was approximately 126 minutes. The experimental design and display order among subjects followed a 4x4 Latin square design (Appendix).

After completing each display during the final repetition, subjects completed surveys on 1) body region-specific perceived efforts, i.e. head and neck, back, right arm, left arm, and lower extremity adapted from Huang (1999), and 2) display usability characteristics, i.e. field of view (FOV), brightness, contrast, color, resolution, and depth. Subjects rated each region and usability characteristic using a 10cm visual-analogue scale (VAS).

3.2.5. Posture measurement

Joint locations (Figure 3.3) were recorded with 31 smart markers from Northern Digital Inc's (NDI) Optotrak Certus motion capture system by two position sensors positioned on the left and right side of the participants. Markers were affixed to each participant using 3M athletic tape and marker locations are shown in Figure 3.3. Optotrak's Smart Marker Rigid Body™ contained three markers each and was used to calculate vectors normal to the Rigid Body or the mid-point of the Rigid Body plane. At the beginning of the experiment, subjects assumed a neutral standing posture with shoulder-elbow-wrist link at 90° flexion and all posture data was calibrated with each individual's neutral standing posture.

3.2.6. Data analysis

Matlab® (The MathWorks, Inc.) scripts were used to calculate posture angles from marker locations. To measure the posture patterns and how they may affect joint loads and perceived efforts (Figure 3.1), the following posture metrics were calculated:

1) posture angles in the neck, upper-extremity, and back (angles defined in Table 3.1),
2) percent-time in static postures, defined as change in angle < 1° per second (Szeto et al. 2012), and
3) number of movements, defined as "the number of times that the joint moved away from the mean angle by...more than 10°" (Szeto et al. 2012, see Appendix).

Statistical analysis of postures and surveys were conducted on IBM SPSS Statistics using a multivariate general linear model with display and task as fixed factors and subject as covariate.

Differences in postures among displays were calculated using Bonferroni's pairwise comparison. Univariate models with Tukey’s multiple comparison tests were used to analyze performance data.

3.3. Results

Results from the motion tracking, survey and performance data among the displays are summarized in the following sections. Sixteen subjects participated in this study, but posture and performance data for one subject was excluded due to trial lengths differences during the final repetition.

3.3.1. Posture Results

3.3.1.1. Posture angles

The definition and descriptive statistics for each posture angle during microsurgery skills tasks are shown in Table 3.1. Example plot of how neck flexion varies among microscope (2D/3D) and video (2D/3D) displays for a representative subject is shown in Figure 3.6. For this subject, neck angle was positive which indicated that the neck was flexed forward on the microscopes throughout the task. This subject were observed to look up or assumed more neutral neck posture, at t=238 seconds for Micro3D and t=197 seconds for Micro2D (Figure 3.6). In contrast, the neck angle for this subject was more erect using the video displays, and the participant increased neck flexion or looked down at the task location at t=166s for Video2D and t=236s for Video3D (Figure 3.6).

Table 3.1: Mean ± standard deviation angles (°) among subjects during all tasks in the final repetition

	All Tasks			
	Micro2D	Micro3D	Video 2D	Video 3D
Angles Definitions: (See Figure 3.3 for Marker abbreviations)	Mean±SD	Mean±SD	Mean±SD	Mean±SD
Left Elbow Flexion: Angle between LEl-LSh and LEl-LWr	87±10	87±9	94±12	89±13
Right Elbow Flexion: Angle between REl-RSh and REl-RWr	91±7 [b]	90±8 [a]	95±11	97±12 [ab]
Left Shoulder Vertical Flexion: Angle between LSh-LHip and LSh-LEl projected on the sagittal plane (defined by vector containing shoulders)	31±13 [a]	31±14	40±11 [a]	33±12
Right Shoulder Vertical Flexion: Angle between RSh-RHip and RSh-REl projected on the sagittal plane (defined by vector containing shoulders)	28±14 [a]	29±13 [b]	35±14	38±14 [ab]
Neck Included: Angle between C7-Ba and C7-He in 3D-space	15±14 [a]	15±15 [b]	2±14 [ab]	6±12
Neck Vertical Flexion: Angle between C7-Ba and C7-He projected on the sagittal plane (defined by vector containing shoulders)	14±15	14±14	9±11	8±11
Neck Rotation: Angle between LSh-RSh and He normal vector projected on the transverse plane (defined by vector containing LHip and LSh) Note: negative indicates head turned to right	1±13 [ac]	2±11 [bd]	-10±14 [cd]	-14±13 [ab]
Back Flexion: Angle between midpoint L/RHip-L/RKn and midpoint L/RHip-Ba projected onto the sagittal plane (defined by vector containing hips)	3±5	3±6	8±11	8±19
Back Rotation: Angle between LHip-RHip, and Ba vector normal projected on the transverse plane (defined by knee and hips) Note: negative indicates back turned to right	1±8	5±9	5±13	2±12

Matching superscript letters in each row indicate significant differences between displays ($p<0.05$) using Bonferroni's pairwise comparisons

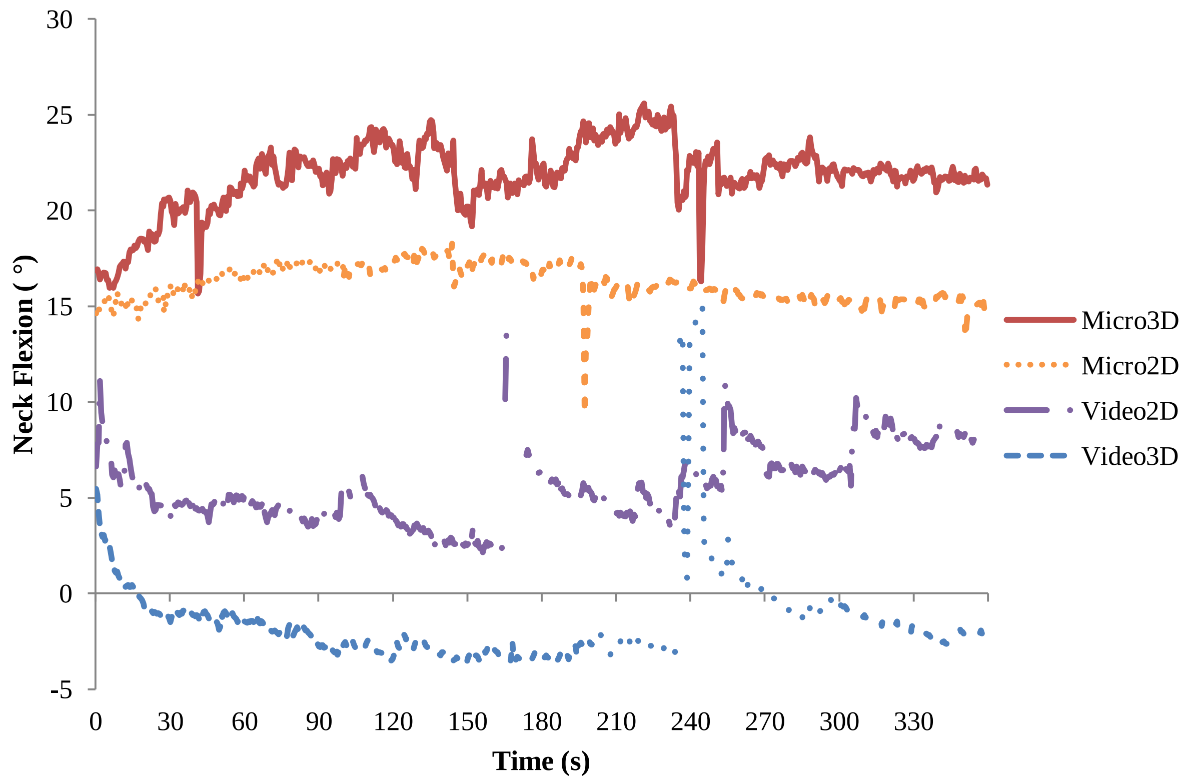
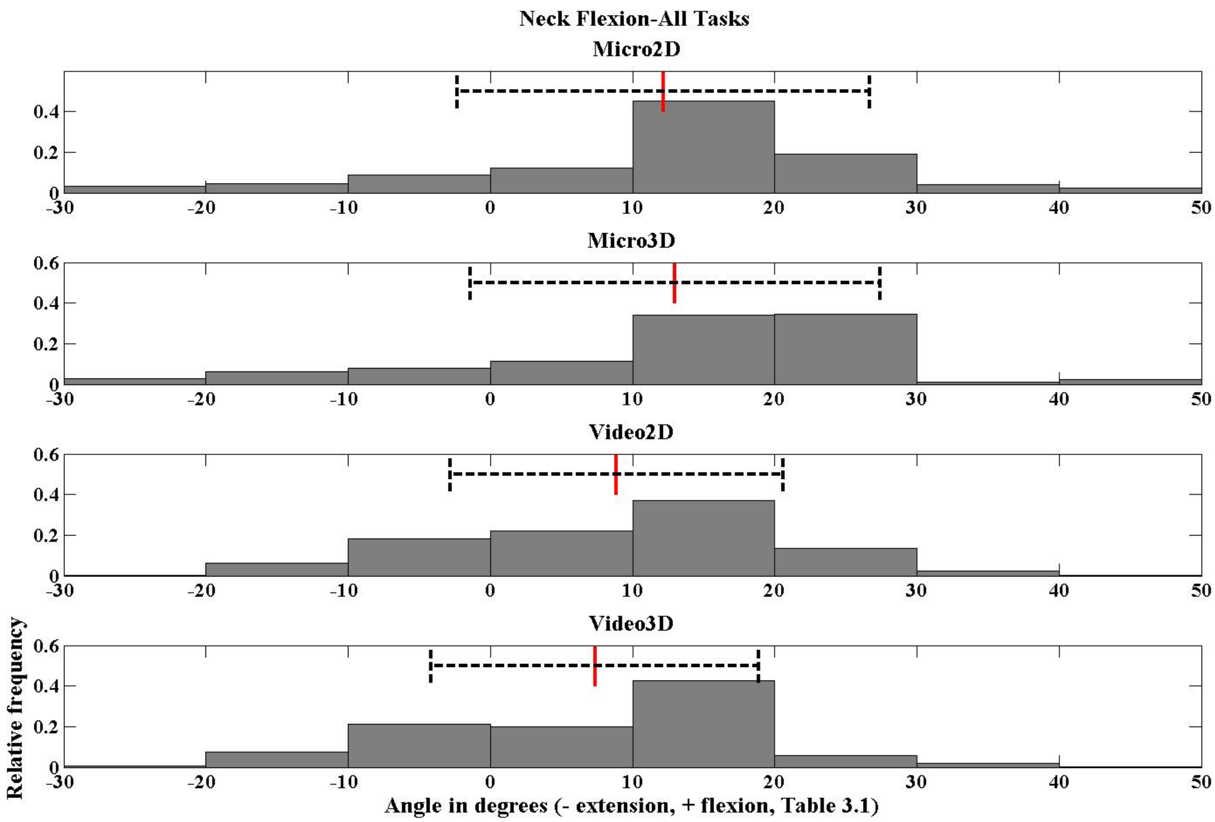


Figure 3.6: Sample time plot of neck posture on the microscopes and video displays for a representative subject during the tube threading task

Mean neck flexion was 6° more erect for Video3D display (8±11°) than microscopes (14±14°); however, it was not statistically significant (Table 3.1). In comparison to microscopes, mean neck included angles were 9-13° more erect for the video displays, and angles were significantly different ($p<0.01$) between the microscopes and Video2D. In addition, mean neck rotation was 11-16° larger ($p<0.001$) for the video displays than microscopes. Significant differences were also observed among displays for elbow and shoulder flexion. Specifically, right elbow angles on Video3D (97±12°) were 6-7° more extended ($p<0.05$) than microscopes. Right shoulder flexion angles on Video3D (38±14°) were 9-10° further from the torso than the microscopes ($p<0.05$). No significant differences in postures were observed due to the monoscopic/stereoscopic condition, i.e., between the 2D and 3D video display or between the 2D and 3D microscopes.

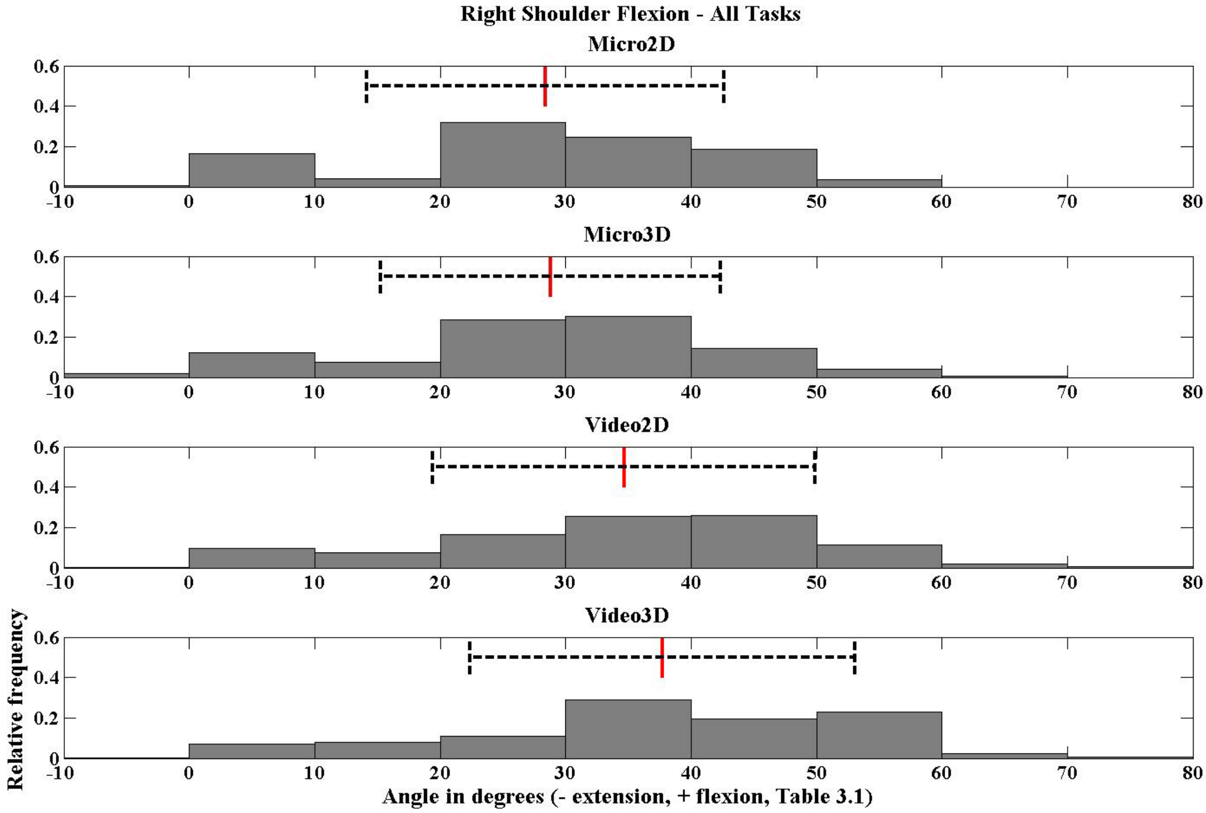
Neck and shoulder postures are shown in Figure 3.7a and Figure 3.7b to illustrate the distribution of angles during the final repetition. The percent times observed in 0-10° neck flexion (recommended by McAtamney & Corlett 1993) for 2D and 3D video displays were 22% and 20% respectively, and these percentages were greater than the percent time observed for 2D and 3D microscopes, 12% and 11% respectively (Figure 3.7a). The percent times observed in -20-20° right shoulder flexion (recommended by McAtamney & Corlett 1993) for the 2D and 3D flat-panel displays were 15% and 17% respectively, and these percentages were less than the percent time observed for 2D and 3D microscopes, 21% and 22% respectively (Figure 3.7b).

a)



- Means and SD are as follows: Micro2D (12±14°), Micro3D (13±14°), Video2D (9±12°), and Video3D (7±12°)

b)



- Means and SD are as follows: Micro2D (28±14°), Micro3D (29±14°), Video2D (35±15°), and Video3D (38±15°)

Figure 3.7: Frequency distribution of (a) neck vertical flexion angles and (b) right shoulder vertical flexion angles (definitions in Table 3.1) from all subjects observed for each display during the final repetition. Mean and standard deviation are shown above each graph.

3.3.1.2. Static postures

Static postures were defined as percent time that angle change was <1° per second (adapted from Szeto et al. 2012), and subjects performing the bimanual microsurgical skill tasks, i.e., pegboard task and threading task, were primarily in static postures (Table 3.2),. Mean right upper extremity postures (i.e., right shoulder and elbow) were 3-9% less static than the left extremity postures (i.e., left shoulder and elbow). Neck postures (73-86% static) were the least static of all observed postures. No statistical differences in time spent in static postures were observed between displays. However, left upper extremity, neck, and back postures were significantly more static in Task 1, i.e., pegboard, than Task 2, i.e., threading (Table 3.2).

Table 3.2: Mean ± SD of the % time in static postures among subjects for pooled tasks during the final repetition, by display.

Angle	% Time Static Postures for Pooled tasks			
	Micro2D	Micro3D	Video 2D	Video 3D
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Left Elbow Flexion[1]	89% ± 10%	90% ± 9%	90% ± 10%	89% ± 10%
Right Elbow Flexion	83% ± 10%	83% ± 9%	86% ± 9%	86% ± 10%
Left Shoulder Flexion[1]	90% ± 9%	91% ± 7%	90% ± 12%	89% ± 12%
Right Shoulder Flexion	81% ± 9%	81% ± 8%	84% ± 9%	85% ± 10%
Neck Included[1]	80% ± 10%	79% ± 11%	76% ± 15%	76% ± 15%
Neck Flexion[1]	86% ± 10%	86% ± 8%	80% ± 14%	79% ± 15%
Neck Rotation[1]	77% ± 11%	76% ± 10%	73% ± 15%	73% ± 14%
Back Flexion	92% ± 9%	92% ± 8%	91% ± 8%	91% ± 9%
Back Rotation	85% ± 15%	86% ± 14%	85% ± 14%	84% ± 15%

[1] indicates significant differences ($p<0.05$) in % time spent in static postures between Task 1 and Task 2

Additional analysis was conducted on neck, back, and shoulder postures, which were areas with high prevalence of musculoskeletal pain and disorders among surgeons who used optical magnification (Sivak-Callcott et al. 2011; Capone et al. 2010; Statham et al. 2010). Table 3.3 shows the number of movements per minute by displays during the final repetition. Definition of movement was adapted from Szeto et al. (2012) as described in the methods and further clarified in Appendix. Movements in neck angle were observed to be 3.22 times more frequent ($p<0.05$) in Video3D than Micro3D (Table 3.3). Back movements were observed to be 1.9 times more frequent ($p<0.10$) when subjects used Video3D than Micro3D. No significant differences were found for right shoulder movement (Table 3.3).

Table 3.3: Mean "number of movements per minute" among all subjects during the final repetition.

	Microscope	Video 3D
Neck Included	0.22 ±0.35*	0.93 ±0.86*
Back Flexion	0.18 ±0.31^	0.52 ±0.96^
Right Shoulder Included	0.38 ±0.83	0.15 ±0.30

* indicates significant differences between displays ($p<0.05$) from paired t-test analysis
^ indicates differences between displays at $p<0.10$

3.3.2. Survey results

Mean perceived efforts for all body regions ranged from 3.7 to 5.4, where 0=no perceived effort and 10=worst perceived effort (Table 3.4). Lower extremity and back required less perceived efforts than arms and head. Head and neck regions had the highest perceived efforts. No significant differences in perceived efforts were found among displays.

Table 3.4: Mean ± SD perceived efforts ratings among all subjects (n=16) responding to five region-specific 10cm visual analogue scales, where 0=no effort and 10=most effort.

	Micro2D	Micro3D	Video 2D	Video 3D
Body region	Mean±SD	Mean±SD	Mean±SD	Mean±SD
Head and neck	4.6±2.8	4.5±2.5	5.4±2.7	5.3±2.3
Back	3.9±2.8	3.4±2.0	4.0±2.4	4.0±2.4
Right arm	4.6±2.9	4.5±2.7	4.6±2.5	4.8±2.6
Left arm	4.2±2.9	4.1±2.6	4.4±2.4	4.2±2.6
Lower extremity	3.7±2.9	3.7±2.8	3.9±2.8	3.9±2.6

Mean ratings on usability characteristics for the displays ranged from 4.4 to 8.6, where 0=worst imaginable and 10=best imaginable (Table 3.5). All ratings were better than neutral (i.e. score of 5.0) except for depth of field on the video displays. On the microscopes, field of view (FOV) was rated the lowest, and colour was rated the highest. For the video systems, depth was rated the lowest, and color was rated the highest. The Video3D was rated 0.6-3.4 points lower ($p<0.05$) than microscopes (2D and 3D) for every usability characteristic, except for the FOV.

Although not statistically significant, depth on Video3D was rated only 0.4 points higher than Video2D.

Table 3.5: Mean ± SD for display usability ratings among all subjects (n=16) on six visual analogue scales, where 0=worst imaginable and 10=best imaginable.

	Micro2D	Micro3D	Video 2D	Video 3D
	Mean±SD	Mean±SD	Mean±SD	Mean±SD
Field of view	6.0±2.1	5.9±2.5	6.6±1.7	6.2±2.5
Brightness	7.8±1.1[b]	8.1±1.0[a]	7.2±1.8	6.2±2.2[ab]
Contrast	8.2±1.2[b]	8.6±1.1[a]	7.2±1.8	5.8±2.0[ab]
Color	8.3±1.3[c]	8.6±1.0[ab]	7.1±1.9[a]	6.3±2.0[bc]
Resolution	8.0±1.4[b]	8.5±1.3[a]	6.9±2.2	5.1±2.6[ab]
Depth	7.7±1.7[bd]	8.1±2.1[ac]	4.4±2.8[ab]	4.8±2.8[cd]

Matching superscript letters in each row indicate significant differences between displays ($p<0.05$)

3.3.3. Task performance

Performance measures for each display on each task are shown in Table 3.6. Completion time was reported as time needed to complete each tube during the task. Errors were reported as number of handling errors observed for each tube during the task (defined in Section 3.2.3). For example, if mean number of errors is 1.0, i.e., Task 1: Pegboard on Micro2D, subjects committed one error for each tube they completed during the pegboard task while using Micro2D.

Table 3.6: Mean performance among subjects during final repetition. Completion time is reported as mean time (s) needed to complete each tube. Errors are reported as mean number of errors observed to per tube. Smaller means represents faster performance and fewer errors.

	Task 1: Pegboard				Task 2: Threading			
	Micro2D	Micro3D	Video 2D	Video 3D	Micro2D	Micro3D	Video 2D	Video 3D
	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD
Completion time per tube (seconds)	5.6±3.1[ac]	5.9±3.9[bd]	10.2±5.6[ab]	9.8±3.6[cd]	34.5±29[a]	33.9±45[b]	52.9±40	71.3±84[ab]
Handling Errors (# errors per tube)	1.0±0.6	0.9±0.5	1.1±1.2	1.1±1.0	5.7±3.2[ad]	3.7±2.7[cd]	3.7±3.4[ab]	5.8±4.7[bc]

Matching superscript letters in each row indicate significant differences between displays ($p<0.05$) using Tukey's multiple comparison tests.

For the pegboard task (Task 1), mean completion times ranged from 5.6-10.2 seconds per tube, and mean number of errors ranged from 0.9-1.1 per tube (Table 3.6). Video displays required 3.9-4.6 seconds or 66-82% more time than microscopes ($p<0.05$) to complete each tube in the pegboard task. Mean number of errors were not significantly different among displays on the pegboard task. For task 1, no significant differences in performance were found between mono/stereoscopic condition, i.e., mean times and errors were similar between Micro2D and Micro3D, and means were similar between Video2D and Video3D.

Mean times were longer on the threading task than the pegboard task (Table 3.6). Mean completion time ranged from 33.9-71.3 seconds per tube, and mean number of errors ranged from 3.7-5.8 per tube. Video3D required 36.8-37.4 seconds or 107-110% more time than microscopes ($p<0.05$) to complete each tube. Mean number of errors were significantly higher ($p<0.05$) for Video3D (5.8) and Micro2D (5.7) than Micro3D (3.7) and Video2D (3.7). On average, 2.0 more errors were observed when subjects used Micro2D than Micro3D ($p<0.05$). On average, 2.1 less errors were observed on Video2D than Video3D ($p<0.05$).

3.4. Discussion

3.4.1. Posture demands using microscope and the effect of video displays

3.4.1.1. Postures angles

Observed mean neck angles were 15° on the microscope (Table 3.1), and consistent with the 10-20°+ range estimated by Statham et al. (2010) using posture matching software during microlaryngoscopy. In contrast to microscope, mean neck angles were 9-13° more erect when subjects used video displays (Table 3.1). Observed differences may have implications for reducing biomechanical loads and muscle exertions during microsurgical tasks. Using biomechanical model developed by Snijders et al. (1991) that relates neck angles with joint loading and the mean neck angles observed in this study (i.e., 14° on Micro3D and 8° Video3D in Table 3.1), moments at the cervical 7-thoracic 1 joint was 23N or 17% higher for Micro3D than Video3D. Previous studies observed that neck moments were associated with neck muscle activity during the use of video displays (Villanueva et al. 1997). The study found that neck extensor activity significantly increased with neck flexion during computer tasks. Specifically, percent maximum voluntary contraction (%MVC) of the neck extensor was 10.4%MVC at 12°

neck flexion, 7.8%MVC at 1.1° flexion, and 5.4%MVC at 11.3° extension. Based on muscle exertion measurements by Villanueva et al. (1997) and the smaller neck flexion during video display use observed in the present study than microscope, results suggest that mean neck extensor muscle activity requirements are reduced during video display use. However, it is important to note that no differences between displays in perceived efforts were reported by subjects.

The predicted neck loads on either microscope or video displays may still be higher than recommended static load of 2-5% MVC for static work (Villanueva et al. 1997). The use of mean postures to calculate neck loads may underestimate the physical demands during the microsurgery skill tasks and does not take into account the percent time subjects spend at postures deviating further from neutral (Figure 3.7). McAtamney and Corlett (1993) suggested that neck flexion beyond 0-10° can increase joint loads and injury risks, but neck flexion in the present study was observed to exceed these guidelines 88% of the time on the Micro3D and 80% of the time on Video3D (Figure 3.7a). The cumulative and daily exposures experienced by surgeons may further increase the risk factors for fatigue and musculoskeletal symptoms among practicing professionals (Armstrong et al. 1993).

Subjects were observed in neck extension 22% of the time while using video displays (Figure 3.6, Figure 3.7a). Extended neck postures have been suggested to greatly increase the risk of musculoskeletal disorders (McAtamney & Corlett 1993), but biomechanics studies showed that neck extension can reduce neck moments from gravity and lower neck extensor muscle activity levels (Straker et al. 2009; Villanueva et al. 1997). The observations of neck extension and neck movements during video displays (Table 3.1, Figure 3.6-Figure 3.7a) may illustrate a mechanism that allowed subjects to reduce or shift muscle loads. However, it is important to note that display location was not controlled in this study, and subjects placed the displays according to their preferences. This may indicate that neck extension was preferred or had no significant effect when subjects positioned the monitor.

Mean right shoulder angles (defined in Table 3.1) were 9° greater for Video3D display than microscope (Table 3.1). However, mean observed shoulder flexion angles for all displays were within the 20-45° shoulder flexion range recommended for laryngeal microsurgery (Chen et al., 2012; Statham et al., 2010). Modeling the mean postures (Table 3.1) in 3D Static Strength

Prediction Program^{TM} (University of Michigan) and using the conservative shoulder strength of the 5th percentile male, the required shoulder strength was estimated to be 20% MVC for Video3D and 17% MVC for microscope. The larger shoulder angles on the video displays than microscope were unexpected because 1) shoulder loads were predicted to increase with shoulder angles and 2) video displays were hypothesized to reduce posture constraints and allow subjects to choose comfortable postures that reduce musculoskeletal stresses. Specifically, postures using video displays were only constrained by task area, and shoulder angles could be reduced by moving the torso closer to the task area (Figure 3.3, Figure 3.4). Although increased joint loads and fatigue from the large shoulder flexion may be a concern (Figure 3.1), possible explanations for the larger shoulder angles while using video displays may be 1) larger shoulder angles and elbow angles allowed subjects to assume a more comfortable distance from the task area (i.e., table) and/or the display or 2) upper extremity loads were reduced by resting their hands and arms on the task area (Figure 3.8). However, display distances and table locations were not controlled in the present study. Further studies are needed to investigate the effect of display distances, table distances, and limit subject's ability to rest hands and arms (Figure 3.8) on the table since this ability is limited during live surgical procedures.

Figure 3.8: Unique posture observation while using the 3D flat-panel display. Unconstrained by microscope eyepieces, illustrated subject was observed to lean and rest upper extremity on table.

3.4.1.2. Sustained exertions

Previous studies have suggested that sustained postures without sufficient recovery time are major concerns for fatigue and musculoskeletal injuries during surgery (Berguer et al. 1997; Szeto et al. 2012). In the present study, observed upper extremity postures were 6-10% more static (defined as percent time that angle change was <1° per second and adapted from Szeto et al.

2012) on the left than the right. This was expected since subjects were right-handed, and tasks were designed based on observed microsurgery techniques where one hand, typically dominant hand, uses forceps to excise tissue, while the other hand use forceps to hold the tissue stable (Yu et al. 2014; Evans & Evans 2007). No significant differences in percent time in static postures among displays were observed (Table 3.2). Lack of significant differences among displays are reasonable, because the task requirements that dictate postures remained similar for each display, i.e., the small task area and need to look at one stationary display. However, because movement time for adjusting posture was short compared to the duration of the task, "% time in static postures" may not the best metric to assess the prevalence of sustained exertions.

Posture adjustments or movements may be important for reducing the prevalence of sustained loads and static muscle contractions during microsurgery tasks. Previous studies suggested that sustained postures may contribute to fatigue and musculoskeletal disorders (Kilbom et al. 1986; Berguer et al. 1997; Szeto et al. 2012). Park et al. (2010) emphasized that 84% of surveyed laparoscopy surgeons indicated that postures adjustments were used to prevent fatigue, and the present study observed that the number of movements per minute was larger during Video3D than microscope (Table 3.3). This observation supports our hypothesis that video displays can reduce constraints and allow subjects to adjust their postures more frequently. However, no differences in surveyed perceived efforts were found among displays (Table 3.4) despite differences in postures and posture patterns, and this may be due to the short task durations that were not long enough to distinguish differences in perceived efforts. Additional research is needed to investigate whether posture movements had any effect on effort and fatigue.

3.4.2. Performance and errors

Previous studies proposing video display systems for microsurgery reported that surgeons have commented favorably on the system's comfort and educational potential, but technological limitations of the video systems prevented surgeons from achieving comparable performance with conventional microscopes (Franken et al., 1995, Gorman et al., 2001). Franken et al. (1995) did not report surgical performance times on rats due to frequent "technological adjustments" when using the video system and Gorman et al. (2001) reported that surgeons required 71% more time to complete microsurgery on rats using a 2D video system compared to conventional microscope. Similar performance trends were observed in the present study. Subjects required

66-110% more time to complete the skills tasks using the 3D flat-panel than the conventional microscope (Table 3.6), and these differences may be due to technical limitations (i.e. brightness, contrast, color, resolution, and depth, Table 3.5) in video systems.

Handling errors may be relevant to patient outcomes in microsurgery, as failed attempts to grasp the delicate blood vessels may damage the vessel walls and lead to thrombosis of the transplanted tissue (Yu et al. 2014). For pegboard task, errors were not significantly different among the displays (Table 3.6). For threading task, significantly fewer errors were observed in the 3D microscope than 2D microscope. The differences in 2D and 3D errors may be explained by task difficulty. The pegboard task consisted of placing tubes on a pegboard fixed to the work surface; however, the other task required subjects to manipulate both the thread and tube in 3D-space. This suggests that binocular vision from the 3D microscope may be beneficial for tasks in 3D-space. In contrast, the stereoscopic video resulted in more errors than 2D video, and these differences may be due limitations in camera resolution, reduced brightness from shutter glasses, or camera alignment when using Video3D display.

3.4.3. Future research

Further studies are needed to understand if alternative displays can improve surgeon postures in 1) prolonged continuous tasks, 2) increased task complexity, and 3) improved alternative display systems.

One limitation of this study is the time duration that subjects continuously worked with using each display. Microsurgery typically lasts 1-2 hours in length, but subjects only work with each display for 12 minutes per repetition before changeover to a different display. Although our study length averaged four hours, short task durations were necessary to execute our study design of four treatments with three repetitions in one session. We found significant differences in postures between the displays within the short task lengths; however, no significant differences in perceived efforts were observed among displays. It is important to note that participants in this study were university students with no prior surgical experience; therefore, participants in this study lacked the continuous posture exposures accumulated by surgeons that perform the procedures daily. In addition, subjects occasionally reduced musculoskeletal stresses by assuming postures that are not feasible in a surgical work environment (Figure 3.8). Longer testing periods with experienced subjects merit further investigation to 1) more accurately simulate the task demands and workplace restrictions of surgery and 2) provide opportunities to quantify perceived efforts and physical symptoms from participants with experience on daily microscope use. We hypothesize that differences in posture, fatigue, and efforts due to the display effect will be more pronounced in longer tasks due to continuous exposure to posture constraints.

The microsurgical skills tasks performed in this experiment may under-represent the task and posture demands of microsurgery and is a limitation of having a controlled laboratory study. Despite differences in tasks, postures observed in this study are similar to surgeon postures published in other studies (Statham et al. 2010). Further investigations of more representative tasks are merited to observe how higher task demands affect posture stresses and patterns using different displays.

Results from this study provided insights into how postures are affected by microscope constraints; however, studies are needed to investigate these findings with 1) better displays and 2) optimal display locations. Differences in task performance (Table 3.6) and subjective ratings (Table 3.5) indicate that improvements to video systems are needed to match the image quality of microscopes. Improved technology is available (Berguer and Smith 2008; Nissen et al. 2011; Nissen et al. 2013; Munz et al. 2004; MagnaVu™, Olympia, WA), and future studies can examine whether postures improvements observed in this study is consistent in these displays. Finally, previous studies showed that display locations significantly affected surgeon postures, discomfort, and performance (Berguer 1999; van Veelen et al. 2002; Hanna et al. 1998). Similar to previous posture-display studies conducted in the operating room (van Det et al. 2008), subjects in the present study could adjust the display location based on their preferences. In surgery, Park et al. (2010) showed that 58% of surgeons had limited awareness of ergonomics; thus, chosen display locations may not be the optimal location. However, despite this limitation, more neutral neck postures and increased neck movements were observed on video displays. Additional studies are needed to systematically vary display locations and compare chosen locations with optimal display to further measure the impact of displays (i.e., microscope versus video) on postures.

3.5. Conclusions

Previous studies have shown that musculoskeletal symptoms are highly prevalent in surgery. Research on workplace redesign and alternative displays that reduce surgeon discomfort and risk for musculoskeletal disorders may improve surgeon performance and increase their career longevity.

Three hypotheses comparing video and microscope displays were investigated in the current study. Results found that mean neck postures on video displays were more erect than microscopes. These observations suggest that video displays can reduced biomechanical loads and muscle exertions. In addition, increased posture movements were observed on video displays than microscope, which may be due to reduced constraints provided by the video displays. However, it is important to note that the ability to choose postures do not necessarily mean subjects will chose the most ergonomic postures (Figure 3.8). Second hypothesis focused on the relationship between displays and perceived efforts, and no differences in perceived efforts were observed among displays. However, several study limitations, e.g., small sample size, short task durations, high variability in subjective ratings, may have affected the statistical analysis. Finally, video displays were hypothesized to improve task performance times; however, task completion times were 66-110% faster on the microscopes than video displays, and further studies are needed to understand why and under what conditions video displays perform worse than microscopes.

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3.8. Appendices

Table 3.7A: Experimental design

Subject	Display order, where A is Micro2D, B is Micro3D, C is Video2D, D is Video3D
Subject 1	1st repetition: ABCD, 2nd repetition: BDAC, 3rd repetition: CADB
Subject 2	1st repetition: BDAC, 2nd repetition: CADB, 3rd repetition: DCBA
Subject 3	1st repetition: CADB, 2nd repetition: DCBA, 3rd repetition: ABCD
Subject 4	1st repetition: DCBA, 2nd repetition: ABCD, 3rd repetition: BDAC
Subject 5	1st repetition: ABCD, 2nd repetition: BDAC, 3rd repetition: CADB
…	
Subject 16	1st repetition: DCBA, 2nd repetition: ABCD, 3rd repetition: BDAC

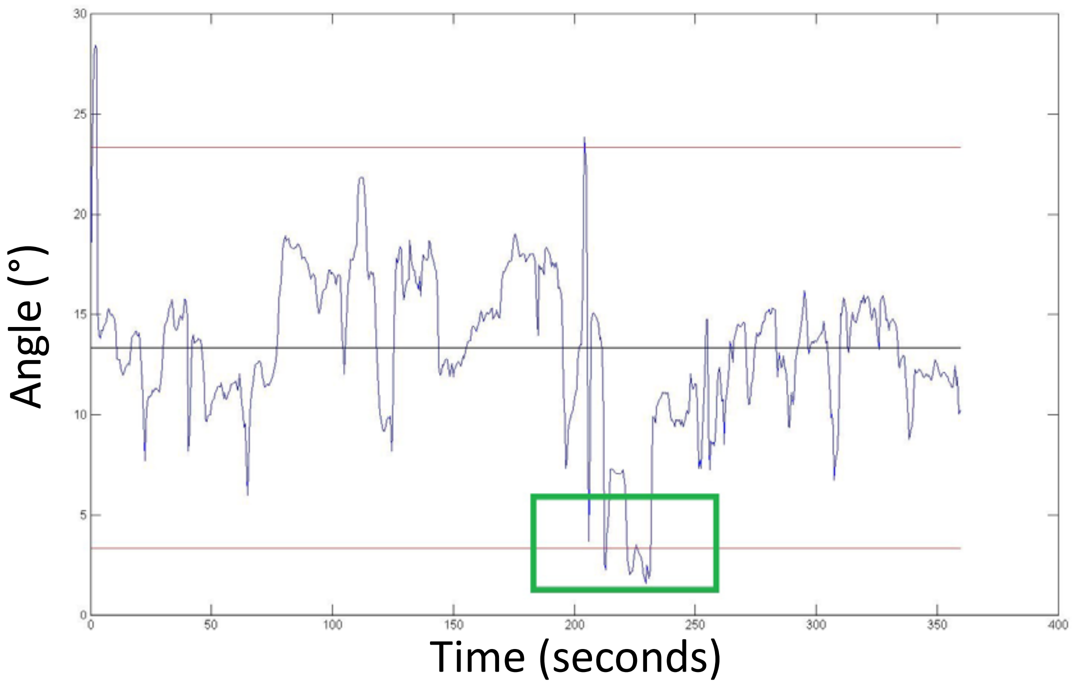


Figure 3.9A:Example of a subject's neck angle over time to demonstrate how "number of movements" was quantified (definition is adapted from Szeto et al. 2012).

Lines in the figure are defined as follows:

- Blue line: angle change over time
- Black line: mean angle
- Red line: 10° above and below mean angle (black line)

The green thick-lined box contains intersections where the subject's neck angle deviates greater than 10° from the mean angle. Only **one** "crossing" is contained within the box because *"movements" must cross both the mean (black line) and 10° from the mean (red line)*. Total number of crossing in this example is **three**.

CHAPTER 4

EFFECT OF DISPLAYS ON TARGETING TASK IN 3D SPACE: COMPARISION OF MICROSCOPES, LOUPES, AND VIDEO DISPLAYS

Abstract: Task speed and accuracy are vital components to microsurgery, which affect the time it takes to complete the procedure and impact surgical outcomes. The purpose of this study was to measure the impact of microscope, loupes, and video displays on speed and accuracy in movements within 3D space. The targeting task was designed to test the effects of 1) target distance, 2) target axis, 3) target direction, 4) display type, and 5) display 2D/3D factor. Data from 5,290 target trials were collected from 12 university participants. Performance with 2D displays were 11-29% worse than 3D for targets on z-axis for all measured performance metrics. Movement times were fastest for loupes and slowest for video. Times on video were 6-18% slower than microscopes and loupes for targets on x and y-axes. On vertical z-axis, times were 26-34% slower on the video than loupes and microscope. Video displays were better or not significantly different than other displays for distance moved, overshoot, and submovements for targets on x and y-axes. A third of the participants performed better on the Video3D than Micro3D, suggesting that individual factors, e.g., stereoscopic visual acuity, advance fine-motor skills, and experience with 3D displays, may impact performance differences among displays. In addition, differences in viewing angle and camera position were identified as possible factors that warrant further research to improve performance on video displays. Video displays may provide comparable performances to microscope and loupes during targeting tasks that primarily require motion in the left/right or fore/aft directions, but video may be limited for targeting tasks in the vertical direction.

4.1. Introduction

4.1.1 Background

Microsurgery tasks require efficient and accurate movements in 3D space (Pederson 2010; Temple & Ross 2011; Kalu et al. 2005; Grober et al. 2003), but current literature is mostly limited to 1) performance metrics during live surgeries that occur in highly variable environments or 2) times and accuracy in one-dimension (1D) or two-dimension (2D) targeting tasks.

Microsurgery training and assessments have largely focused on animal models, skills task modules, and live surgeries (Chan et al. 2007; Pederson 2010; Temple & Ross 2011; Kalu et al. 2005; Grober et al. 2003). Although the highly technical, complex environments, and unstandardized conditions may provide validity during surgeon training, these conditions present a challenge for the close examination and measurement of how differences in visualization equipment, i.e., microscope, loupes, video, fundamentally affect performance.

Although rigorous investigation of accuracy and movement time is limited in microsurgery literature, human performance studies on targeting tasks can provide a more theoretical understanding on how task conditions affect speed and accuracy. For example, Lin & Drury (2013), Fleischer (1989), and Lee & Bang (2013) found that movement time, overshoot distances, and number of submovements were affected by target distances, angle of approach, and time pressure. It is important to note that these studies only examined one-dimensional (1D) and two-dimensional (2D) target tasks using a mouse or tablet. Studies on 3D movement is limited, but several investigations concluded that: 1) movement time is significantly affected by movement direction and the 3D target's dimension during an arm targeting task in 3D-space (Grossman & Balakrishnan 2004), 2) movement distance significantly affect movement times and errors in X, Y, and Z axes during an arm targeting task in 3D-space (Lin & Ho 2011), and 3) depth size of the target, i.e., z-component, during tapping tasks does not significantly impact task performance (Hoffmann, Drury, & Romanowski 2011). However, these studies were performed with target sizes of 5mm-60mm and target distances of 50mm-600mm.

In microsurgery, movement distances and the size of anatomical objects are typically smaller than the conditions explored in human performance literature. Magnification is needed during microsurgery to help the surgeon expose, prepare and join the small delicate vessels that are typically 1-4mm in diameter. During these procedures, the field of view in microsurgery for microvascular anastomosis is in the scale of 6cm x 10cm and typical magnification of 6-20x (Yu et al. 2014). In general, surgical microscopes have field of views of 16.5mm-180mm in diameter, zooms of 1.2x-12.8x, and working distances of 200-500mm (Leica). These conditions may limit the application of previous findings in the human performance literature, and authors have indicated that not much is known about the relation between movement time and Fitts' index of difficulty during small-scale movement (Boyle & Shea 2013). Thus, additional research is needed to investigate movement at smaller targets and smaller magnitudes that require the magnification conditions surgeons typically use.

4.1.1.1. Magnification and human performance

Optical magnification is essential in microsurgery (Safwat et al. 2009) and provides surgeons the visual feedback necessary to assess and manipulate small anatomical structures (e.g., blood vessels, side-branches), tools (e.g., needle), and materials (e.g., suture) (Yu et al. 2014). Surgical studies have shown that precision during microsurgery positioning task improved as magnification increases until 10x (Safwat et al. 2009). However, this need for optical magnification may affect the application of current performance theories, e.g. Fitts' Law. In addition, the findings in previous 3D movement literature (Grossman & Balakrishnan 2004; Lin & Ho 2011; Hoffman et al. 2011) may have limited application for microsurgery due to the smaller movement distances and target sizes.

Early studies of human performance in electronics assembly may provide insights on the impact of magnification on surgery performance. Langolf & Hancock (1975) observed no differences in performance between tested magnification ranges of 3.5x to 15x, and this range of magnification was similar to those used in microvascular anastomosis (Yu et al. 2014; Safwat et al. 2009). In addition, Langolf et al. (1976) studied microscope scale movements during peg transfer tasks, and observed that movement at the distance of 0.25cm mainly consist of finger movements, while larger movements at the distance 1.27cm required both fingers and wrist.

More recent studies on targeting task at small distances, i.e., 16mm and 49mm, found that movement times were affected by both arm component and Fitts' Index of Difficulty (ID)

(Hoffmann & Hui 2010; Boyle & Shea 2013). The authors observed that movement time increased as ID and arm component increased, e.g. finger versus wrist, and suggested that limb mass moment of inertia can be used to model the differences (Hoffmann & Hui 2010). Similar to Hoffmann & Hui (2010), Boyle & Shea (2013) found that Fitts' model of movement time and ID fitted "remarkably" well during small amplitude movements of 4-16° with the wrist. These studies suggest that human performance literature may be applicable to assessing performance under magnification; however, it is important to note that these previous studies were conducted with 1D targeting tasks, and further work is needed to examine these trends for 2D and 3D movements.

4.1.1.2 Display types and performance

Previous findings in human performance literature, magnification tasks, and further investigations of 3D movement during micro-tasks can be used to build hypotheses when measuring how surgeon performance can be improved with different visualization equipment. As mentioned in Section 4.2.1, microscopes provide the magnification needed to perform microsurgery; however, microscopes may impact the musculoskeletal health, discomfort, and fatigue of the surgeon (Franken et al. 1995; Gorman et al. 2001; Yu et al. 2012; Nissen et al. 2013).

Although widely used, operating microscopes have been suggested to restrict and constrain postures, which may lead to fatigue and discomfort during prolonged procedures (Franken et al. 1995; Gorman et al. 2001; Yu et al. 2012; Nissen et al. 2013). Surgical loupes can be another option for microsurgery, and loupes have advantages over the microscope by removing posture constraint (Maillet et al. 2007; Sunell & Rucker 2004; Shah & Pellegrini 2010). However, surgical studies have observed that surgeons using loupes were in non-neutral postures for 85% of the time it takes to complete ophthalmic surgeries (Nimbarte et al. 2013). In addition, the investigators have noted that wearing head-mounted loupes and/or headlamps increased neck loads. The increased weight and the observed prolonged and poor postures have been suggested to increase surgeon's risk for musculoskeletal disorders (Nimbarte et al. 2013).

Alternative video display systems may provide ergonomic benefits (e.g., improved postures) during microsurgery (Franken et al. 1995; Gorman et al. 2001; Nissen et al. 2013; Jianfeng et al.

2014; Chapter 3) and improved team performance, e.g. communication. However, many studies observed that video systems increased microsurgery times in comparison to conventional microscopes (Franken et al. 1995; Gorman et al. 2001; Yu et al. 2012; Nissen et al. 2013). Compared to microscopes, rat vessel anastomosis completion times were 720 seconds or 70% longer with 2D video systems (Gorman et al. 2001), and 600 seconds or 37% longer with 3D video systems (Cheng et al. 2012). Similarly, operating times for pancreaticoduodenectomy were 53 minutes or 13% longer with 2D video systems than conventional microsurgery equipment (Nissen et al. 2013). In addition, performance times in microsurgical skill tasks were 66-100% longer with video displays than microscopes (Chapter 3). However, it is important to note that anastomosis quality, vessel patency, pancreatic fistula rate, or handling errors were not significantly different between the displays (Gorman et al. 2001; Jianfeng et al. 2014; Nissen et al. 2013; Chapter 3).

In contrast, a recent study on rat anastomosis with 3D video system found no significant differences among 40 rat vessel anastomosis times between 3D video and microscope performed by a student with previous experience of completing 50 rat anastomoses with a microscope (Jianfeng et al. 2014). The lack of significant differences observed by Jianfeng et al. (2014) may be due to 1) variability in surgical conditions, 2) learning effect after performing 40 anastomoses, 3) inexperience of the medical student, 4) low sample size of 10 per experimental condition, or 5) improvements in 3D display technology. It is important to note that previous studies with stereoscopic displays were limited by video quality (Franken et al. 1995; Chapter 3) or small sample size, i.e., two patients (Cheng et al. 2012). The findings by Jianfeng et al. (2014) may suggest that 1) surgeons using 3D systems can reach performance levels similar to microscopes after 40 rat anastomoses and/or 2) improved stereoscopic systems may improve surgeon performance over previous 2D and 3D systems.

4.1.1.3 Stereoscopic displays and performance

Availability of 3D displays and stereoscopic technologies has been improving, and its application in surgery has been steadily increasing. Early experiments on 3D displays for microsurgery were met with optimism from surgeons, but technological limitation caused frequent interruptions (Franken et al. 1995). Recent studies with improved displays showed that 3D displays can be feasibly used to complete anastomoses (Cheng et al 2012; Jianfeng et al.

2014). However, investigators reported higher dizziness and fatigue scores from subjects using the 3D system than 2D system (Kong et al. 2010; Hanna et al. 1998). From findings in Chapter 3, subjects also noted disparities between 3D displays and microscopes in resolution, brightness, contrast, color, and depth. Key challenges observed in Chapter 3 included difficulty in streaming high-resolution stereoscopic video and in aligning and focusing at the convergence location of the cameras.

Although the application of 3D displays are limited in surgery, 2D displays are widely used in many surgeries, e.g., laparoscopic, endoscopic. In addition, 2D displays bypass the challenges of streaming high definition video and the issue of camera convergence prevalent in 3D displays. However, there is still much debate whether lack of depth from 2D displays may impact performance. Current laparoscopic literature suggests that 3D systems 1) improved accuracy of skill tasks among novices, 2) did not improve movement times, and 3) made no difference for experts (Kong et al 2010). Literature review in endoscopic surgeries similarly reported that only 50% of papers found significant benefits of stereoscopic systems (Hofmeister et al. 2001; Hanna & Cushieri 2001). In microsurgery, stereoscopic visual acuity was hypothesized to correlate with surgical ability; however, studies associating visual acuity with microsurgery suturing skills were inconclusive (Grober et al. 2003).

The role of stereoscopic displays on task performance has been further studied in the human performance and human-computer interface literature, and this research may offer insights on the application of stereoscopic video systems to microsurgery. Draper et al. (1991) observed that performance times on simple tapping tasks using stereoscopic displays were not significantly different than monoscopic displays and suggested that stereoscopic displays provided redundant cues during simple Fitts' tasks. However, performance on stereoscopic displays was 30-60% faster than performance on monoscopic displays during complex socket-insertion tasks (Draper et al. 1991). In contrast to the simple tapping task, socket insertion tasks were more complicated than tapping tasks, and socket tasks involved movement and targeting in 3D-space. These findings suggested that subjects can adapt to the lack of depth cues on 2D displays by learning other mono-visual cues during simple 1D tapping tasks, but stereoscopic displays may be beneficial for tasks beyond 1D tapping, e.g., socket insertion, surgery, that may require different visual cues for manipulating objects in 3D-space. Further research is needed on human performance in 3D tasks under magnification, and additional research is needed to measure the impact of stereoscopic displays under different 3D conditions.

4.1.2 Study aims and hypotheses

This research aims to measure the impact of displays on speed and accuracy in movements within 3D space. Specifically, aims include identifying: 1) the effect of stereoscopic and monoscopic displays on task performance under different task conditions, and 2) the impact of different displays on performance under different task conditions.

To accomplish these aims, three null hypotheses are proposed:

- H1: Movement time and accuracy is not dependent on displays, i.e., microscope vs. video displays vs. loupes.
- H2: Movement time and accuracy is not dependent on depth information provided by stereoscopic displays, i.e., 2D vs. 3D.
- H3: Movement time and accuracy for microtasks (10-40mm distances) are not dependent on the axis of movement, i.e., x, y, z (Figure 4.1).

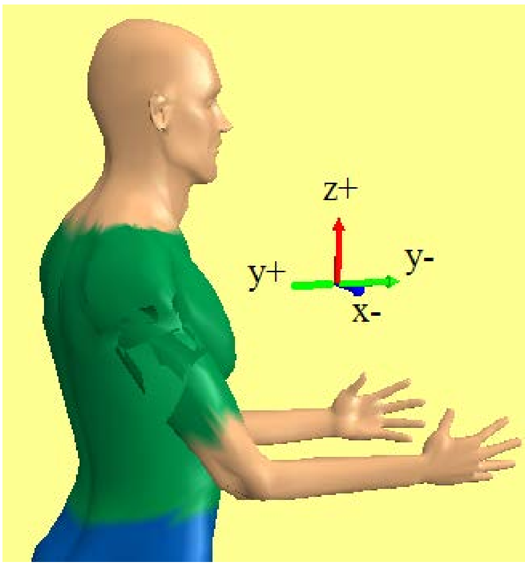


Figure 4.1: Definition of coordinate system

4.2. Methods

A one-day laboratory study was conducted to determine how movement time and distance are affected by target distance, stereoscopic/monoscopic factor, target direction, and display types, i.e., microscope, loupes, and video.

4.2.1. Participants

The study was approved by the university's institutional review board and written informed consent was obtained from 12 university students with no prior surgical experience. The mean age of the participants was 24 ± 4 years old; mean weight was 64kg ± 11kg; mean height was 171cm ± 11cm; and mean elbow height was 107cm ± 9cm. All subjects were right-handed and 50% were males. All of participants had normal or corrected to normal vision. Two participants wore glasses during the study. Ninety-two percent of students had experience using microscopes.

4.2.2. Targeting tasks

Participants performed movement tasks, designed to simulate microsurgery work demands and systematically test the effect of stereoscopic displays on performance times.

Standardized skill assessment tasks were decomposed into basic elements to identify the fundamental task demands in order to design tasks that simulated surgical skills. The motion decompositions of select Fundamentals of Laparoscopic Surgery (Peters et al. 2004) tasks are shown in Table 4.1. Note that extracorporeal stitches, intracorporeal stitches, and endoloops tasks were not decomposed due to limited relevance to microsurgery. During these tasks, a majority of motions involved moving tool (loaded/unloaded), preposition, and hold. These skills were similarly observed during microvascular anastomosis surgery when surgeons align, support, and suture blood vessels (Yu et al. 2014). Specifically, Yu et al. (2014) decomposed microsurgery tasks into granular elements to understand variations among surgeon performance. Surgeon technique at holding blood vessel during "drive needle" element, i.e., support method attribute, was hypothesized to damage tissues and affect surgical outcomes and microsurgery time (Yu et al. 2014). These skills were focused during the task design in this study.

Table 4.1: Motion decomposition of select Fundamental of Laparoscopy Skill (FLS) tasks

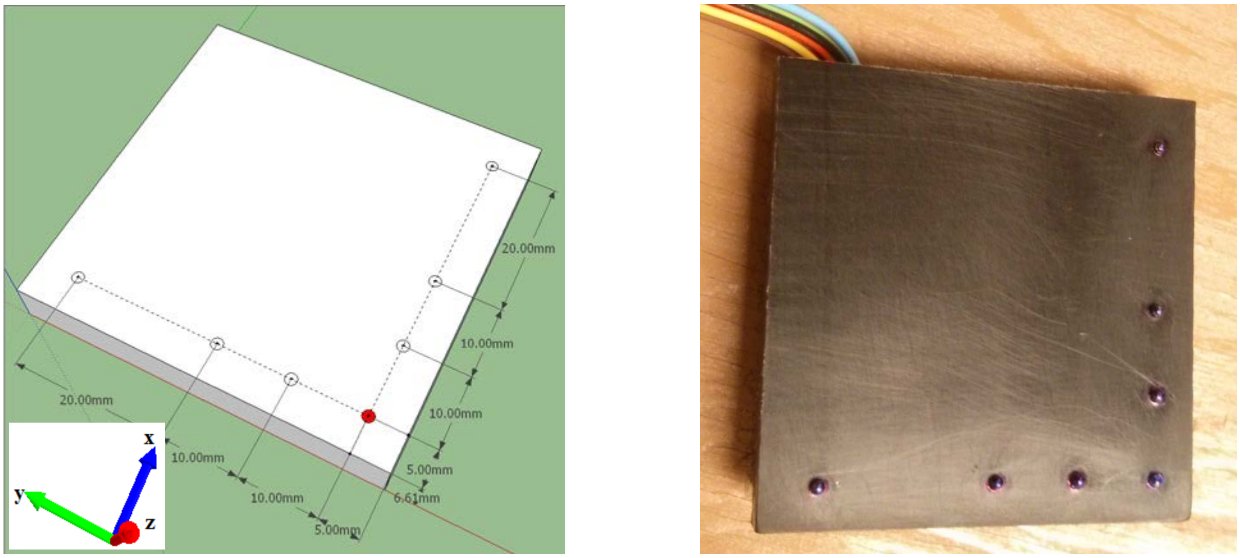
Task	Motion decomposition	
Pegboard transfer task (video from https://www.youtube.com/watch?v=ROUGZ79Paxk)	Left Hand	Right Hand
	1. Transport empty	
	2. Preposition	
	3. Grasp	
	4. Transport loaded	1. Transport empty
	5. Preposition	2. Preposition
		3. Grasp
	6. Release load	
		4. Transport loaded
		5. Position
		6. Release load
	Repeat for other 5 pegs and reverse handedness to return pegs to original position	
Circle cut task (video from https://www.youtube.com/watch?v=ROUGZ79Paxk))	Left Hand	Right Hand
	1. Transport empty	
	2. Grasp	1. Transport empty
	3. Hold	2. Preposition
	4. Hold	3. Use scissors
	5. Preposition	4. Preposition
	6. Hold	5. Use scissors
	7. Preposition	6.
	8. Hold	7. Preposition
	9. Hold	8. Use scissors
	10. Hold	9. Preposition
	11. Hold	10. Use scissors
	12. Hold	11. Preposition
	13. Hold	12. Use scissors
	14. …(video skips)	13. …(video skips)
	15. Transport empty	14.
	16. Grasp	15. Preposition
	17. Hold	16. Preposition
	18. Hold	17. Use scissors
	19. Hold	18. Preposition
	20. Hold	19. Use scissors
	21. Hold	20. Preposition
	22. Position	21. Use scissors
	23. Hold	22. Preposition
	24. Position	23. Use scissors
	25.	24. Preposition
	26.	25. Use scissors
	27. Transport loaded	26. Transport empty
	28. Position	27.
	29. Release load	28.
Cup drop drill (Rosser et al. 1997; video from https://www.youtube.com/watch?v=IWvyB0vgiTI)	Left hand	Right hand
		Bead 1
		1. Transport unloaded
		2. Preposition
		3. Use grasper
		4. Transport loaded
		5. Preposition

	6. Release load
	Bead 2
	7. Transport unloaded
	8. Preposition
	9. Use grasper (miss)
	10. Preposition
	11. Use grasper
	12. Transport loaded
	13. Preposition
	14. Release load
	Bead 3
	15. Transport unloaded
	16. Preposition
	17. Use grasper to move bead
	18. Preposition
	19. Use grasper
	20. Transport loaded
	21. Preposition
	22. Release load
Repeat for other hand	

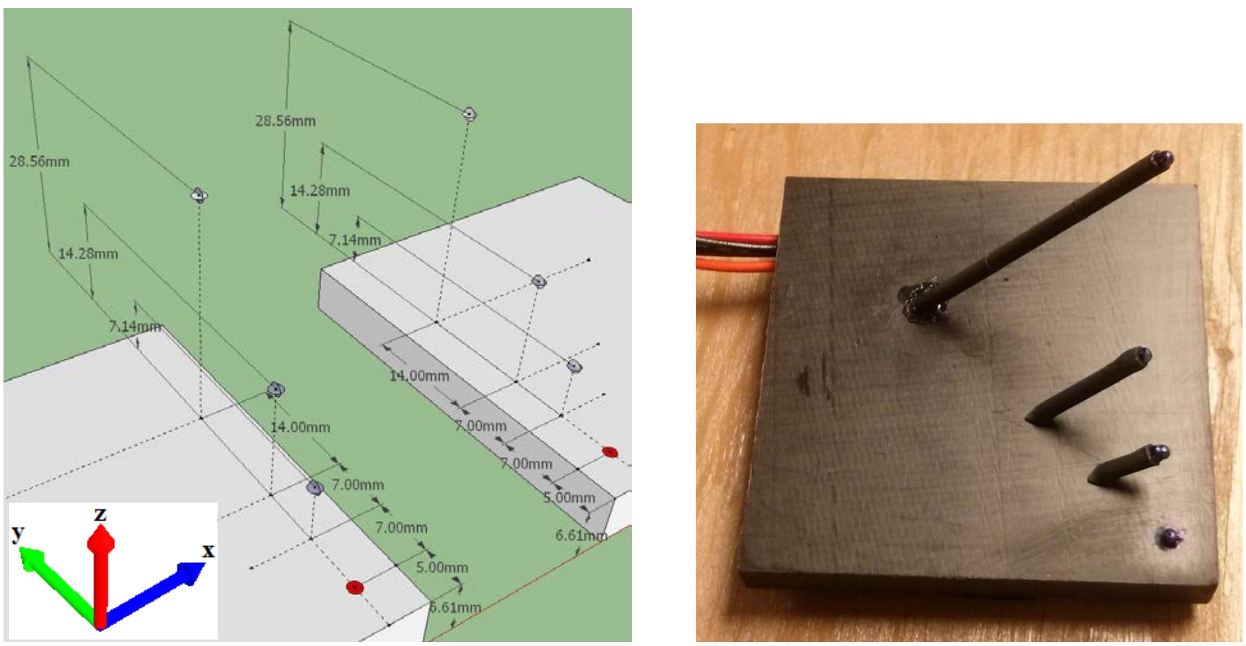
4.2.2.1. Fitts Task

Using the motion decomposition of surgical skills tasks (Table 4.1), a targeting task was designed to emphasize the motions move, hold, and preposition (Figure 4.2). During this task, the subject performed the following steps and received audio feedback (red) as indicated next to the steps:

1. Held position at start for 3 continuous seconds -buzz
2. Moved to specified target -no buzz
3. Prepositioned onto target -no buzz
4. Held position at target 3 continuous seconds -buzz
5. Moved back to start -no buzz
6. Held at start for 3 continuous seconds -buzz
7. Repeated steps 1-6 for next target



a)



b)

Figure 4.2: a) Targets in the x and y directions, with axes defined in Figure 4.1. b) Targets in the zy directions, with axes defined in Figure 4.1. Red indicates start target. Two structures were created in mirror images to prevent obstructing subject movements due to handedness.

Performance time and movement distance were measured between Step 2 to Step 3 above using MaxTraq^{TM} software (Innovision Systems Inc) and video recordings at 30 frames per second. LabView^{TM} (National Instruments) was used to provide audio feedback with two buzzers to the subject upon the successful completion of Step 1, 4, and 5. First buzzer was sounded whenever subject makes contact between the probe at target, while the second buzzer was sounded after three seconds of steady contact between the probe tip and target. Subjects were instructed to always return to start after each target and move from start to the specified target after hearing the 2nd buzzer.

4.2.3. Equipment and materials

4.2.3.1. Displays

During the experiment session, each subject used a microscope, loupes, and video display (Figure 4.3a-c) according to a Latin square order (Section 4.4.4). The microscope display consisted of a benchtop binocular microscope with 3.5x zoom (Scienscope Model: EZ-BD-D2). Loupes display consisted of 2.5x surgical loupes with 460mm working distance (Keeler Instruments Inc.) that allowed subjects to adjust the lenses to their pupil distance and preferred lenses angle. The video display streamed real-time video at ~68ms lag from a depth camera (Sony HDR-TD20) with magnification lenses to a 3.5in viewfinder that displays 3D 16:9 video in 1,229,000 pixels without the need for shutter or polarized glasses. The zoom setting for the video system was 14x.

a) b) c)

Figure 4.3: Participants used a) microscope, b) loupes, and c) video displays.

To test the effect of stereoscopic and monoscopic displays, participants wore a concave eye-patch (Flents Products Co., Inc.) with each display during the monoscopic condition. For the monoscopic video condition, subjects wore the eye-patch and the video camera was set to 2D mode. The range of depth, i.e., range where .4mm spaced lines are in focused, was measured along the viewing axis for each display and 2D/3D factor. Measured ranges were 140mm for Microscope 2D, 170mm for Microscope 3D, 510mm for Loupes 2D, 420mm for Loupes 3D, 260mm for Video 2D, and 200mm for Video 3D.

4.2.3.2. Testing apparatus

Testing apparatus (Figure 4.2a-b) was created using 5cm by 5cm sections of delrin material. Targets consisted of 1.59mm diameter brass spheres attached to 1.59mm diameter brass rods that were embedded onto the delrin material as shown in Figure 4.2. For targets in the z-axis (Figure 4.2b) brass rods were wrapped with non-conductive plastic wrap. Wires were soldered onto each target and attached to a data acquisition device (National Instruments NI USE-6508).

Subjects used a 1.59mm diameter brass probe with grip tape on one end and reflective tape on the other end. Wires were soldered to the probe and attached to the data acquisition device. Testing apparatus were placed on a table, with height set to the subject's standing elbow height.

4.2.4. Study design

This study focused on the independent and dependent variables listed in Table 4.2. The order of the three displays tested in this study followed a 3x3 Latin square design among subjects. Stereoscopic factor was counterbalanced among subjects. The other independent variables, i.e., axes, direction, distance, were consistent among subjects.

Table 4.2: **List and description of factors focused in this study**

Indepen-dent factors	a. Display: 3 levels
	    i. Microscope
	    ii. Loupes
	    iii. Video
	b. Target diameter: 1 level
	    i. 1.59 mm Note: typical diameters of blood vessels are 1-4mm in microsurgery (Yu et al. 2014)
	c. Target distance: 3 levels
	    i. 10mm
	    ii. 20mm
	    iii. 40mm Note: Field of view in Microsurgery is 60x100mm (Yu et al. 2014)
	d. Target axes: 4 levels (Figure 4.1)
	    i. x-axis
	    ii. y- axis
	    iii. zx- axis
	    iv. zy- axis
	    Note: Targets stacked on z-axis were difficult to view by microscope or camera positioned directly above the target since targets are aligned with viewing axis (Figure 4.1).
	e. Target direction: 2 levels
	    i. Positive
	    ii. Negative (Figure 4.1)
	f. 2D/3D condition: 2 levels
	    i. 2D, i.e., with one eye occluded or non-stereoscopic video
	    ii. 3D, i.e., binocular optics or stereoscopic video
	g. Display Location: 1 Level
	    • For Video display
	        o Display was 15° below eye-level (van Veelen et al. 2002; Limerick et al. 2000) and table at elbow height
	    • For microscope and loupes
	        o Table at elbow height
	h. Replication: 3
	    • Each target was targeted three times

Depen-dent factors:	1) **Movement time:** Total time moving from start to stop at target measured using MaxTraq 2) **Movement distance**: Distance traveled in x, y, and z axes measured using MaxTraq 3) **Overshoot:** Distance between target position and probe position on the specified x, y, or z-axes past the target before moving back towards target. Definition is illustrated in Figure 4.4. 4) **Submovements** (adapted from Lee & Bang 2014)**:** The initial movement plus the number of zero-crossings in the velocity on the target axis after thresholding fluctuations near zero (3mm/s) to eliminate noise. By definition, all trials required at least one submovement. Definition is illustrated in Figure 4.5.

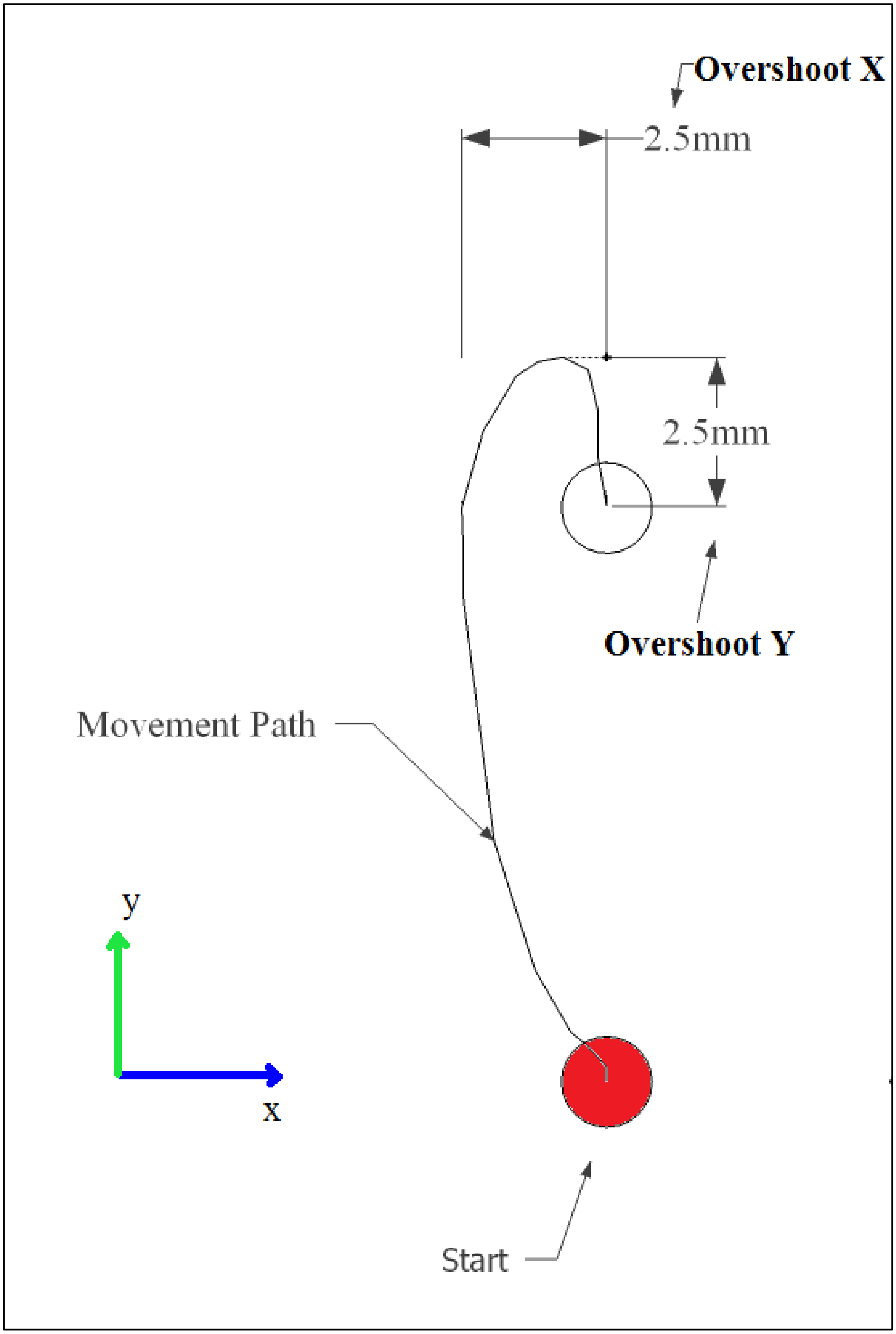


Figure 4.4: **Two-dimensional view of an example movement path taken while moving from start position to target distanced 10mm in the y-axis from start. Overshoot in the x and y-axes is shown for illustrated movement path.**

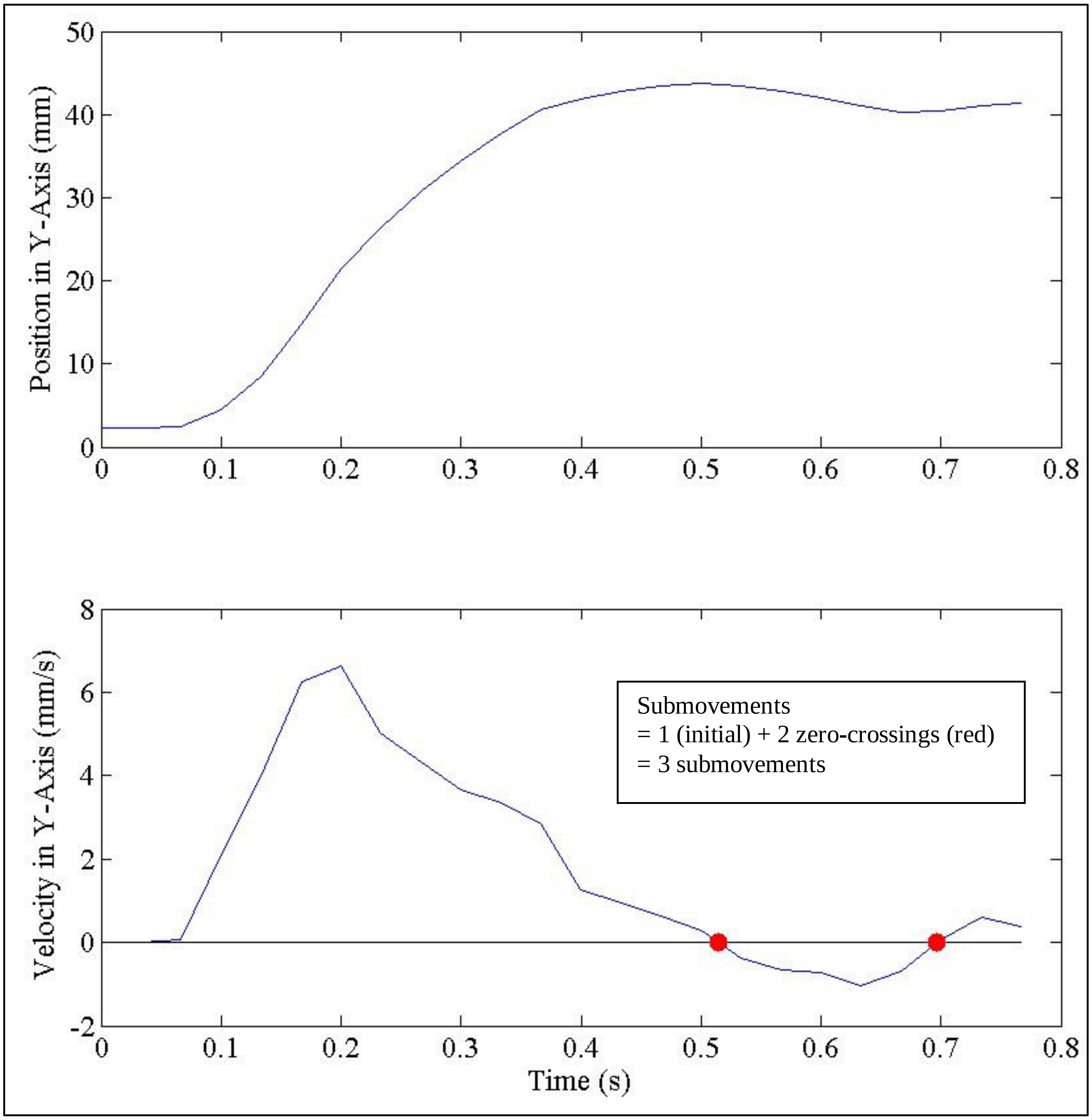


Figure 4.5: Further clarification of the definition and calculation of submovements during a 40mm target in the y-axis. Probe tip position relative to the y-axis (Figure 4.1) over time is shown in first plot and velocity is shown on second plot. Three submovements are observed, i.e., first initial movement plus the two observed zero-crossings of velocity (filled red circles).

Using this experimental design, each subject was instructed to complete 144 targets as accurately and as fast as possible on each display for a total of 432 targets, i.e., 3 target distances x 4 axes x 2 directions x 2 stereoscopy x 3 reps = 144 targets per display). Although previous studies found no learning effect after 40 repetitions for simple mouse selection task (Epps 1986) or targeting tasks (Lee & Bang 2013), an extra session with stereoscopic video was conducted after completing the 432 targets.

4.2.5. Study procedure

Each participant completed the study in a single 3-4 hour session. The study procedure consisted of three blocks. Each block consisted of one display, with the display order dictated by the Latin square design. Subjects had up to ten minutes of practice using the display with a bead-threading task and adjust settings if needed. After the training period, subjects performed a series of target hitting tasks with the testing apparatus (Section 4.4.3). Subjects were instructed to sequentially hit targets from the closest to farthest, i.e., 10mm target, 20mm target, and 40mm target (Table 4.2, Figure 4.2). After successfully hitting the three targets, subjects repeated this process twice for a total of three repetitions before moving to the next axis direction.

The order of axis directions were constant among subjects and followed the order: positive x-axis, positive y-axis, negative x-axis, negative y-axis, positive zx-axis, negative zy-axis, negative zx-axis, and finally positive zy-axis (Figure 4.1 and Figure 4.2). It is important to note that targets in the z-axis were offset to the x or y axis (Figure 4.2b) due to difficulty distinguishing targets stacked upon each other on the viewing axis of the microscope and video displays.

After completing the targets in all axes for a total of 72 targets, subject received another 5-10 minute training period and repeated the procedure with the same display, but with the other stereoscopic/monoscopic setting. For example, if the subject started with the stereoscopic display (i.e., binocular microscope, binocular loupes, or stereoscopic video), subjects will repeat the process using the 2D display (i.e., with one eye occluded). Order of depth was counterbalanced among subjects.

After completing the targeting task for the first display (a total of 144 targets), subjects received a 10-15min break before moving to the next block with a different display. Process is repeated until all three blocks and displays were completed. As mentioned in Section 4.4.4, an extra 3D video session was conducted to test for learning effect.

4.2.6. Data collection and analysis

Subject's task performance was video recorded with four cameras focused on the movement of the probe. The dependent variables (Table 4.2) were quantified for all targets, excluding practice sessions. MaxTraq software (Innovision-Systems) was used to track probe's 3D position at 30 frames per second. To sync and calibrate the camera for MaxTraq, a 17-point static reference frame was used. Matlab scripts were used to calculate all dependent variables (Table 4.2). Movement time was defined as between Step 2 to Step 4, as indicated in Section 4.4.2.1 and Table 4.2. Specifically, movement time began once the probe left the start target; movement time ended when the probe contacts the target and successfully held steady, i.e. < 3mm/s, continuously for 2/3 seconds. Reported movement time was adjusted for this holding time.

Statistical analysis was performed on SPSS Statistics (IBM Corp. 2012, Version 21) using mixed-effects models. Dependent variable included subject performance (i.e. movement time, movement distance, overshoot, and number of submovements movements). Fixed factors included target axis, target direction, display, target distance, and stereoscopic condition. Model included all main effects and two-way interactions as fixed effects and repetitions as repeated effects. Fisher's LSD was subsequently used for multiple comparisons among significant main effects.

4.3. Results

4.3.1. Overview

Four dependent variables and five independent variables (Table 4.2) were investigated to accomplish the stated aims. Distribution was right-skewed for all dependent variables and may impact normality assumptions of mixed effects models. Thus, dependent variables were log transformed and transformed data was observed to approximate normal distribution using normal probability plots. Summary of the statistical analyses on the transformed variables is shown on (Table 4.3). Summary of the effect of independent variables on performance metrics are summarized in Table 4.4 and Table 4.5.All tables and figures are presented with back-transformed data unless otherwise noted. Plots of significant interactions are shown in Appendix.

Table 4.3: **Results from four mixed-effects models of log transformed dependent variables: 1) movement time, 2) movement distance on x, y, and z-axes summed, 3) overshoot in the principal movement direction, and 4) number of submovements**

	Log of Movement Time (log(s))				**Log of Movement Distance (log(mm))**				**Log of Overshoot +1 (log(mm+1+)**				**Log of # Submovements**			
Source	Num df	Denom df	F	Sig.	Num df	Denom df	F	Sig.	Num df	Denom df	F	Sig.	Num df	Denom df	F	Sig.
Intercept	1	3929	851	**0.00**	1	3823	642816	**0.00**	1	3913	8117	**0.00**	1	3913	7131	**0.00**
axis	2	3987	701	**0.00**	2	3903	949	**0.00**	2	3935	1142	**0.00**	2	3972	664	**0.00**
Direction	1	3329	12	**0.00**	1	3254	8	**0.00**	1	3261	222	**0.00**		not significant		
Display	2	4132	89	**0.00**	2	4017	10	**0.00**	2	4128	10	**0.00**	2	4116	14	**0.00**
Distance	2	4135	243	**0.00**	2	4020	3481	**0.00**		not significant			2	4118	40	**0.00**
2D/3D	1	4131	33	**0.00**	1	4017	30	**0.00**		not significant			1	4115	10	**0.00**
axis * direction	1	3331	19	**0.00**		not significant			1	3263	333	**0.00**	1	3315	5	**0.02**
axis * display	4	4098	12	**0.00**	4	3924	23	**0.00**		not significant			4	4052	17	**0.00**
axis * distance	4	3992	5	**0.00**	4	3985	47	**0.00**	4	3938	31	**0.00**	4	3977	2	**0.04**
axis * 2D/3D	2	3987	27	**0.00**	2	3903	25	**0.00**	2	3935	12	**0.00**	2	3972	22	**0.00**
direction * display		not significant			2	3255	3	0.04		not significant			2	3313	5	0.01
direction * distance	2	3335	3	0.04	2	3259	7	**0.00**		not significant				not significant		
direction * 2D/3D		not significant				not significant				not significant				not significant		
display * distance		not significant			4	5111	4	0.00	4	5066	22	**0.00**		not significant		
display * 2D/3D	2	5180	6	0.00		not significant				not significant			2	5175	4	**0.03**
distance * 2D/3D		not significant			2	5120	5	0.01	2	5067	5	**0.01**		not significant		

Note: Degrees of freedom (df) for numerator (Num) and denominator (Denom) have been rounded to nearest integer.

Table 4.4: Mean ± SD of dependent variables a) total movement distance summed for all three axes, b) movement time, c) overshoot, and d) submovements. Results are stratified by movement direction factor for targets in the x, y, and z-axes. (n=5290)

a)		Movement Distance (mm)		
Axis and direction		Mean±SD		
x		**48.4**	±	**1.7**
	-x	47.6	±	1.6
	+x	49.1	±	1.7
y		**37.8**	±	**1.8**
	-y	37.1	±	1.7
	+y	38.6	±	1.8
z		**65.1**	±	**1.6**
	+z	65.1	±	1.6

b)		Movement Time (s)		
Axis and direction		Mean±SD		
x		**0.74**	±	**1.5**
	-x	0.74	±	1.5
	+x	0.73	±	1.6
y		**0.63**	±	**1.7**
	-y	0.59	±	1.6
	+y	0.68	±	1.8
z		**1.27**	±	**1.8**
	+z	1.27	±	1.8

c)		Overshoot (mm)		
Axis and direction		Mean±SD		
x		**0.95**	±	**1.0**
	-x	1.89	±	0.8
	+x	0.35	±	0.7
y		**0.62**	±	**0.8**
	-y	0.56	±	0.7
	+y	0.68	±	0.9
z		**2.99**	±	**1.1**
	+z	2.99	±	1.1

d)		# of Submovements		
Axis and direction		Mean±SD		
x		**1.95**	±	**1.7**
	-x	1.97	±	1.7
	+x	1.93	±	1.7
y		**1.52**	±	**1.7**
	-y	1.46	±	1.6
	+y	1.58	±	1.7
z		**3.28**	±	**1.9**
	+z	3.28	±	1.9

Table 4.5: Mean ± SD of dependent variables a) total movement distance, b) movement time, c) overshoot, and d) submovements. Results are stratified by display and 2D/3D factors for targets in the x, y, and z-axes. (n=5290).

a)

	Movement distances (mm) in the x, y , and z axes								
	Targets on x-axis			**Targets on y-axis**			**Targets on z-axis**		
	Mean	±	**SD**	**Mean**	±	**SD**	**Mean**	±	**SD**
Micro	**48.1**	±	**1.7**	**37.1**	±	**1.8**	**62.6**	±	**1.6**
2D	49.2	±	1.7	37.1	±	1.8	67.2	±	1.6
3D	46.9	±	1.7	37.0	±	1.8	58.2	±	1.6
Loupes	**50.2**	±	**1.7**	**39.3**	±	**1.8**	**61.7**	±	**1.6**
2D	50.6	±	1.7	38.7	±	1.8	68.7	±	1.6
3D	49.8	±	1.6	39.9	±	1.8	55.5	±	1.7
Video	**46.9**	±	**1.6**	**37.2**	±	**1.7**	**71.5**	±	**1.6**
2D	46.6	±	1.6	37.6	±	1.7	75.8	±	1.6
3D	47.1	±	1.6	36.7	±	1.7	67.2	±	1.6

b)

	Movement times (s)								
	Targets on x-axis			**Targets on y-axis**			**Targets on z-axis**		
	Mean	±	**SD**	**Mean**	±	**SD**	**Mean**	±	**SD**
Micro	**0.73**	±	**1.59**	**0.62**	±	**1.66**	**1.19**	±	**1.73**
2D	0.75	±	1.62	0.62	±	1.65	1.31	±	1.68
3D	0.71	±	1.55	0.62	±	1.67	1.08	±	1.75
Loupes	**0.70**	±	**1.48**	**0.57**	±	**1.68**	**1.07**	±	**1.72**
2D	0.71	±	1.49	0.57	±	1.72	1.27	±	1.66
3D	0.69	±	1.48	0.58	±	1.64	0.90	±	1.69
Video	**0.78**	±	**1.54**	**0.70**	±	**1.75**	**1.61**	±	**1.78**
2D	0.76	±	1.53	0.72	±	1.83	1.72	±	1.76
3D	0.81	±	1.56	0.69	±	1.66	1.50	±	1.78

c)

	Overshoot (mm)								
	Targets on x-axis			**Targets on y-axis**			**Targets on z-axis**		
	Mean	±	**SD**	**Mean**	±	**SD**	**Mean**	±	**SD**
Micro	**0.89**	±	**0.94**	**0.62**	±	**0.84**	**2.98**	±	**1.05**
2D	0.83	±	0.93	0.62	±	0.82	3.38	±	1.12
3D	0.96	±	0.94	0.61	±	0.86	2.61	±	0.94
Loupes	**1.06**	±	**1.01**	**0.69**	±	**0.86**	**3.22**	±	**0.98**
2D	0.96	±	0.96	0.59	±	0.81	3.64	±	0.99
3D	1.17	±	1.06	0.78	±	0.89	2.84	±	0.94
Video	**0.90**	±	**0.91**	**0.55**	±	**0.74**	**2.79**	±	**1.15**
2D	0.82	±	0.82	0.59	±	0.78	2.98	±	1.15
3D	0.97	±	0.98	0.52	±	0.68	2.60	±	1.15

d)

	Number of Submovements								
	Targets on x-axis			**Targets on y-axis**			**Targets on z-axis**		
	Mean	±	**SD**	**Mean**	±	**SD**	**Mean**	±	**SD**
Micro	**1.95**	±	**1.70**	**1.47**	±	**1.68**	**2.99**	±	**1.85**
2D	1.96	±	1.71	1.42	±	1.65	3.26	±	1.88
3D	1.94	±	1.69	1.52	±	1.71	2.74	±	1.79
Loupes	**1.95**	±	**1.68**	**1.59**	±	**1.68**	**3.08**	±	**1.83**
2D	1.95	±	1.74	1.57	±	1.70	3.58	±	1.85
3D	1.95	±	1.63	1.60	±	1.67	2.65	±	1.73
Video	**1.94**	±	**1.70**	**1.49**	±	**1.68**	**3.83**	±	**1.87**
2D	1.86	±	1.70	1.49	±	1.68	4.14	±	1.85
3D	2.03	±	1.69	1.49	±	1.69	3.53	±	1.88

Sample plot illustrating the targeting task for a 40mm distanced target on the zy-axis, i.e., target is distanced 28.6mm in z-axis and 28mm in y-axis from the start location (Figure 4.2b), is shown on Figure 4.6. Each line represents the movement path and distanced traveled by the subject from start to the target. In particular, different paths can be taken to reach the target and Figure 4.6 highlights three strategies. Subject approached target from the bottom (red), the top (green), or from both top and bottom using multiple submovements (blue).

In the bottom approach example (red in Figure 4.6), subject moved towards the target smoothly from 0mm y-position to 28mm y-position (i.e., towards the subject's body) and from 5mm z-position to 19mm z-position (i.e., towards target and upwards toward the ceiling, see graphics in Figure 4.6). At the end of this motion, the probe tip covered the necessary y-distance; however, the probe tip was still underneath the target (z-axis). Thus, the subject then performed submovements in the positive z-axes (i.e., upwards toward the ceiling in graphics) to reach the target. In the last repetition or top approach example (i.e., green movement path Figure 4.6), subject moved the probe tip in a smooth motion to cover the necessary 28mm distance in the y-axis. However, the probe tip traveled from 5mm in the z-axis to 33mm in the z-axis, which necessitated subsequent submovements to move the probe tip down (i.e., z-axis or towards the floor) to reach the target.

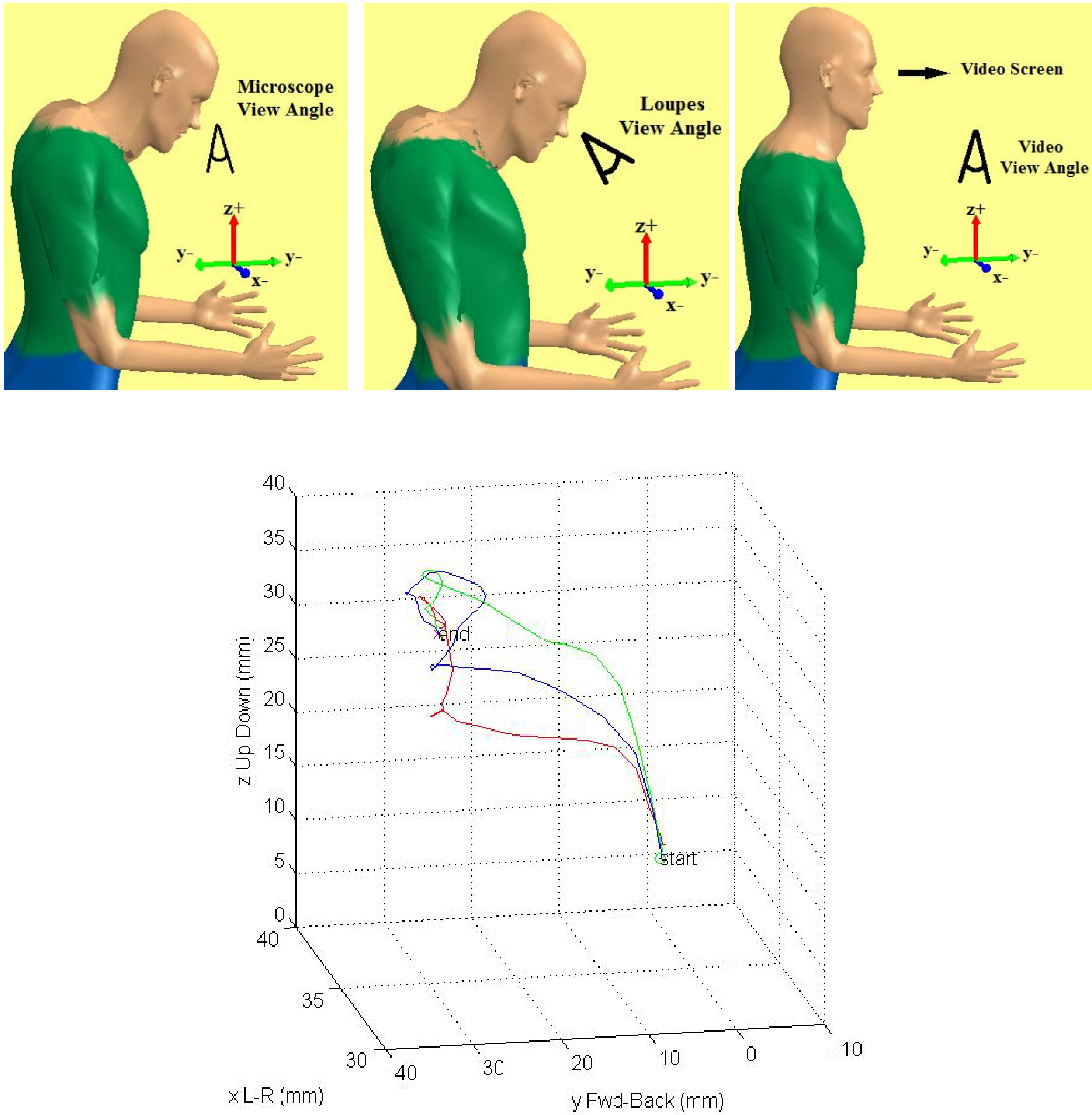


Figure 4.6: **Sample 3D plot of movement traces during observed for the 40mm targets in the zy-axis for one subject performed on the 2D microscope. "Start" indicates the location of the start target, and "end" indicate the location of the 40mm target. The three curves on the plot represents the 1st repetition (blue), 2nd repetition (red), and 3rd repetition (green). Note: Subject position and view angle for each display is represented in the three graphics above the 3D plot. View angle is similar between video and microscope.**

4.3.2. Movement distance

4.3.2.1. Overview

Movement traces and distance traveled varied between trials (Figure 4.6 and Section 4.5.1). The dependent variable, distance moved, was defined as the total distance travelled, i.e., sum of distanced travelled in the x, y, and z-axes, during the trial (Table 4.2). Distanced move was summarized for all subjects performing the *40mm* targeting task in the y (Figure 4.7) and z-axes (Figure 4.8) to illustrate how movement distance vary in all three axis for targets distanced 40mm from start on the y and zy-axes (Figure 4.2). Full results of all task factors will be reported in Section 4.5.2.2.

As expected, movement distances were largest in the axis of the target (Figure 4.7). For example, median distance traveled on the y-axis for targets distanced 40mm ranged from 40.8mm to 43.3mm, i.e., 102-108% of target distance in y-axis or fore/aft). Although no movement in the x and z-axes was needed to reach the target, median movement in these axes ranged from 9.5mm to 16.3mm (Figure 4.7).

Trends were slightly different for targets in the z-axes since each target was offset in the x or y-axes (Figure 4.2b, y-axis offset shown in Figure 4.8). Although start to target distance on the z-axis was 28.6mm, median distance moved ranged 34.9-46.2mm, i.e., 125-165% of target vertical distance, in the z-direction (Figure 4.2b, Figure 4.8). Although start to target distance on the y-axis was 28mm, median distance moved ranged 34.7-40.8mm, i.e., 124-146% of target fore/aft distance, in the y-axis (Figure 4.2b, Figure 4.8). Finally, although start to target distance on the x-axis was 0mm, median distance moved ranged 13-20.9 mm in the x-direction (Figure 4.2b, Figure 4.8).

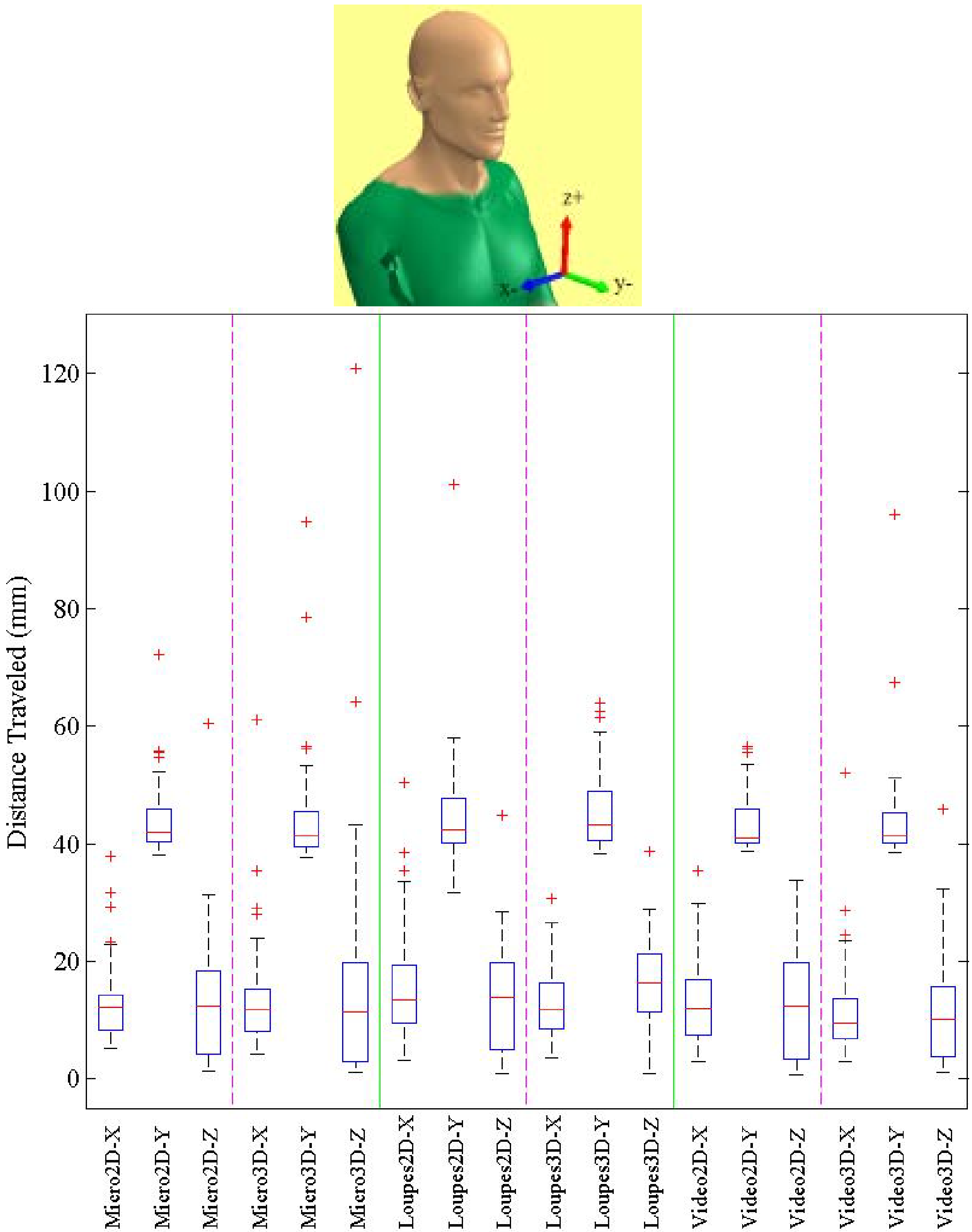


Figure 4.7: **Boxplots for the untransformed movement distance (mm) in each axis for pooled 40mm distance targets in the y-axis for each display and 2D/3D factor. Red line=median; box = 25th and 75th %tile values; whiskers=min and max values; and points represents outliers. Sample size for each box plot ranged from 69-75 targets. Note that an outlier for Micro3D-Y is not shown.**

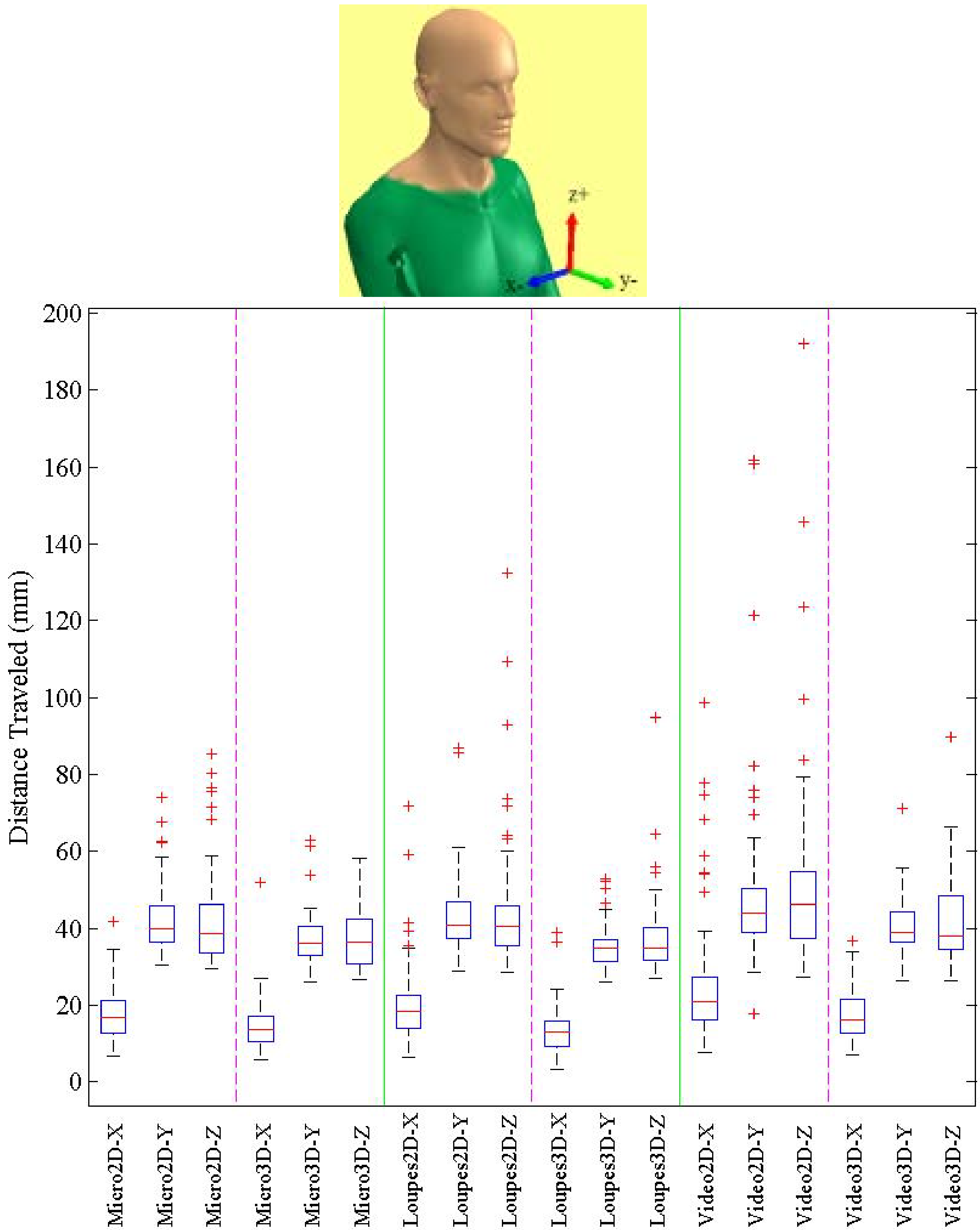


Figure 4.8: **Box plots for untransformed movement distance (mm) in each axis, pooled for 40mm distance targets in the z-axis with offset in the y-axis (Figure 4.2b) for each display and 2D/3D factor. Red line=median; box = 25th and 75th %tile values; whiskers=min and max values; and points=outliers. Sample size for each box plot ranged from 70-80 targets**

4.3.2.2. Direction and distance factors on movement distance

Mean distance moved (Table 4.2) for targets in the negative direction were 1.4mm less for targets on y-axis) and-1.5mm less for targets on the x-axis (3-4%) less than targets in the positive direction ($p<0.01$) (Table 4.3 and Table 4.4). Note that positive direction was a) away from body for the fore/aft y-axis, b) towards the left hand for the left/right x-axis, and c) towards ceiling for the vertical z-axis. Also note that positive direction in the vertical z-axis meant going in line toward the viewing angle for the microscope and video display, but only partly aligned with the loupes (Figure 4.6).

As expected, movement distances significantly increased as target distance increased (Table 4.3). Relationship between distanced moved in the target direction and target distance is summarized in Figure 4.9. Depending on axis, display, and 2D/3D factors, regression intercepts ranged from 0.8mm to 19mm, and slopes ranged from 0.9 to 1.1.

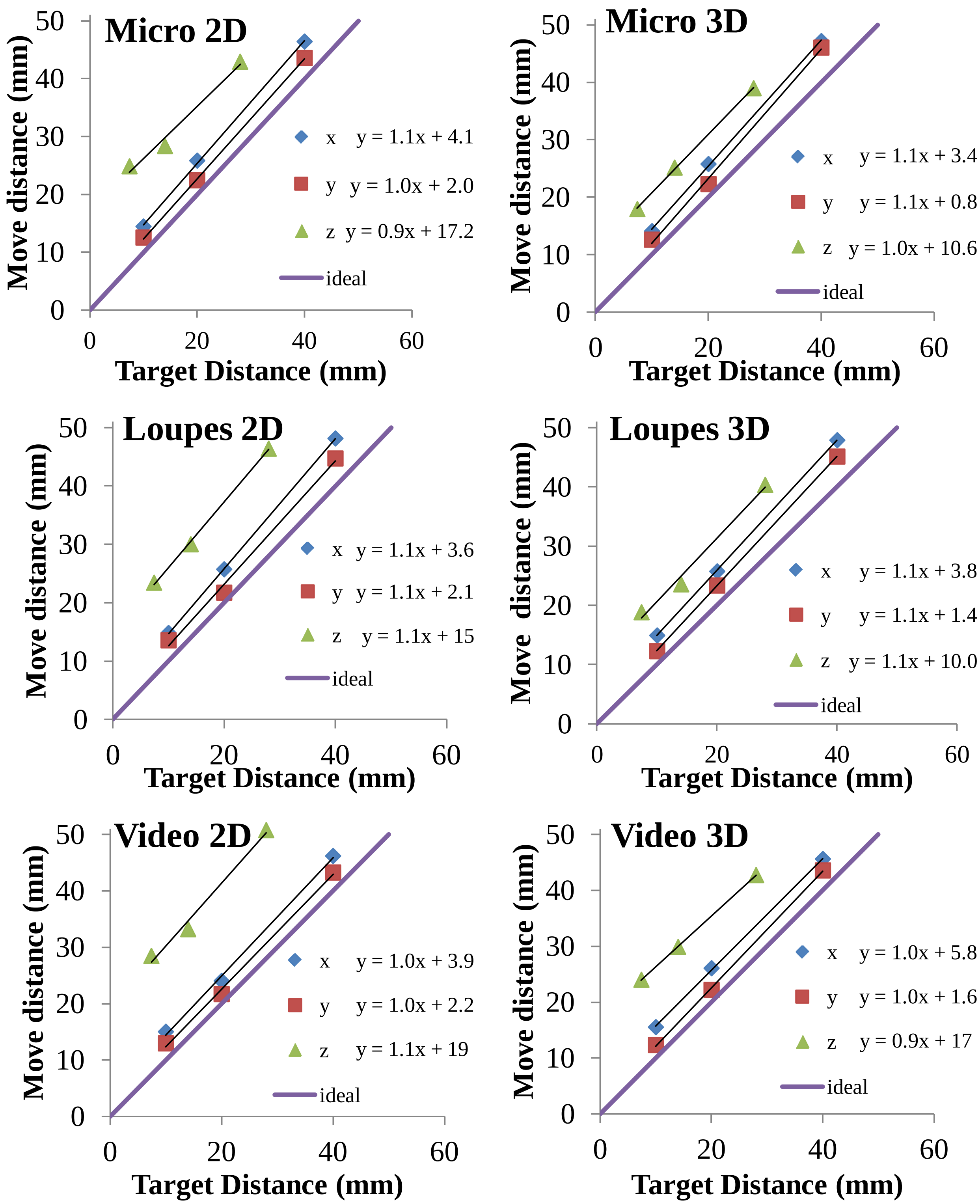


Figure 4.9: Graphs comparing required movement distance with observed movement distance *in the axis of target*. Plots are stratified by axis, display, and 2D/3D factors. Each point represents mean untransformed distance. Points above the idea line indicate observed movements were greater than required movement.

4.3.2.3. *Axis, display, and 2D/3D factors on movement distance*

Targets on the y-axis, i.e., fore/aft, had the lowest observed movement distance ($p<0.01$) between start & end of movement (Table 4.3, Table 4.4, and Table 4.5). Distance moved for targets on the y-axis, i.e., fore/aft, was 11mm (28%) less than targets on the x-axis, i.e., left/right, and 27mm (72%) less than targets on the z-axis, i.e., vertical ($p<0.01$) (Table 4.3 and Table 4.4).

Table 4.5 and interaction plots in the appendix summarize the interactions between axis, display, and 2D/3D factors on movement distance. Mean movement distances were not statistically different between video and the other displays ($p>0.05$), but distance on the microscope was 2mm or 4-6% shorter ($p<0.01$) than loupes for targets on the x and y-axes (Table 4.3 and Table 4.5). Significant interactions ($p<0.01$) was observed between display and axes (Table 4.3, Table 4.5, and Appendix). Although mean distances when using video was less than the other displays for targets on the x and y-axes, mean distances when using video was 9mm (12%) greater than the microscope and 10mm (14%) greater than the loupes for targets on the z-axis (Table 4.5).

Significant interaction ($p<0.01$) was observed between 2D/3D factor and target axis (Table 4.3, Table 4.5, and Appendix). For targets in x and y-axes, effect of 2D on movement distances ranged from 5% more to 3% less than 3D (Table 4.5). For targets on the z-axis (Table 4.5), observed distances for 2D factor were 9-13mm or 11-19% more than 3D factor. Interactions between 3D/2D and displays were not significant (Table 4.3).

4.3.3. Movement time

4.3.3.1. *Overview*

Movement time (MT) from start to stop at target was measured for each trial (Table 4.2). Distribution and summary of movement times for the y and z-axis is summarized in Figure 4.10. Distribution of movement times was right-skewed, and outliers were concentrated on the right (Figure 4.10). Log transformation was performed for movement times to better approximate normal distribution. Shortest median movement time was 0.5 seconds with 75^{th}%tile of 0.6 seconds on the Micro2D and Loupes3D for 10mm targets on the y-axis (Figure 4.10). Longest median movement time 2 seconds with 75th%tile of 2.7 seconds on the Video2D for 40mm targets on the z-axis (Figure 4.10).

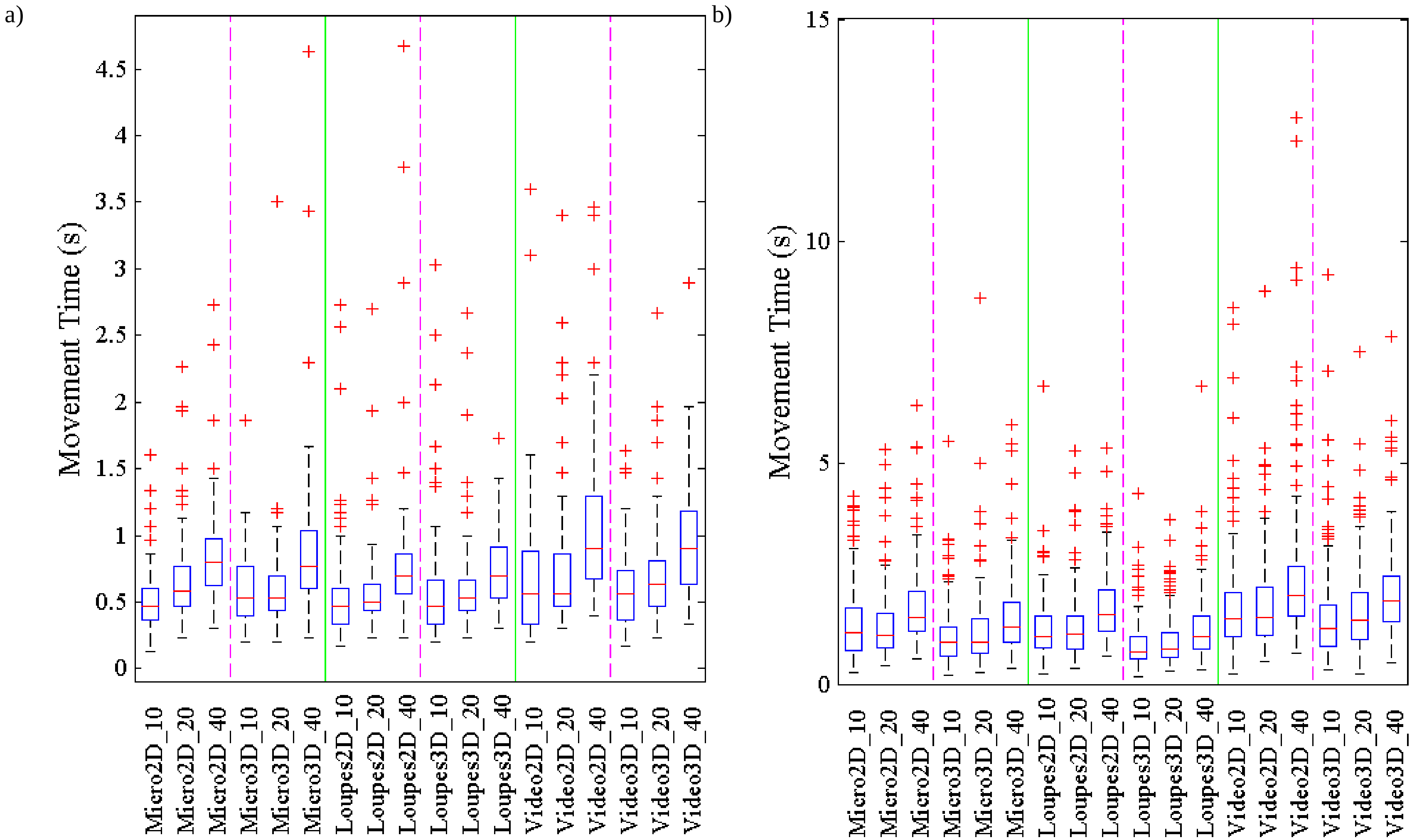


Figure 4.10: Box plots of untransformed movement time for targets on the a) y-axis and b) z-axis by display factor, 2D/3D factor, and target distance (i.e., 10, 20, 40mm). Red solid line represents the median. Box represents the 25th and 75th percentile. Red markers represent outliers. Note, one outlier is not shown in b) for Video2D 40mm.

Movement times were modeled with Fitts's Law (Figure 4.11). The target diameter was 1.59 mm (Table 4.2) and target distances were 10mm, 20mm, and 40mm (Table 4.2 and Figure 4.2). Thus, task index of difficulty was calculated to be 3.7, 4.7, and 5.7 using Shannon's formulation. Movement time for given conditions varied widely, e.g., shortest movement time was 133ms and longest movement time was 12770ms (Figure 4.11). Fitting Fitts's law with average movement times found strong association, i.e., R^2=0.77-0.97, between movement times and Index of Difficulty (Figure 4.11). Predicted microscope movement times using previous literature were also plotted, i.e., movement time (ms)=168 + 81*ID (Langolf & Hancock 1975). Mean observed times were higher than predicted times (Figure 4.11).

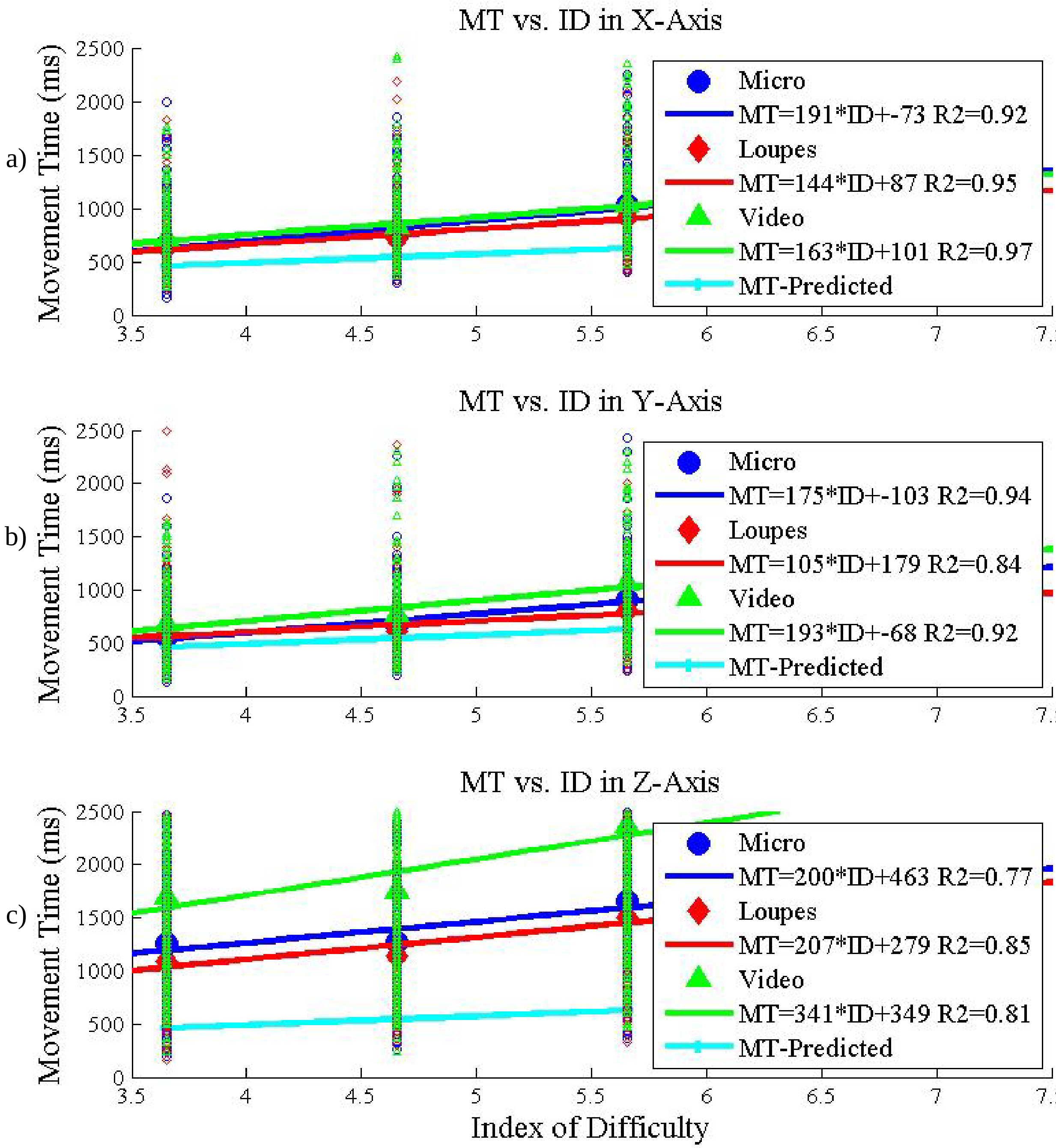


Figure 4.11: **Plots of untransformed movement time (MT) in milliseconds vs. Index of difficulty (ID) by display types for targets on the a) x-axis, b) y-axis, and c) z-axis. MT for all targets was plotted as small colored markers. Average MT for all targets given display conditions was represented by large markers. Regression analysis used average MTs. Bolded cyan line represents predicted movement time using previous literature (Langolf & Hancok 1975). Note: MT outliers greater than 2500ms are not shown in figure.**

4.3.3.2. Direction and distance factors on movement time

Mean movement time (Table 4.2) in the negative direction was 0.09 seconds or 15% faster for targets on y-axis, i.e., fore/aft ($p<0.01$) (Table 4.3 and Table 4.4). As shown previously, movement times increased as target distance increase (Table 4.3, Figure 4.10, and Figure 4.11).

4.3.3.3. Axis, display and 2D/3D factors on movement time

Mean movement time for targets in y-axis, i.e., fore/aft, was 0.1 seconds or 17% faster than targets on the x-axis, i.e., left/right and 0.6 seconds or 101% faster than targets on the z-axis ($p<0.01$) (Table 4.3 and Table 4.4). It is important to note that z-axis targets required movements that were closest to the viewing axis (Figure 4.6) for all displays.

Mean movement time was fastest on the loupes and slowest for the video ($p<0.01$); however, significant interactions were present between displays and axis factors (Table 4.3, Table 4.5, and Appendix). For targets on the x (left/right) and y (fore/aft)-axes, movement times on the video were 0.05-0.13 or 6-18% seconds slower ($p<0.01$) than both loupes and microscope (Table 4.3 and Table 4.5). For targets on the z-axis, i.e., vertical axis along the viewing axis of microscope and video (Figure 4.6), movement times on video displays was 0.4-0.5 or 26-34% slower than loupes and microscopes (Table 4.3 and Table 4.5).

The main effect of 2D/3D factor and it's interaction with axis on movement times was significant ($p<0.01$) (Table 4.3, Table 4.5, and Appendix). For targets in the x (left/right) and y (fore/aft) axes, the effect of 2D displays on movement times varied and ranged from 7% slower to 5% faster (Table 4.5). For targets on the vertical z-axis, movement times on 2D displays were 0.2-0.4 seconds or 13-29% slower than 3D displays (Table 4.5). The 2D/3D factor also interacted with the display factor, where time difference between 2D and 3D were 28-38% more on the loupes than the microscope and video (Appendix).

4.3.4. Overshoot

4.3.4.1. Overview

The distribution of overshoot (Table 4.2 and Figure 4.4) in the principal movement direction was right skewed (Figure 4.12). Zero overshoot was observed during the experiment for several targets (Figure 4.12). Therefore, log transformed was performed on overshoot plus one to better approximate normal distribution. Other than the 2D/3D main effect, statistical trends (including interactions with 2D/3D factor) were identical between the transformed and untransformed models.

The smallest median overshoot was zero on Loupes3D for 10mm distanced target on the y (fore/aft)-axis (Figure 4.12a). The largest median overshoot was 4.9mm on the Micro2D for 10mm target on the vertical z-axis (Figure 4.12b).

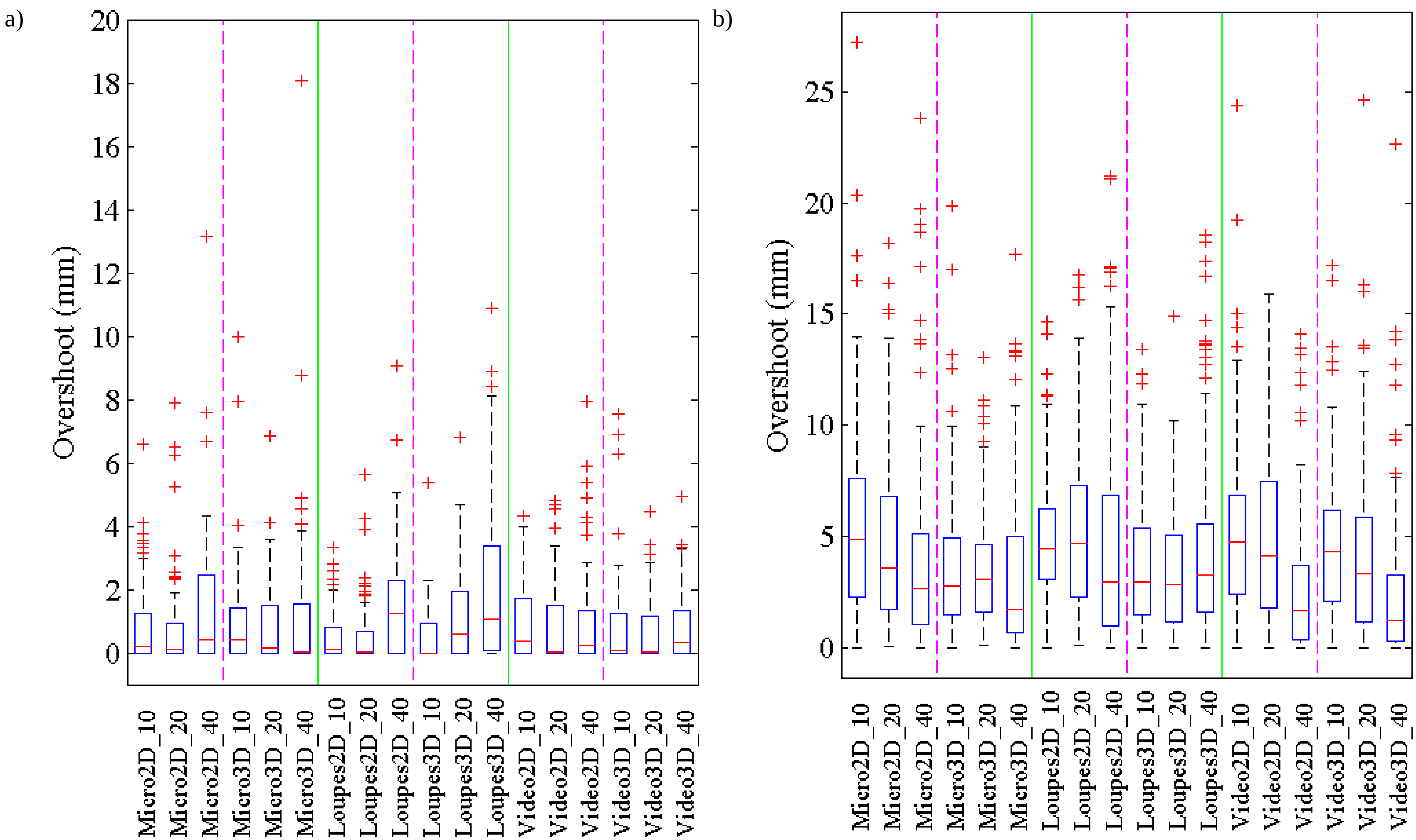


Figure 4.12: Box plots of untransformed overshoot (mm) in target direction for targets on the a) y-axis and b) z-axis by display factor, 2D/3D factor, and target distance (i.e., 10, 20, 40mm). Red solid line represents the median. Box represents the 25th and 75th percentile. Red markers represent outliers. Note, two outliers are not shown in (a).

4.3.4.2. Direction and distance factors on overshoot

Main effect of distance factor and multiple comparison of direction factor were not statistically significant (Table 4.3). Direction and distance factors interacted with axis, display, and 2D/3D factor, and plots of the interactions are shown in Appendix.

4.3.4.3. Axis, display, and 2D/3D factors on overshoot

Overshoot was the smallest for targets on y-axis, i.e., fore/aft (Table 4.4). Specifically, mean overshoot for targets on the y-axis was 0.3mm or 53% less than targets on the x (left/right)-axis ($p<0.01$) and 2.4mm or 383% less than targets on the vertical z-axis ($p<0.01$) (Table 4.3 and Table 4.4).

Overshoot was the smallest on the video displays (Table 4.5). Specifically, mean overshoot for targets on video was 0.1-0.2mm or 18-24% less than loupes ($p<0.01$), but mean overshoot on video was not different than microscope (Table 4.3 and Table 4.4). Interaction between distance and display factor ($p<0.01$) indicate that overshoot was 33-80% less for the video display than loupes and microscopes only for targets distanced 40mm (Appendix).

Interactions between 2D/3D and distance factors ($p<0.05$) was significant, where 3D factor reduced overshoot more for 10mm and 20mm targets than 40mm targets (Table 4.3 and Appendix). Interactions between 2D/3D and axis factor was significant ($p<0.01$). For targets on the x-axis, overshoot was 17-21% greater with 3D than 2D. In contrast, overshoot for targets on the z-axis was 0.4-0.8 or 13-23% less with 3D than 2D (Table 4.3, Table 4.5, and Appendix).

4.3.5. Submovements and time elapse after 1st submovement

4.3.5.1. Overview

The distribution of submovements (Table 4.2) in the principal movement direction was right skewed (Figure 4.13). Log transformation of submovements was conducted to approximate normal distribution. The smallest median number of submovements was zero on targets in the y (fore/aft)-axis for most display, 2D/3D, and distance combinations (Figure 4.13a). The largest median number of submovements was 5 with a 75th% tile of 7 for Loupes2D and Video2D for 40mm target in the vertical z-axis (Figure 4.13b).

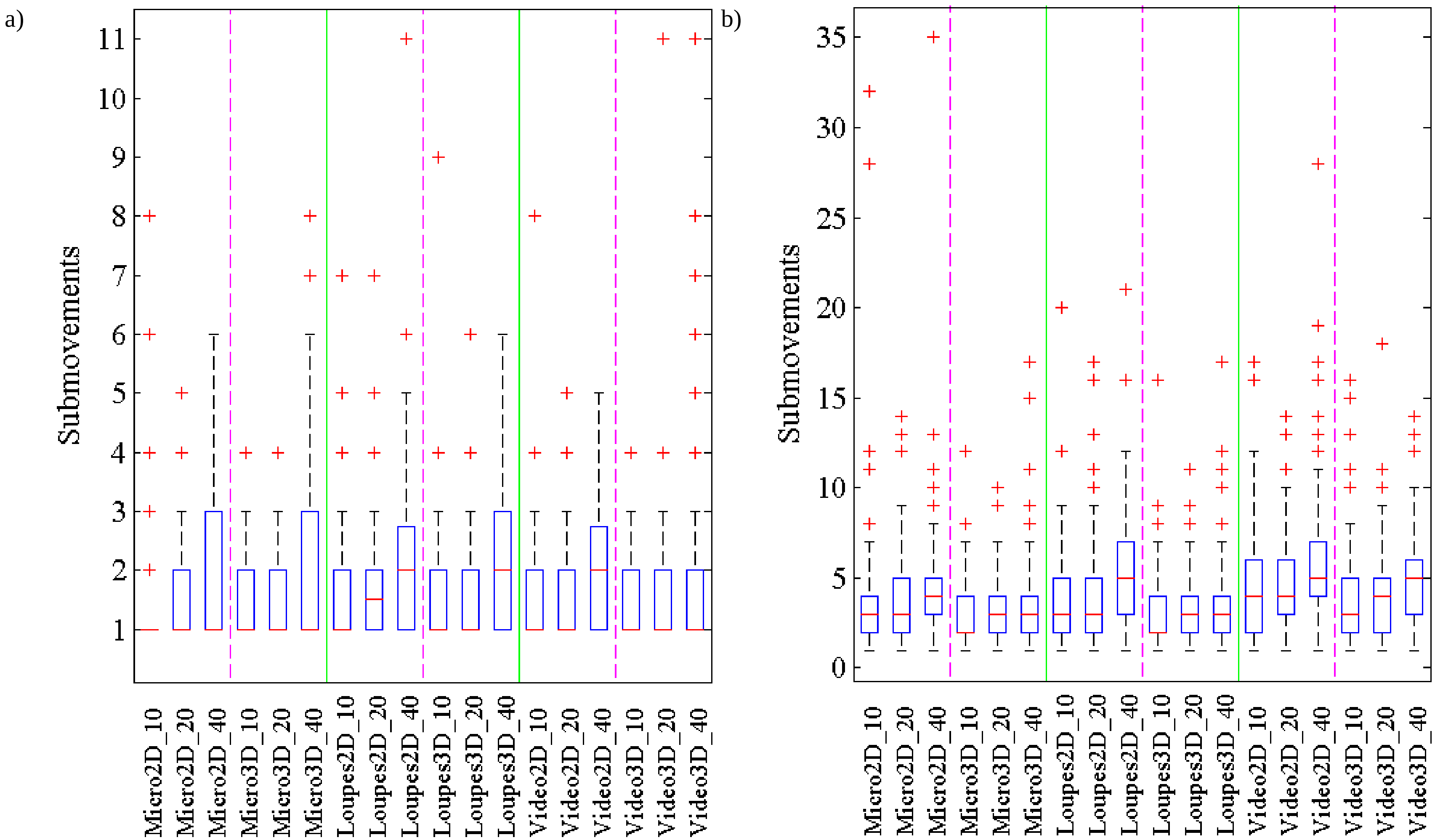


Figure 4.13: **Box plots of untransformed submovements in principal axis of movement for targets on the a) y-axis and b) z-axis by display factor, 2D/3D factor, and target distance (i.e., 10, 20, 40mm). Red solid line represents the median. Box represents the 25th and 75th percentile. Red markers represent outliers.**

4.3.5.2. Direction and distance factors on submovements

Submovements were defined in Table 4.2 and Figure 4.5. All main effects (Table 4.3), except for direction, were statistically significant ($p<0.01$). Interactions of direction with axis and display factors are shown in the Appendix. Mean number of submovements was not significantly different ($p>0.10$) between the 10mm and 20mm targets; however, the mean number of submovements was 0.4-0.5 (15-18%) greater for 40mm targets than the other targets ($p<0.01$).

4.3.5.3. Axis, display, and 2D/3D factors on submovements

Submovements for targets in the y (fore/aft)-axis were 0.4 or 29% less ($p<0.01$) than targets in the x (left/right)-axis (Table 4.4). Submovements for targets in the vertical z-axis was 1.3-1.8 or 40-54% more than targets in the y and x-axes were less ($p<0.01$).

Significant interactions ($p<0.01$) were observed between displays and target axis (Table 4.3 and Appendix). No differences in submovements were observed among displays for x (left/right) and y (fore/aft)-axes; however, 0.8 more submovements (22%) were observed on the video displays in the z-axis, i.e., vertical axis closest to the viewing angle (Table 4.5).

Significant interactions ($p<0.01$) on submovements were observed between 2D/3D factor and target axis (Table 4.3, Table 4.5, and Appendix). For x and y-axes, effect of 2D on mean number of submovements ranged from 9% decrease to 1% increase (Table 4.5). In contrast, 0.8 or 20-22%) more submovements was observed for 2D than 3D displays (Table 4.5).

4.3.6. Additional analysis

4.3.6.1. Relationship between time and distance

An association of R^2=0.21-0.52 was observed between the dependent variables movement time and movement distance (Figure 4.14). The movement time and distance relationship was 7.2-10.6 milliseconds per 1mm for the targets on the x-axis (Figure 4.14a), i.e., left/right, and y-axes, i.e., fore/aft (Figure 4.14b). It's important to note that targets on the x and y-axes have both start position and target position on a plane perpendicular to the viewing axis of the microscope and video display (Figure 4.6).The time and distance relationship was 14.2-27.7ms per 1mm for targets on the z-axis (Figure 4.14c), i.e., vertical with respect to the subject and the axis aligned with the viewing axis on the video and microscope displays and most closely aligned with the viewing axis on the loupes.

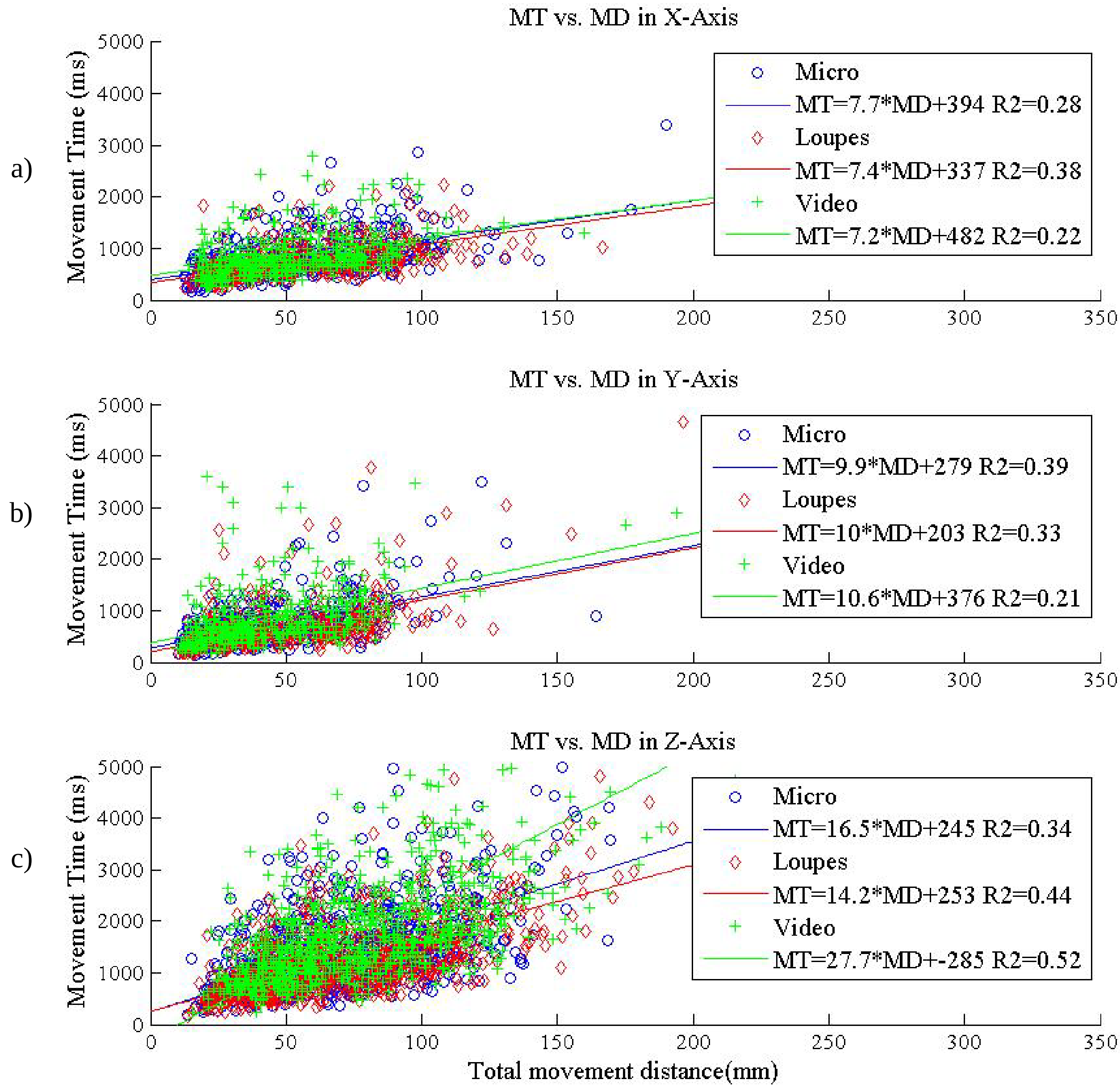


Figure 4.14: **Plots of movement time (MT) in milliseconds vs. movement distance (MD) in mm by display types for targets on the a) x-axis, b) y-axis, and c) z-axis. Note: MT outliers are not shown in z-axis plot.**

4.3.6.2. Relationship between time and submovements

Figure 4.15 illustrates the relationship between movement time and submovements in the principal axis of movement, and R^2 values ranged from 0.32 to 0.47. Slopes of the regression were higher for 2D than 3D for Loupes and Video. Although slopes for Micro3D and Video3D are similar, Video 3D had higher intercept values.

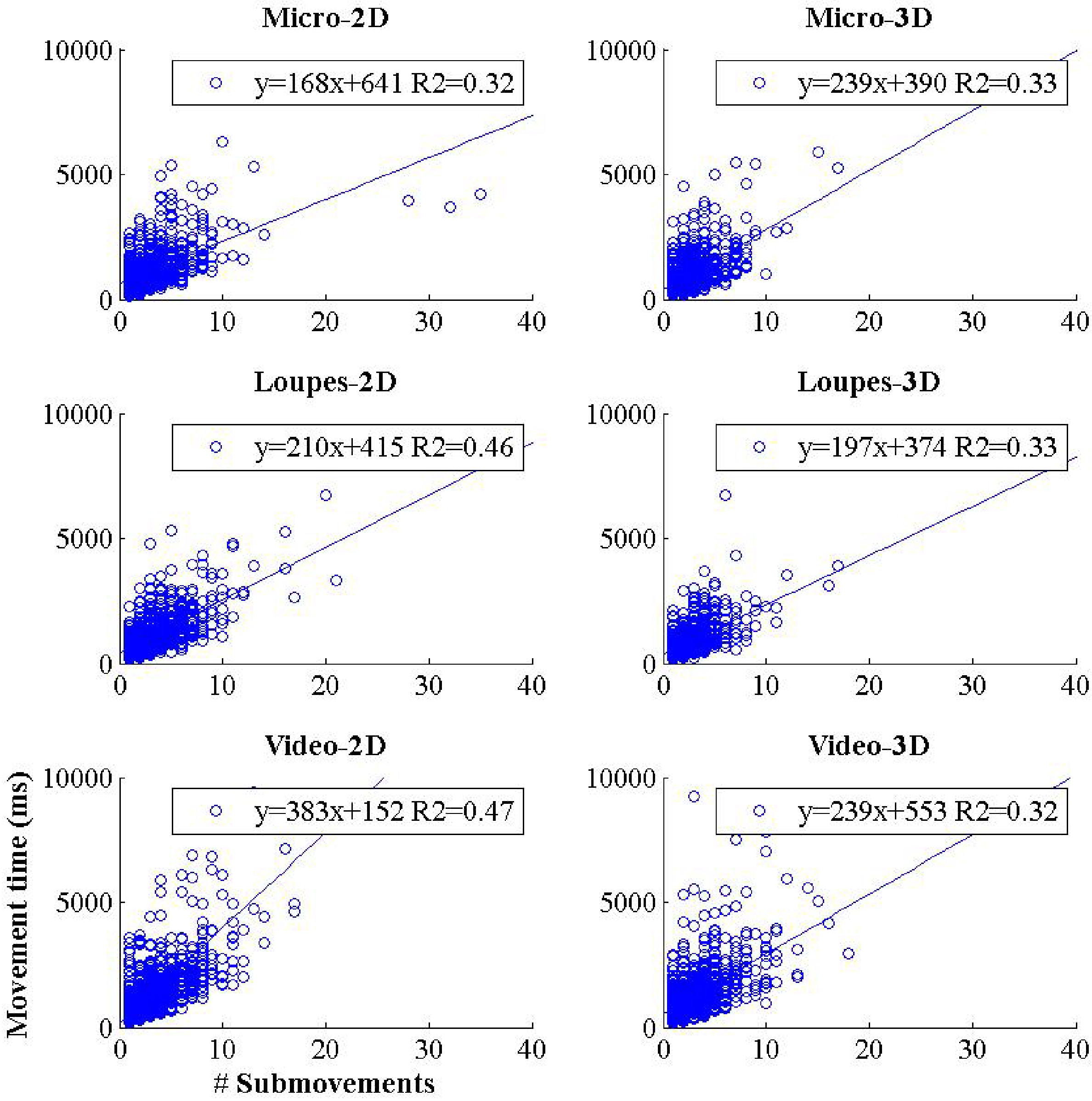


Figure 4.15: **Relationship between movement time (ms) and number of submovements by display and 2D/3D factor. Outliers beyond the axis ranges are not shown.**

4.3.6.3. Top six performers on Video3D analysis

Further analysis was completed to investigate the performance of the six participants, i.e., top half, with the fastest Video3D movement times (Figure 4.16 and Table 4.6). Four subjects performed better using Video3D than Micro3D (Figure 4.16). It was observed that 75% of the subjects grouped in Latin square order one, i.e., Microscope 1^{st}, Loupes 2^{nd}, Video 3^{rd}, typically had faster Video3D performance (Table 4.6). Further analysis found that Latin square order had significant effect, where participants in both the first and third group, i.e., Loupes 1^{st}, Video 2^{nd}, Microscope 3^{rd}, performed better than the second group.

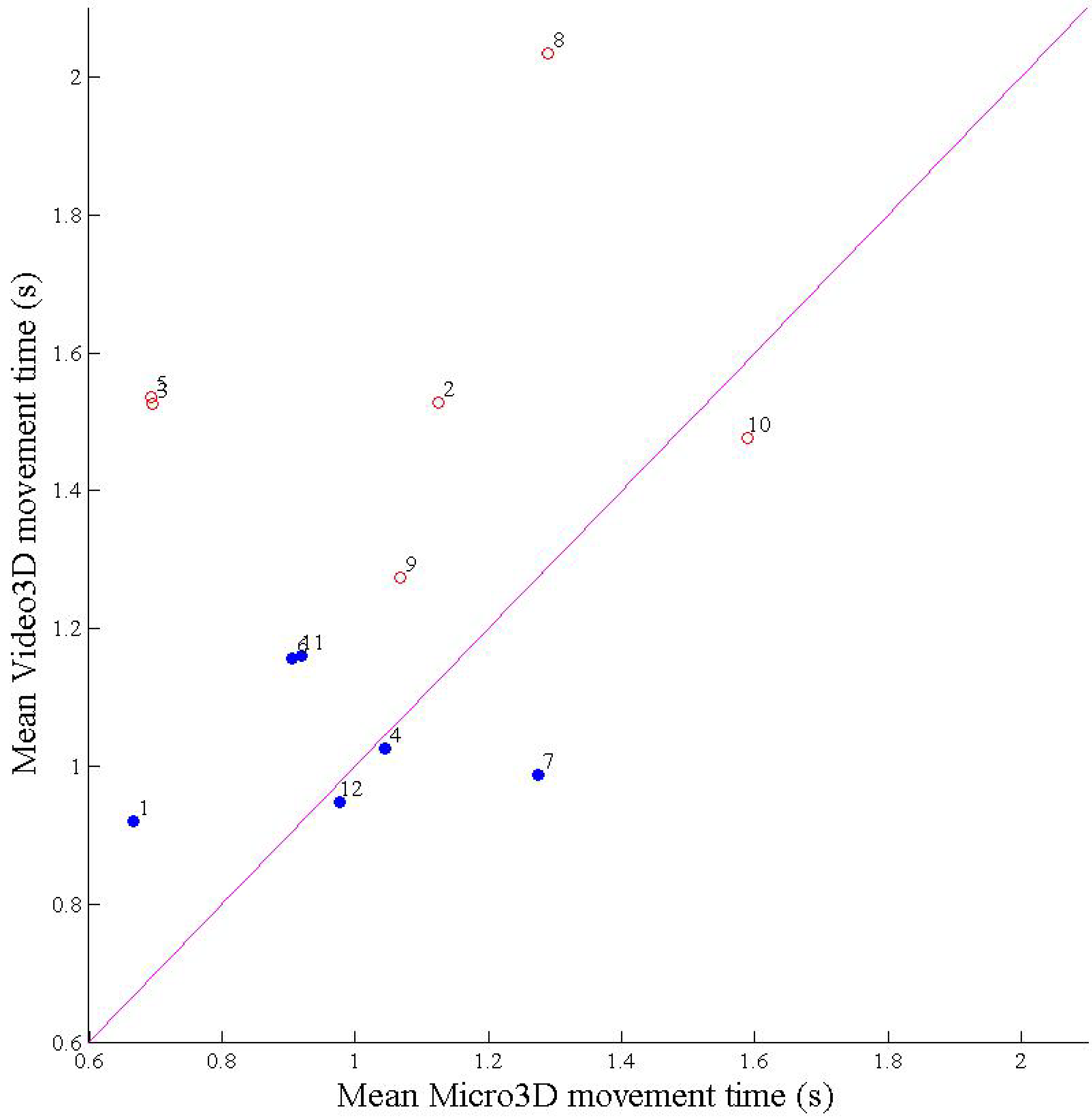


Figure 4.16: **Mean untransformed movement times for Video3D and Micro3D in seconds. Point labels indicate subject number. Filled points indicate top half performers on Video3D. Points on solid line indicate identical performance times both displays.**

Table 4.6: **Movement time (s) pooled for all targets by subject. Latin group order for each subject is also listed. Video3D-Micro3D column represent the difference in mean movement time between Video3D and Micro3D, and highlighted numbers indicate that mean time on Video3D was faster than Micro3D for that subject.**

Subj#	Micro2D	Micro3D	Loupes2D	Loupes3D	Video2D	Video3D	Latin group	Vid3D-Mic3D
1	0.8 ± 0.6	0.7 ± 0.4	0.9 ± 0.7	0.6 ± 0.3	1.0 ± 0.5	0.9 ± 0.6	1	-0.3
2	1.5 ± 1.0	1.1 ± 0.5	1.1 ± 0.6	1.1 ± 0.9	1.7 ± 1.7	1.5 ± 1.2	2	-0.4
3	0.9 ± 0.4	0.7 ± 0.3	1.1 ± 0.5	0.8 ± 0.3	1.2 ± 0.7	1.5 ± 1.2	3	-0.8
4	1.4 ± 0.8	1.0 ± 0.5	1.2 ± 0.8	1.1 ± 0.6	1.1 ± 0.6	1.0 ± 0.8	1	0.0
5	0.9 ± 0.4	0.7 ± 0.4	0.8 ± 0.5	0.8 ± 0.5	1.3 ± 0.9	1.5 ± 1.2	2	-0.8
6	1.1 ± 0.6	0.9 ± 0.5	1.0 ± 0.5	0.9 ± 0.6	1.2 ± 0.6	1.2 ± 0.6	3	-0.3
7	1.2 ± 0.9	1.3 ± 0.8	1.1 ± 0.8	0.8 ± 0.5	1.2 ± 0.6	1.0 ± 0.5	1	0.3
8	1.5 ± 1.0	1.3 ± 0.6	1.2 ± 0.9	0.9 ± 0.6	3.4 ± 4.0	2.0 ± 1.3	2	-0.7
9	1.2 ± 0.8	1.1 ± 0.8	1.3 ± 1.0	0.9 ± 0.6	1.4 ± 0.9	1.3 ± 0.9	3	-0.2
10	1.4 ± 1.0	1.6 ± 1.6	1.2 ± 0.8	0.8 ± 0.5	1.5 ± 1.2	1.5 ± 1.2	1	0.1
11	1.0 ± 0.7	0.9 ± 0.4	1.0 ± 0.7	0.9 ± 0.5	1.5 ± 0.8	1.2 ± 0.6	2	-0.2
12	1.0 ± 0.6	1.0 ± 0.6	1.0 ± 0.9	0.9 ± 0.6	1.5 ± 1.5	0.9 ± 0.7	3	0.0
Mean	1.1 ± 0.3	1.0 ± 0.3	1.1 ± 0.1	0.9 ± 0.2	1.5 ± 0.6	1.3 ± 0.3		

Table 4.7 shows the movement time and distance for the top six performers on the 3D video display. Other than targets in the z-axis, top performers have similar movement times on the Video3D as the other displays. Statistically, only 3D Loupes are better than 3D Video ($p<0.05$). No statistical differences were found between displays for movement distances.

Table 4.7: Mean ± SD of untransformed movement time and total distance moved by 3D display type for six subjects with fastest average Video3D movement times (n= 1301 targets)

Display/Axis	Movement Time (s)			Movement Distance (mm)		
Micro3D	**0.96**	±	**0.57**	**57.55**	±	**27.59**
x	0.79	±	0.42	57.18	±	29.07
y	0.70	±	0.40	43.77	±	21.15
z	1.19	±	0.63	64.92	±	27.12
Loupes3D	**0.86**	±	**0.54**	**59.03**	±	**32.88**
x	0.75	±	0.32	56.50	±	25.28
y	0.71	±	0.47	51.05	±	28.47
z	0.99	±	0.62	64.07	±	37.07
Video3D	**1.04**	±	**0.64**	**57.00**	±	**28.72**
x	0.79	±	0.34	52.18	±	21.64
y	0.69	±	0.32	41.77	±	20.09
z	1.36	±	0.72	67.69	±	31.57

4.3.6.4. Learning effect Video3D analysis

After completing all the targets on all three displays, subjects immediately redid the experiment using the Video3D display to evaluate potential learning effects during the targeting task. Mean movement time among subjects while using the 3D video display was 1.4 seconds during the experiment session and 1.3 seconds during the extra session. Paired t-test analysis found no significant differences between the two sessions ($p>0.30$).

4.4. Discussion

Several types of display equipment, i.e., microscopes, loupes, and video, are currently used for surgical procedures, but the impact of display type on surgeon performance and musculoskeletal health is unclear. Chapter 3 observed more neutral neck postures from video displays and indicated more work is needed to understand the performance differences between video and microscope displays. This study brings together literature from human performance, magnification work, and visualization equipment to determine of performance on different displays, given different task conditions and to address the three proposed hypotheses.

4.4.1. Displays and performance (Hypothesis 1)

As noted by Boyle & Shea (2013) who tested movement amplitudes of 4-16°, enhanced displays are required for the performance of small amplitude movements. Current magnification displays used by microsurgeons include operating microscope, loupes, and video systems. However, gaps in performance remain between video and conventional equipment (Franken et al. 1995; Gorman et al. 2001; Cheng et al. 2012). Hypothesis one focuses on the impact of visualization displays on selected performance metrics during targeting tasks.

4.4.1.1. Movement time

Time is an important performance metric and has implications in time that flap tissue is deprived of blood-flow, prolonged work for the surgeon, and operating costs (Yu et al. 2014). Loupes were reported to be one of the most popular magnification equipment in dentistry, and previous studies suggested that, when used, loupes 1) improved postures, 2) reduced eye fatigue, and 3) may reduce dental practitioners' risk for musculoskeletal disorders (Branson et al. 2010; Sunell & Rucker 2004; Valachi 2009). However, limited studies compared performance times between loupes and operating microscopes. Operating microscopes are typically used in tissue transfer surgeries, and a comparison study showed that loupes can be feasibly used for tissue transfers (Ross et al. 2003). Specifically, Ross et al. (2003) showed that mean operating time with loupes were not significantly ($p>0.05$) 6% faster than microscope (Loupes = 613min versus Microscope = 652mins). In addition, patient outcomes were not significantly different between the two visual equipments (Ross et al. 2003). This comparison between microscope and loupes may be limited, because 1) operating time metric includes non-microscope segments and 2) impact of variability among techniques on surgical time (Yu et al. 2014) was not controlled. However, the authors believed "empirically" that loupe took less time. Results from this study showed that loupes were 5-18% faster than microscope for targeting tasks (Table 4.5), and these findings support the beliefs published by Ross et al. (2003).

Similar to performance trends in previous studies (Franken et al. 1995; Gorman et al. 2001; Yu et al. 2012; Cheng et al. 2012; Nissen et al. 2013), the current study observed that movement times were 6-26% slower on video displays than microscopes (Table 4.5). A key finding from this study was that movement time disparity between video and other displays was influenced by interactions between display and target axis factors (Table 4.3, Table 4.4, and Table 4.5). Video displays were only 0.05-0.13 seconds (6-12%) slower than microscope for targets in the x (left/right) and y (fore/aft) axes (Table 4.5). These observations suggest that differences among displays were much smaller for movement on the x and y-axes, i.e., axes that were orthogonal to the viewing axis of video and microscope displays. However, when targets were on the vertical z-axis and closely aligned with the viewing angle, performance on video was 26% slower than the microscope and 34% slower than the loupes. Using average microsurgery times of 3608 ± 438 seconds sampled by Yu et al. (2014), microsurgery time can be roughly estimated to require 216-678 more seconds.

Several unique characteristics among the displays may explain the interaction of the z-axis on movement times. In contrast to the fore/aft and left/right targets that lay flat on the table surface, targets in the z-axis (vertical) required subjects to visually assess the location of target in respect to the probe in 3D-space (Figure 4.6). To assess 3D-space, depth perception strategies may include occlusion (where subjects judge the location of the probe with the vertical z-axis target by how the two overlap) or convergence using binocular vision. However, these strategies may be impacted by display used. For example, the optics for both the microscope and video displays were positioned directly above the targets and orthogonal to the x (left/right) and y (fore/aft)-axes (Figure 4.6). The optics of the loupes were worn by subjects at an offset (Figure 4.6) and provided an oblique view of the targets during the experiment. These differences in optic position can affect where the optics converge (Shah & Pellegrini 2010) and may explain differences among displays targeting tasks.

In addition, other differences in display designs may impact performance. For loupes, the distance between the optics was approximately the subject's pupil distance, and the distance from optics to targets was the farthest. For microscope, the optics were also spaced at pupil distance, but several internal lenses converged the optics to a shorter working distance from the task. Finally, for video, differences between video and the other displays include: 1) the two lenses were closely spaced together in the depth camera and not at pupil distance, 2) higher zoom was needed to achieve similar field of view, 3) 3D video screen was needed to display the stereo images which reduces the image resolution of the images, and 4) depth of field range is affected by zoom and camera convergence, therefore, depth of field was 160mm to 320mm less than loupes, but 30mm to 120mm larger than the microscope. Despite these technical differences, movement times on video displays were comparable for targets on the right/left and fore/aft axes. Further investigation on the aforementioned factors in video display design may further improve performance for vertical targets.

4.4.1.2. Movement distance, overshoot, and submovements

Contrary to the trends observed for the movement times, video displays were not significantly worse than loupes or microscopes for overshoot distances for targets in all axes (Table 4.3 and Table 4.5). In addition, mean distance moved, overshoot, and submovements on video displays were either better or not significantly different than loupes and microscope for targets on the left/right and fore/aft axes (Table 4.3, Table 4.5, and Appendix).

Surgical studies have similarly emphasized movement metrics beyond movement times. Although some surgeons indicate that additional research is needed to associate improved hand motion statistics with quality of the anastomosis (Kalu et al. 2005), other studies noted that hand motion have both construct validity and biological impacts (Grober et al. 2003; Temple & Ross 2011; Yu et al. 2014). For example, overshoot during tasks like “drive needle” and “strip adventitia” identified in Yu et al. (2014) may result in failed needle drives and contact with the intima. In addition, the lack of differences among video and other displays on movement distances, submovements, and overshoot distances observed in this study may explain findings from previous works that showed no differences among displays for anastomosis quality, vessel patency, and pancreatic fistula rate (Gorman et al. 2001; Jianfeng et al. 2014; Nissen et al. 2013). However, to maintain this quality of the anastomosis, the tradeoff on the video display may be increased movement time (Table 4.3, Table 4.5, Figure 4.14, and Figure 4.15). For example, every millimeter of movement distance required more movement time on the video than the other displays (Figure 4.14c), and this may indicate that movement velocities were slower on video displays than the other displays. In addition, each submovement required more time on the video displays than the loupes and microscope (Figure 4.15). Previous literature on human performance can give further insight on this behavior. As observed in the present study (Figure 4.15), Lin & Drury (2013) noted that submovements are correlated with motion time, and each submovement is needed to iteratively correct misalignments. Similarly, Fleishcer (1989) observed that targeting involved an initial gross movement followed by long positioning time.

Results in the present study indicate that increased time per distance moved and per submovement number is needed to accomplish the targeting task with similar movement distances and overshoot on the video display as with other displays.

4.4.2. Stereoscopic displays and performance (Hypothesis 2)

The current study measured selected performance metrics between 2D and 3D video displays that are currently available in surgery, e.g. microsurgery, endoscopic, laparoscopic, robotic (Gorman et al. 2001; Jianfeng et al. 2014; Munz et al. 2004). In addition, the differences between 2D and 3D in loupes and microscopes were also measured by occluding vision to one optic. Effect of 2D for targets on the x and y-axes ranged from 13% decrease to 32% increase in measured performance metrics (Table 4.5). However, results showed a consistent 11-29% decrease in all performance metrics with 2D than 3D for targets on the vertical z-axis (Table 4.3, Table 4.5, and Appendix).

Other investigators have similarly observed improved task performance of 3D over 2D (Munz et al. 2004). For example, Munz et al. (2004) examined performance metrics similar to the present study, i.e., time, number of movements, distance traveled, and number of errors, and also found statistically significant improvements of 3D over 2D video displays when subjects performed tasks using a robotic surgery system, (Munz et al. 2004). In contrast to the present study, Munz et al. (2004) evaluated eleven surgeons with limited robotic experience and examined custom designed skills tasks like “pick and place,” “Rope passing,” intracorporeal knot tying, and “V-box.” Despite differences in subject experience (i.e., university subjects vs. surgeons), video equipment (i.e., depth camera vs. robot system), and tasks (i.e. targeting vs. surgical skill tasks), comparisons between 2D/3D displays were similar between Munz et al. (2004) and the present study.

It is important to note that other studies did not find conclusive evidence showing that 3D performance is better than 2D displays (Hanna et al. 1998; Kong et al. 2010; Gurusamy et al. 2011; Chapter 3). Differences in findings may be partially explained by task differences. Studies by Hanna et al. (1998) and Kong et al. (2010) focused on performance times and subjective observations of errors during either live laparoscopic surgeries or simulated laparoscopic tasks. Results from the present study found that task factors, i.e., target axis and distance, significantly interacted with 2D/3D factor. For example, results from the current study observed that 2D/3D factor consistently interact with axis for every performance metric (Table 4.3). Specifically, differences between 2D and 3D were small or negligible for targets in the x (left/right) and y (fore/aft)-axes that were closely orthogonal to the viewing axis and large for the vertical z-axis that was closely aligned with the viewing axis (Appendix). Although performance differences between 2D and 3D are influenced by task conditions, task conditions of previous studies beyond the surgical procedure is unknown (Hanna et al. 1998; Gurusamy et al. 2011).

Compared to the simple targeting tasks examined in the present study, the technical and highly variable task conditions observed in laparoscopic live and simulated surgeries may explain finding differences between previous studies (Hanna et al. 1998; Kong et al. 2010; Gurusamy et al. 2011) and the present study. Techniques and surgeon choices have been emphasized to vary greatly among surgeons (Yu et al. 2014; Gawande 2012). *In contrast to the targeting task that systematically varied task factors in the present study, technique variations among participants may be greater during the unstructured tasks, and this may further explain the lack of significance found between 2D and 3D displays of previous studies* (Hanna et al. 1998; Kong et al. 2010; Gurusamy et al. 2011). Additional studies are needed to examine the task conditions during laparoscopic surgeries to understand the 2D/3D performance results of previous studies (Hanna et al. 1998; Kong et al. 2010).

4.4.3. Task factors and performance (Hypothesis 3)

4.4.3.1. Target distance

The goal of Hypothesis 3 was to measure how targeting performance is affected by task factors and the applicability of current human performance literature on the small-scale tasks prevalent in microsurgery. As with findings of previous studies of movement tasks (Fitts 1954; Lin & Drury 2013; Lin & Ho 2011; Lin et al. 2011; Fleischer 1989; Lee & Bang 2013), results from this study support previous observations that movement times increased with target distance, even at the small amplitudes of 10mm to 40mm and under magnification (Table 4.3 and Figure 4.11). Previous work observed that movement time (ms) while using 3D microscope followed the relationship 168 + 81*Index difficulty (Langolf & Hancock 1975). The observed movement times for the 3D microscope in this study were longer than predicted times, i.e., slopes were 175-200 and intercepts were -73 to 463 (Figure 4.11). In particular, differences between predicted movement times and observed times were largest for targets in the vertical z-axis (Figure 4.11). Several factors may contribute to the differences in microscope tapping time between observed in the current study and predicted times using previous findings (Langolf & Hancock 1975). First, target distances and target sizes tested in this study were larger than the 2.5mm-7.6mm distances and 0.025mm -0.11mm radiuses in the previous study (Langolf & Hancock 1975). Secondly, tasks instructions were different. Subjects in Langolf & Hancock (1975) tapped targets. In the current study, subjects were required to tap target *and hold* the probe steady on the target. Specifically, the hold requirement led to observations the probe tip slipping from the target before subjects can hold position steady. This resulted in subjects requiring several tap attempts (or repositions) to successfully hold the probe with steady contact with the target which resulted in performance outliers, right-skewed distributions, and prolonged movement times. Finally, previous results (Langolf & Hancock 1975) were limited to 2D tapping tasks. Findings in this study found that the differences between predicted and observed times was the greatest for targets in the z-axis (Figure 4.11c). Given these differences, findings in the present study suggests that Fitts's models need to consider 1) axis of movement, 2) task goals, i.e., reciprocal tapping versus tap and hold, and 3) display used. Since microsurgery involves moving delicate tissues (Yu et al. 2014) and performing precise tasks that require prepositioning and steady holds (Table 4.1), movement results and Fitts' models from the target and steady hold tasks may be more applicable than reciprocal tapping tasks.

4.4.3.2. Target direction

Target direction in this study was defined as positive or negative (Figure 4.1) for targets in the x (left/right, where negative is towards right hand) and y (fore/aft, where negative is forward away from torso)-axes. Only positive direction was tested for targets in the z-axis. Note that all subjects were right-handed. For targets on the y-axis, results found that movement in the negative direction was 4-22% better, i.e., less time and distance, than the positive direction for all of measured performance metrics (Table 4.3, Table 4.4, and Appendix). Performance differences observed for the direction factor may represent biomechanical differences in terms of fingers or wrist exertions. For example, movement in the negative y-axis required finger extension and/or wrist extension. Previous work (Langolf et al. 1976) found different limbs (e.g., finger, wrist, arm) differ in movement times. However, more recent studies (Hoffman & Hui 2010; Boyle & Shea 2013) found no differences in movement times between hand and finger movements and suggested that the results observed by Langolf et al. (1976) were due to visual enhancements by the microscope. Literature on performance during micro-movements remains limited (Boyle & Shea 2013), but findings in the present study suggests that fore/aft movements away from the torso resulted in faster movement times, less movement distance, and smaller overshoot for 10mm-40mm distanced targets (Table 4.4).Additional work is needed to investigate whether improved performance was due to subjects utilizing 1) finger extension, 2) wrist extension, and 3) combinations of both.

4.4.3.3. Target axis

Discussion of the impact of target axis on performance was previously discussed in the context of displays (Section 4.6.1), and this section will discuss the contributions of the present study to current human performance literature. Results in the present study found that target axis (i.e., fore/aft, left/right, or vertical) was a significant factor for performance (Table 4.3, Table 4.4, Table 4.5, and Appendix). Although performance was worse for targets on the vertical z-axis, it is important to note that performance metrics for targets in the y-axis was 17-53% better than the x-axis for every performance metric examined in this study (Table 4.3 and Table 4.4). Limited studies have examined the impact of target axis on performance, especially in the context of different visual displays for small amplitude movement. Early works on micro-movements have focused on either 1D tapping tasks or basic electronic assembly tasks (Hancock et al. 1973, Langolf & Hancock 1975, Langolf et al. 1976). Moreover, axis of motion was not an experimental factor in more recent studies with micro-movements (Boyle & Shea 2013; Hoffman & Hui 2010). Several studies in larger amplitude movements, i.e., 56mm-212mm, found that 1) movement times were faster in the x (left/right)-axis than y (fore/aft)-axis during targeting with mouse (Lee & Bang 2013) and 2) movement in the y-axis (forward and back) was significantly slower than moving left and right during trivariate targeting tasks (Grossman & Balakrishnan 2004). These observations were contrary to the trends between x and y-axes observed in the present study. The rationales for observed differences during large amplitude movements were arm inertia (Lee & Bang 2013) or the natural force of gravity (Cha & Myung 2013). However, arm inertia effect or moving against gravity may have limited relevance for the micro-movement tasks examined in the present study since subjects were primarily observed to stabilize their hand on the table. Hand stabilization may explain the different impact of axis on performance between large and small amplitude tasks, and results of the present study further contribute to the limited literature examining the effect movement axis in microscope performance.

Limited studies have systematically tested performance on the vertical z-axis, and available studies focused on movements of the whole arm (Grossman & Balakrishnan 2004; Hoffmann et al. 2011; Cha & Myung 2013). For example, Hoffmann et al. (2011) found that the z-dimension of the target was of "minor importance" while tapping targets with height, width, and length. In contrast, subjects in the present study needed 88-105% more time when targets were on the z-axis (Table 4.3, Table 4.4, and Table 4.7). Although findings regarding the effect of the z-axis on performance were different between the two studies, it is important to note the key differences in task design. Although the targets had vertical z-component (Hoffmann et al. 2011), their task design still resembled a 1D tapping tasks. Specifically, both start and end targets had identical dimensions so the vertical start positions were same as end start positions, and this design required limited visual assessment of the vertical z-axis (Hoffmann et al. 2011). In addition, the present study used optical magnification equipment like microscopes and video displays. As emphasized previously, viewing axis (Figure 4.6) may be an important factor when visualization equipment are used, and differences in viewing axis may affect depth perception strategies like convergence and occlusion that may be critical for tasks in the vertical z-axis.

4.5. Conclusions

The findings from this study addressed the hypotheses in the stated aims to measure how micro-movement performance was impacted by the factors: 1) displays, 2) stereo and non-stereoscopic display, and 3) task factors. Results found faster performance for the following factors: 1) y-axis, 2) negative direction, 3) and shorter movement distances (Section 4.6.3, Table 4.4, and Table 4.5). Performance times were slower on video displays than microscopes and loupes. However, performance differences were smaller on the x (left/right) and y (fore/aft)-axes than the vertical z-axis. In addition, video displays were not significantly different than other displays in overshoot and distance moved metrics that may be indicative of mechanical stress blood vessels are exposed to in microsurgery. Finally, results showed better performance with 3D than 2D for targets in the vertical z-axis.

Further work is needed to investigate 1) video displays improvements, 2) application of targeting task, and 3) impact of subject factors. Several differences in display design among video and other displays were identified that can be used to improve video displays. For example, oblique viewing angle, screen resolution, and large distance between cameras were major differences between the best performing loupes and video displays, and these factors may have potential to improve video performance. Targeting tasks were designed through decomposition of surgical skill tasks to motions and through comparison of published microsurgery tasks. In addition, task conditions were systematically controlled to investigate subject performance on selected metrics. Further work is needed to investigate the concurrent and predictive validity of the targeting tasks and the selected performance metrics on skill and performance in microsurgery. Finally, participants in the current study had no surgical experience. Although the lack of experience may have allowed unbiased comparison of displays (i.e., surgeons would have prior experience with surgical microscopes), effect of displays varied among subjects. Specifically, a third of participants performed better on the Video3D than Micro3D, and additional Video3D sessions did not improve performance. This suggests that individual factors, e.g., stereoscopic visual acuity, advance fine-motor skills, experience with 3D displays, may impact how performance is different among the displays; however, additional studies are needed to investigate.

4.6. Acknowledgements

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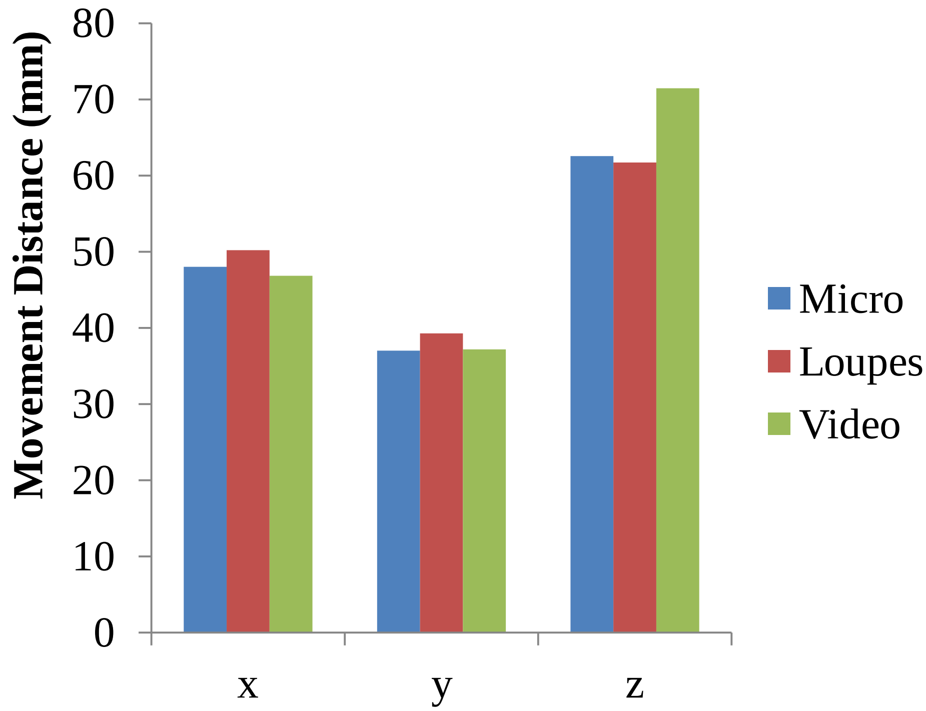
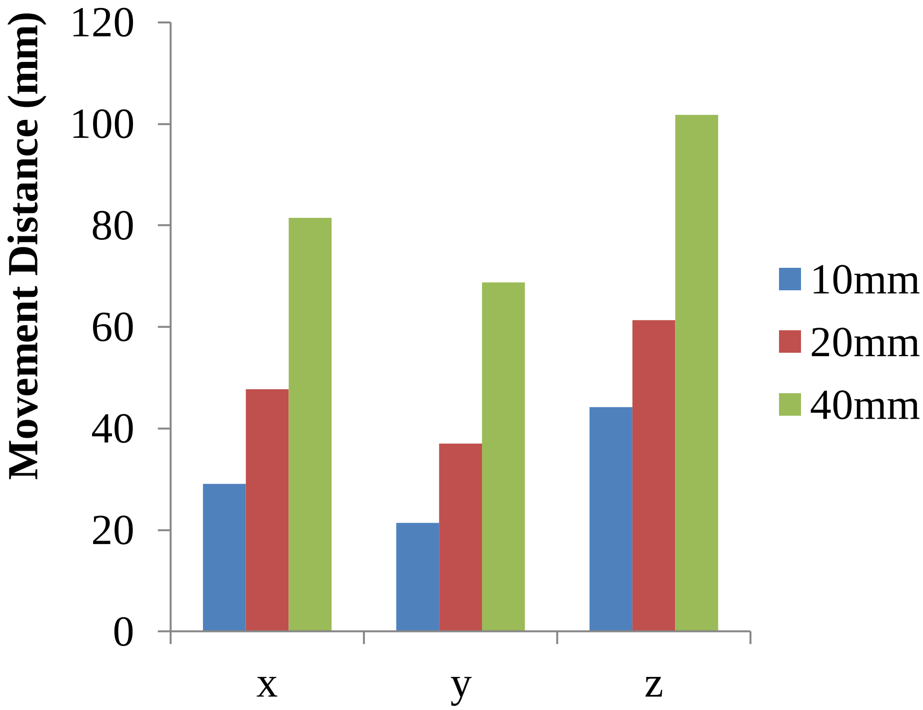
4.8. Appendices

Figure 4.17A: Interactions of independent factors on a-g) Movement distance, h-m) Movement times, n-q) Overshoot, and r-w) Submovements



a)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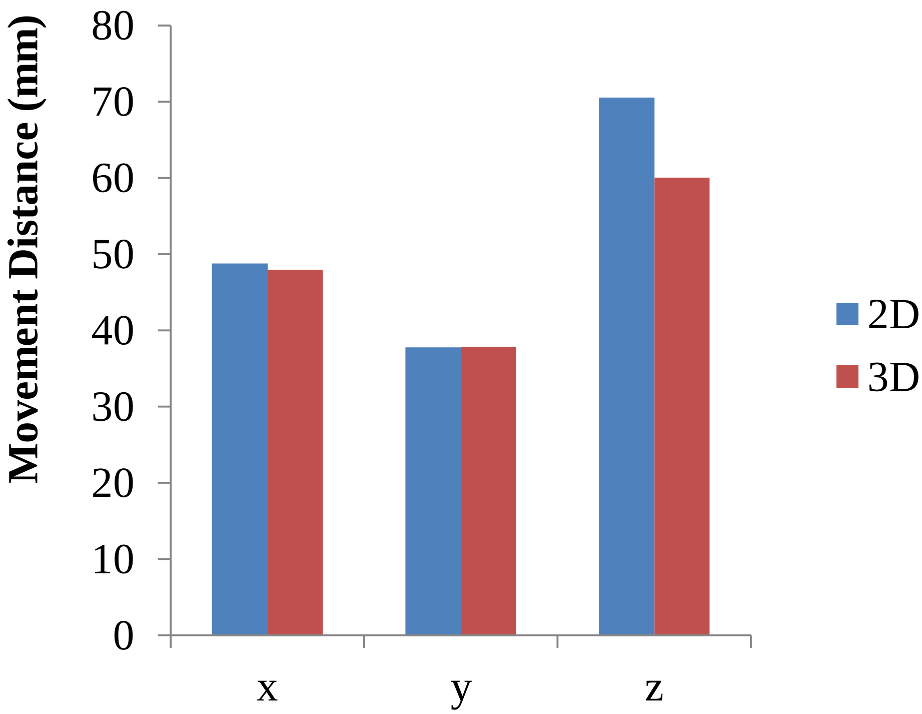
120
100
80
60
40
20
0
x
y
z
10mm
20mm
40mm
b)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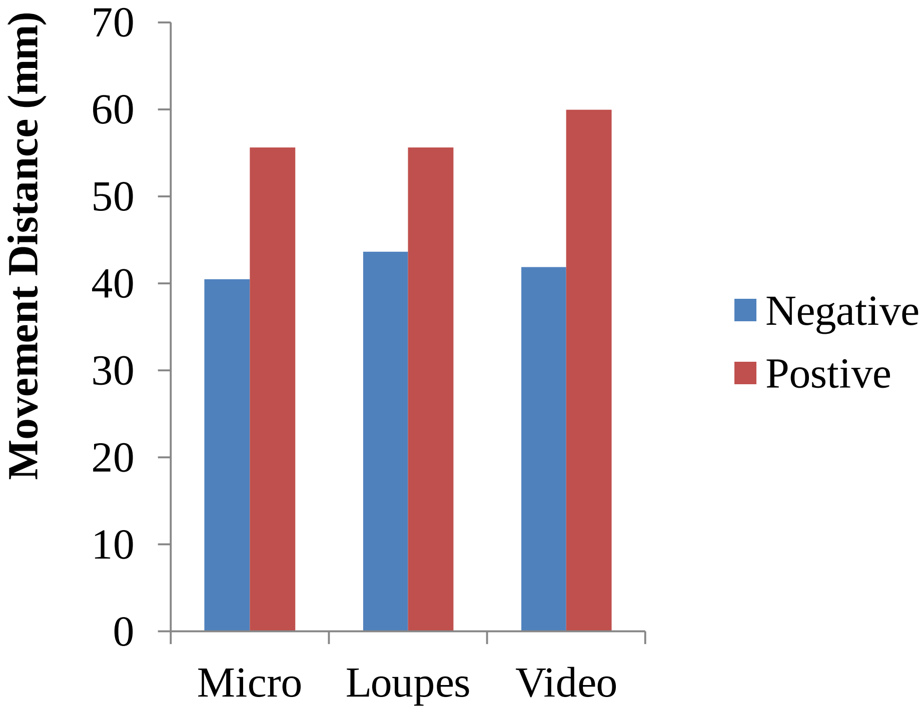
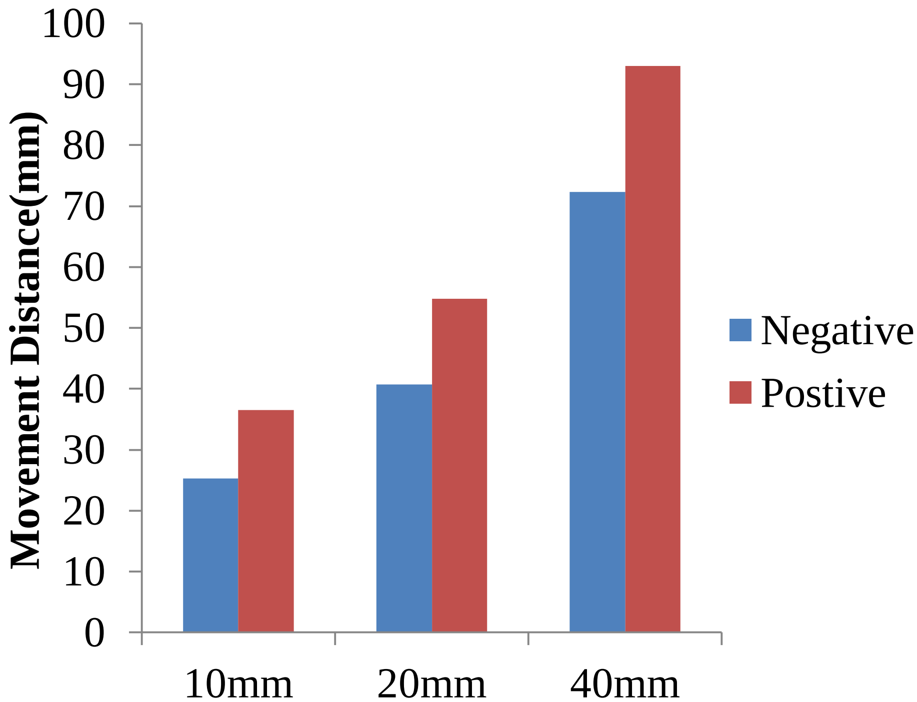
80
70
60
50
40
30
20
10
0
x
y
z
2D
3D
c)


Movement Distance (mm)
70
60
50
40
30
20
10
0
Micro
Loupes
Video
Negative
Postive

d)


Movement Distance(mm)
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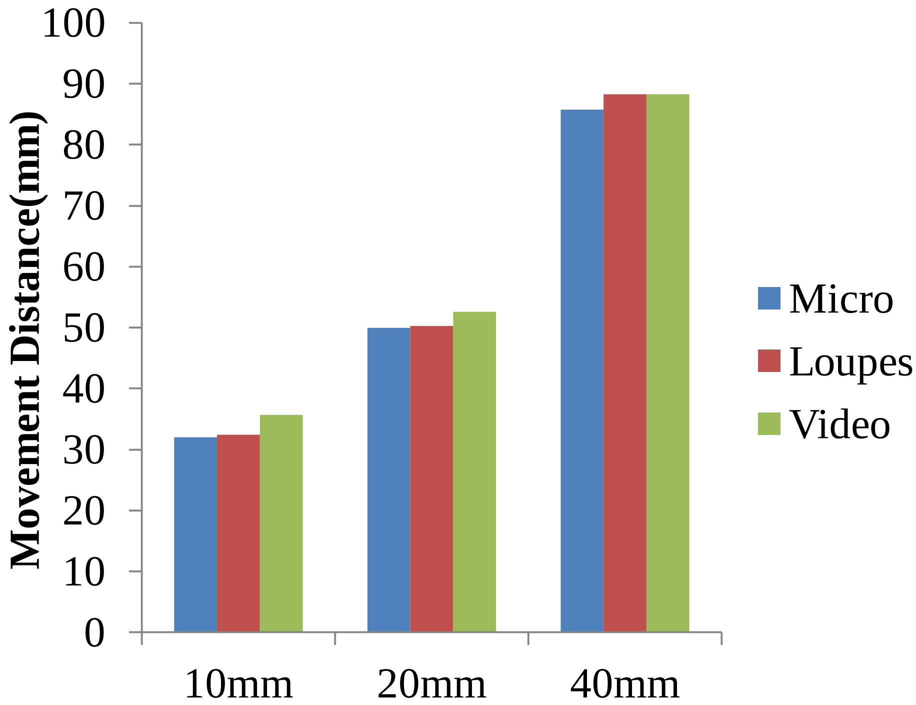
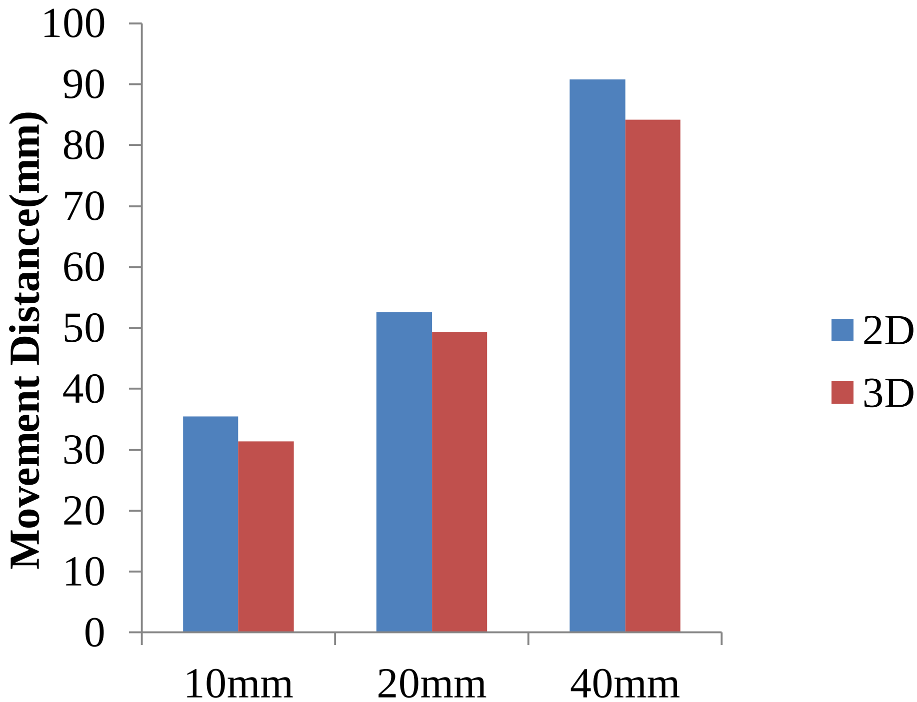
90
80
70
60
50
40
30
20
10
0
10mm
20mm
40mm
Negative
Postive

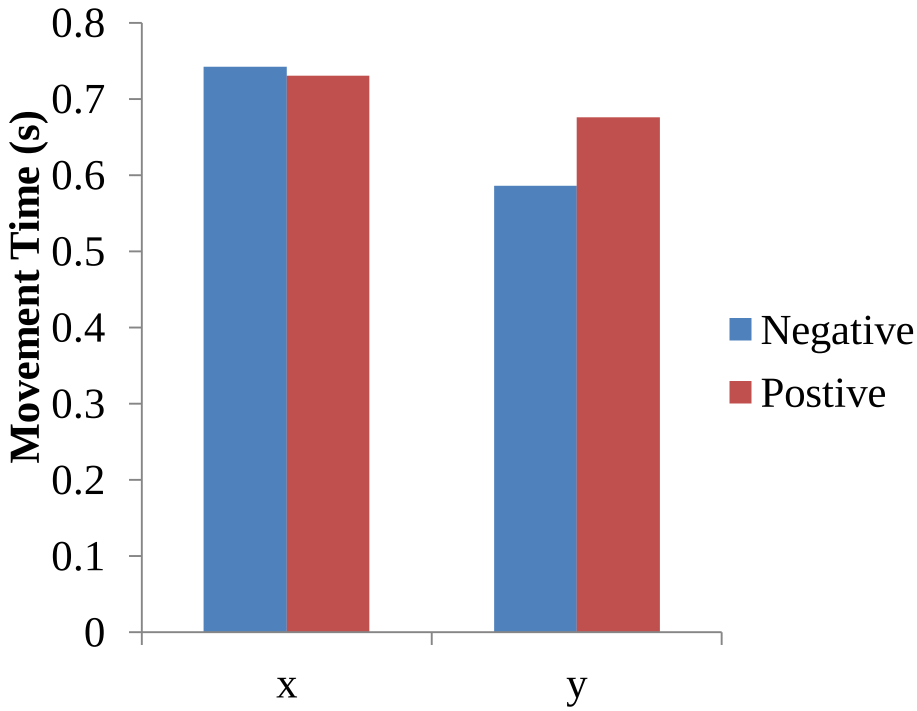
e)


100
90
80
70
60
50
40
30
20
10
0
Movement Distance(mm)
10mm
20mm
40mm
Micro
Loupes
Video

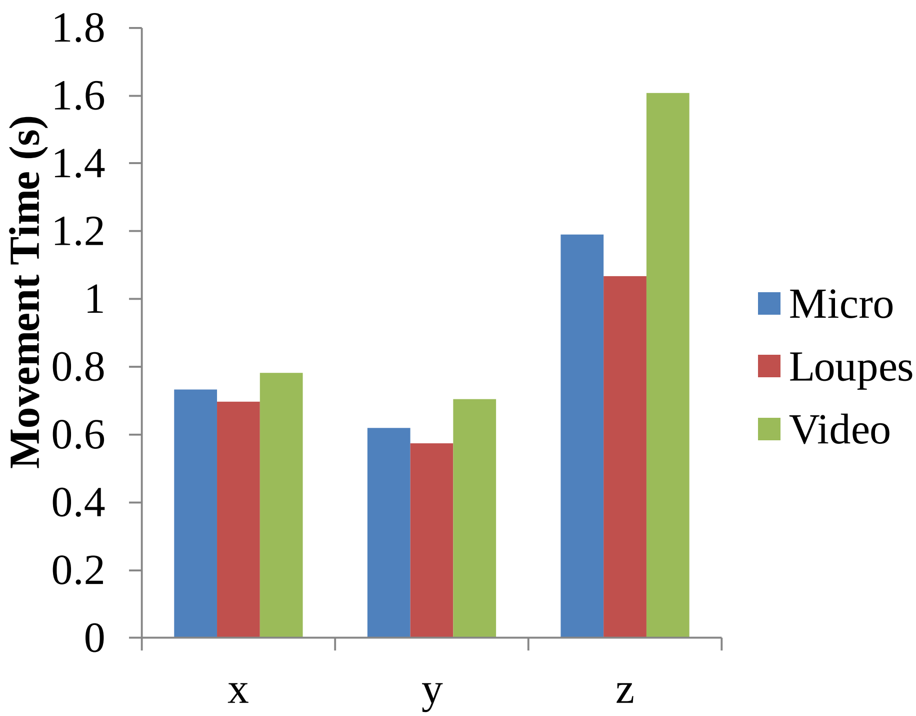
f)


100
90
80
70
60
50
40
30
20
10
0
Movement Distance(mm)
10mm
20mm
40mm
2D
3D

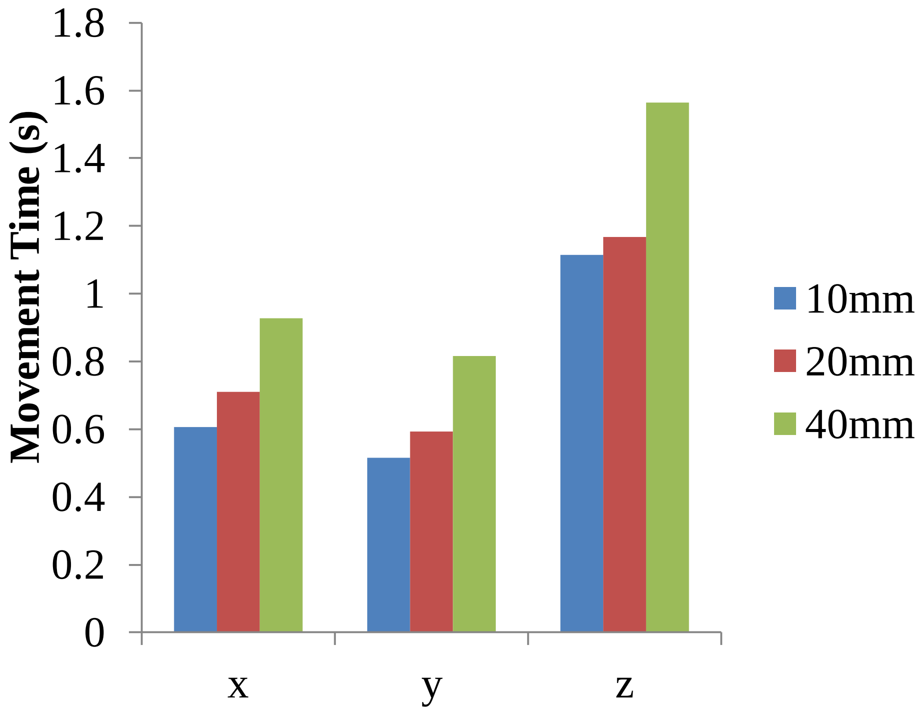
g)


0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Movement Time (s)
x
y
Negative
Postive

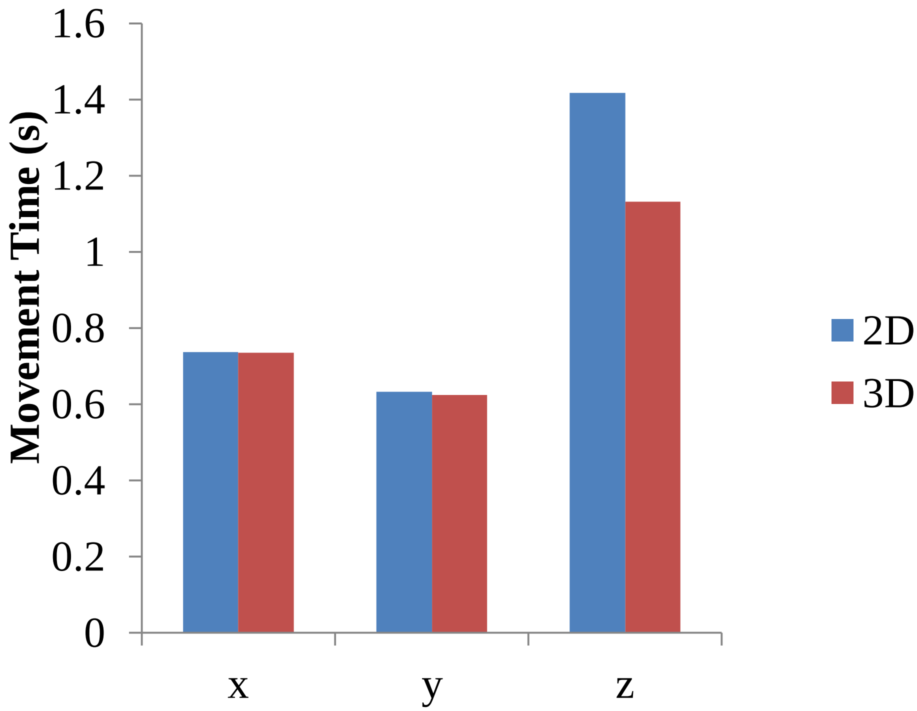
h)


1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Movement Time (s)
x
y
z
Micro
Loupes
Video

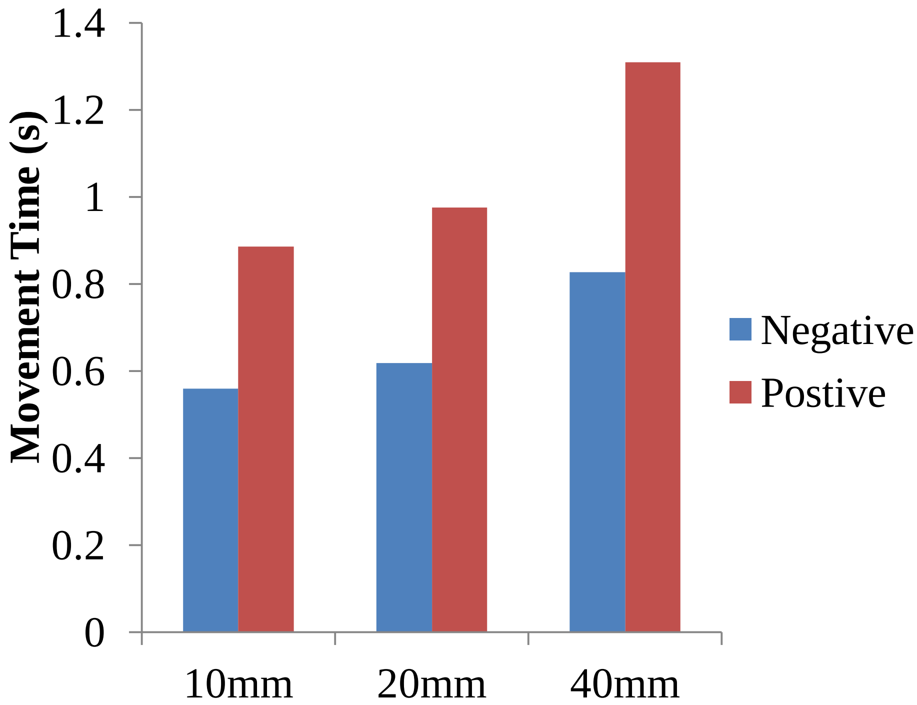
i)


1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Movement Time (s)
x
y
z
10mm
20mm
40mm

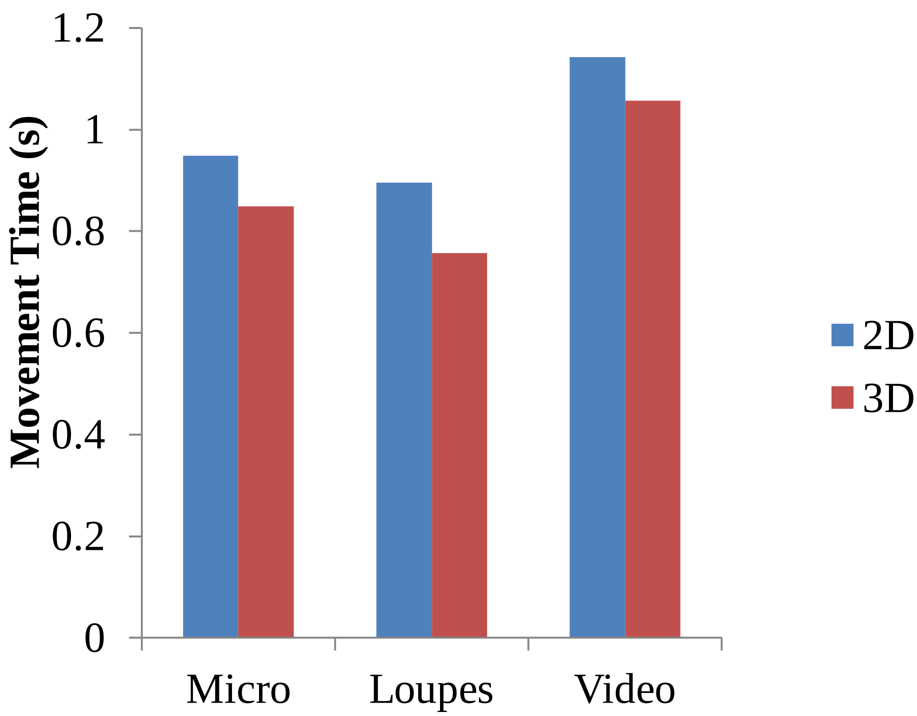
j)


1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Movement Time (s)
x
y
z
2D
3D

k)


1.4
1.2
1
0.8
0.6
0.4
0.2
0
Movement Time (s)
10mm
20mm
40mm
Negative
Postive

l)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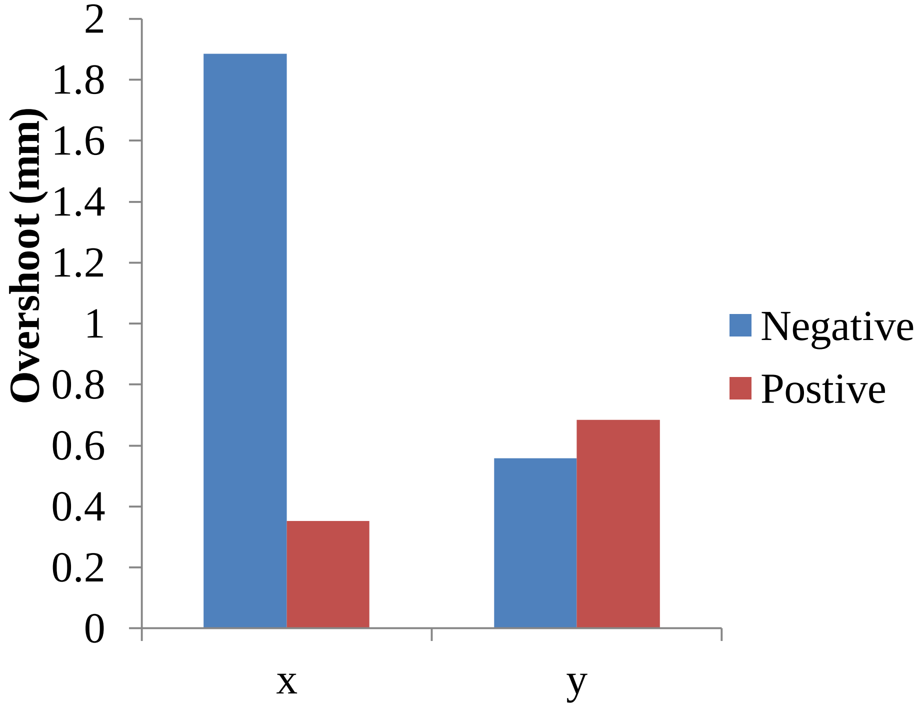
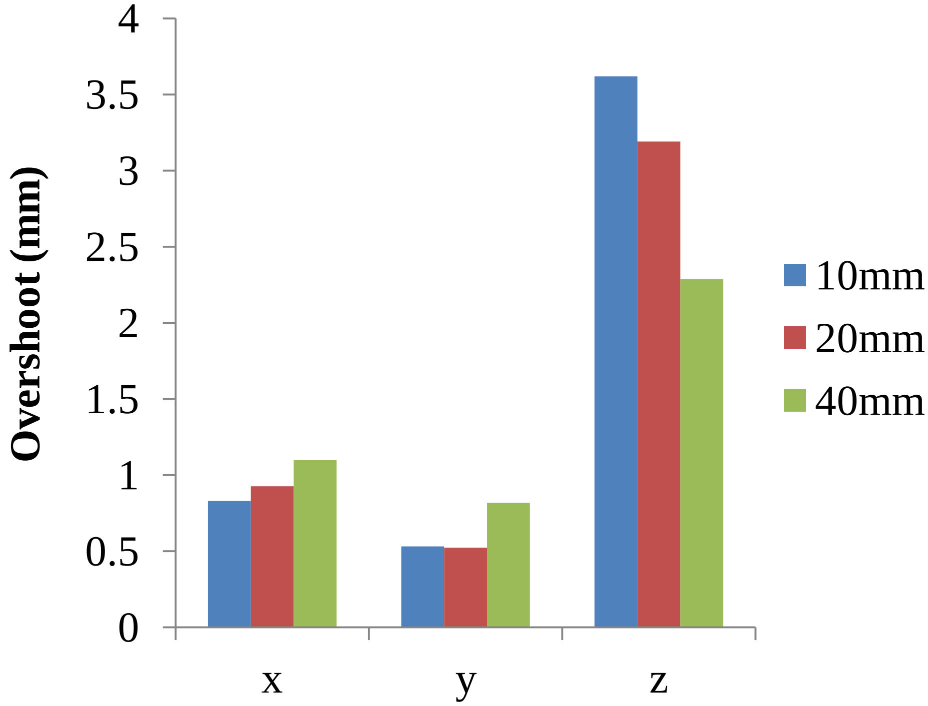
1
0.8
0.6
0.4
0.2
0
Movement Time (s)
Micro
Loupes
Video
2D
3D

m)

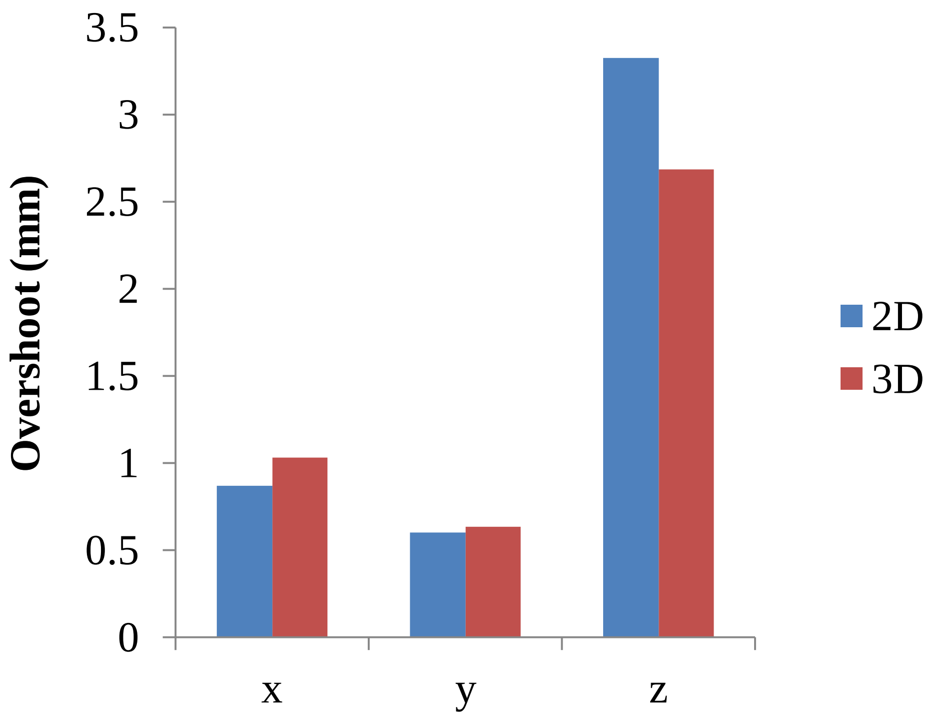


n)

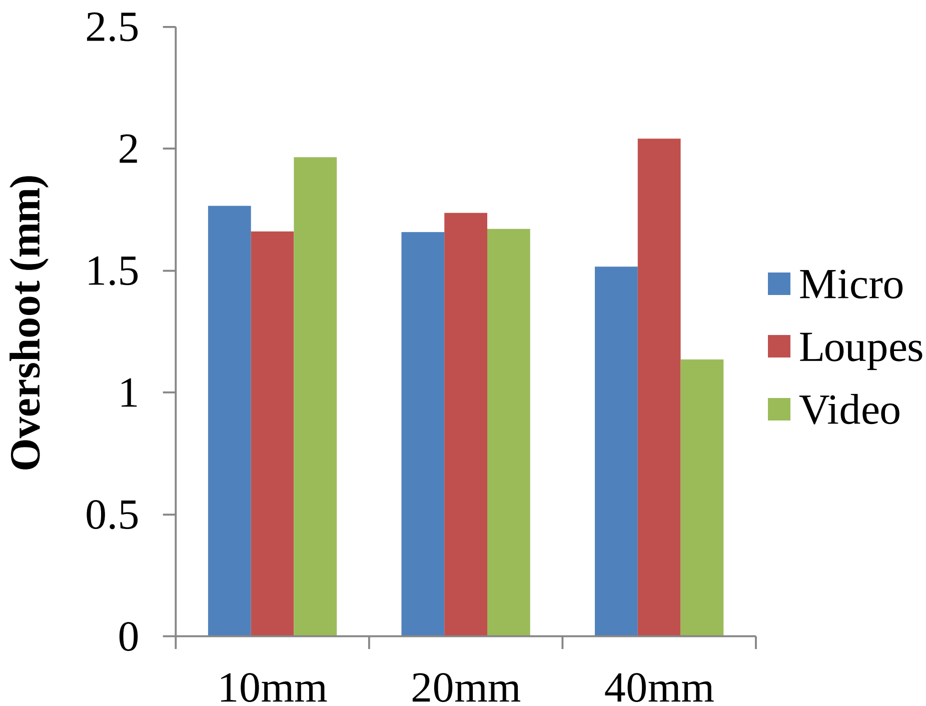


4
3.5
3
2.5
2
1.5
1
0.5
0
Overshoot (mm)
x
y
z
10mm
20mm
40mm

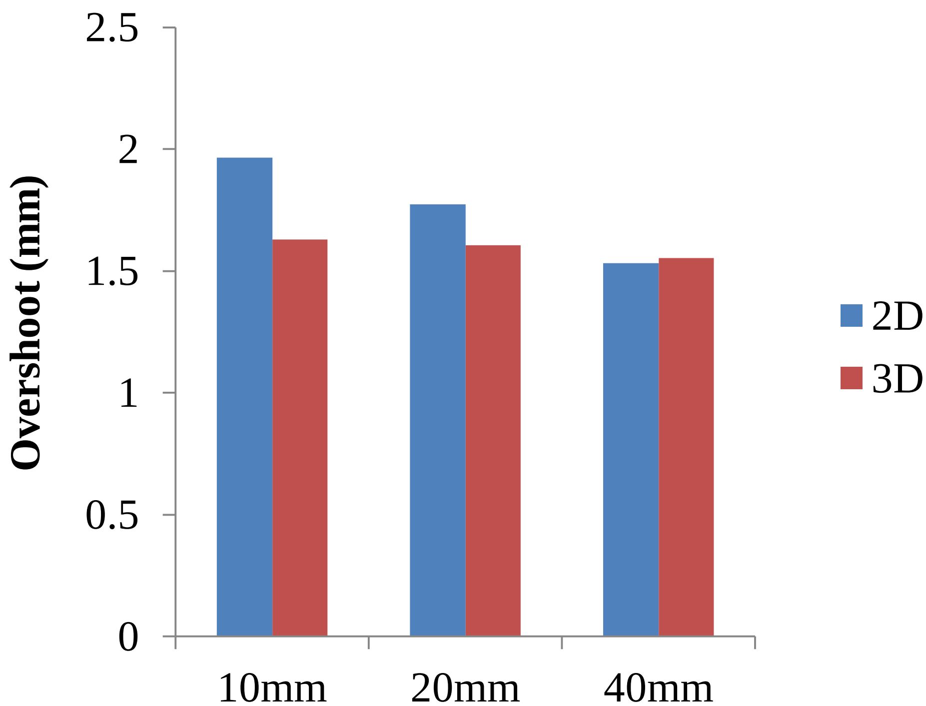
o)



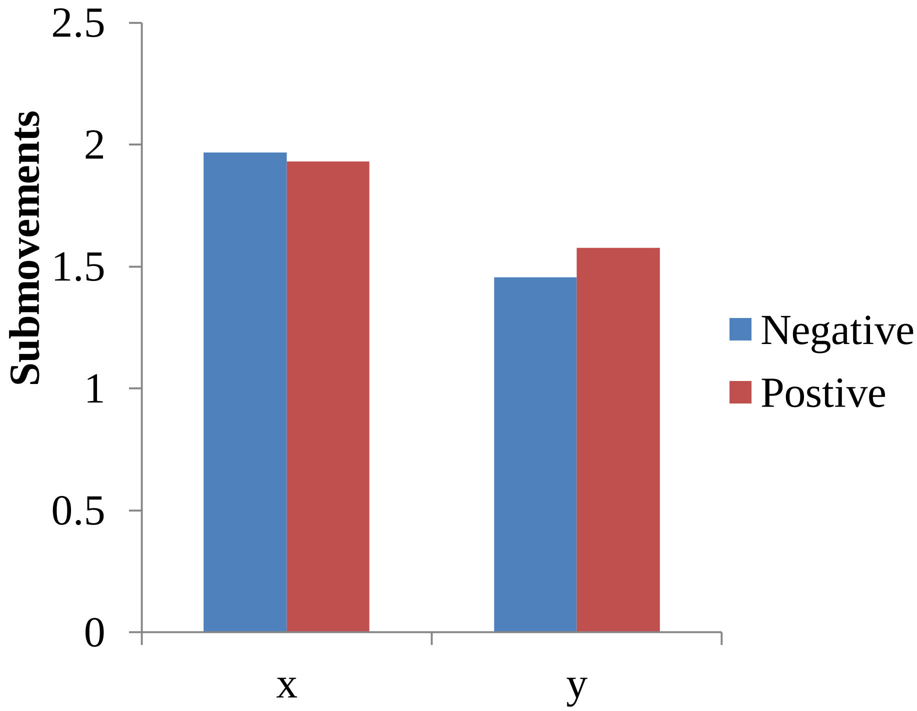
3.5
3
2.5
2
1.5
1
0.5
0
Overshoot (mm)
x
y
z
2D
3D


2.5
2
1.5
1
0.5
0
Overshoot (mm)
10mm
20mm
40mm
Micro
Loupes
Video

p)


2.5
2
1.5
1
0.5
0
Overshoot (mm)
10mm
20mm
40mm
2D
3D

q)



2.5
2
1.5
1
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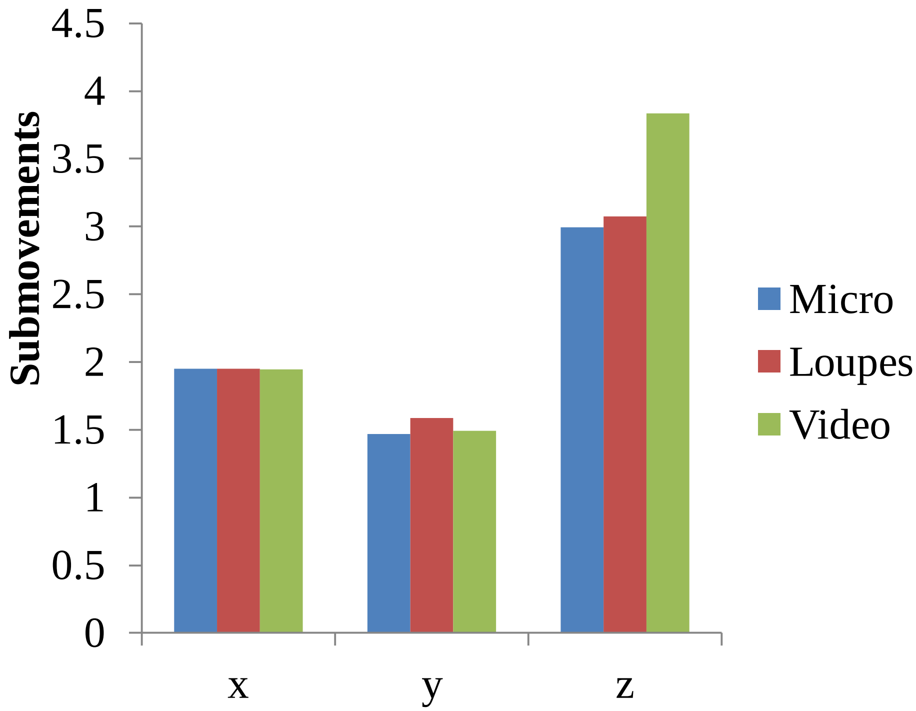

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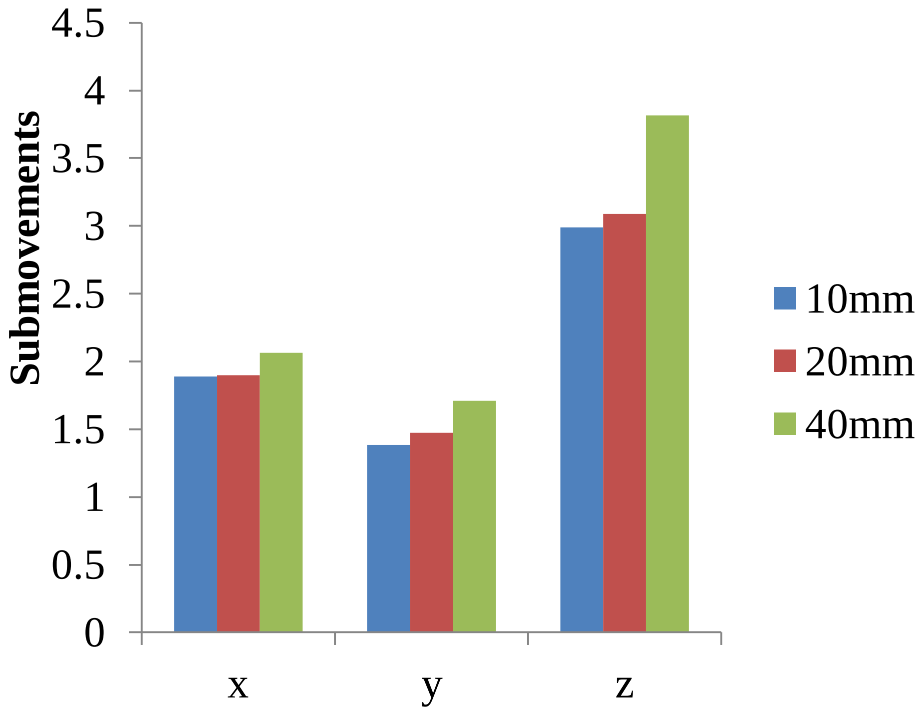
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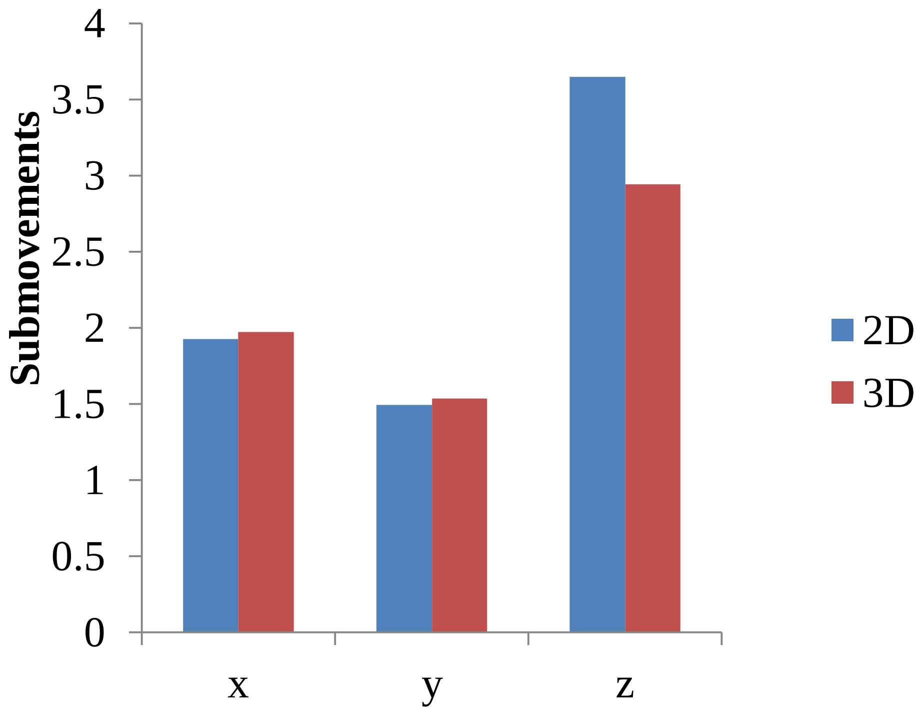
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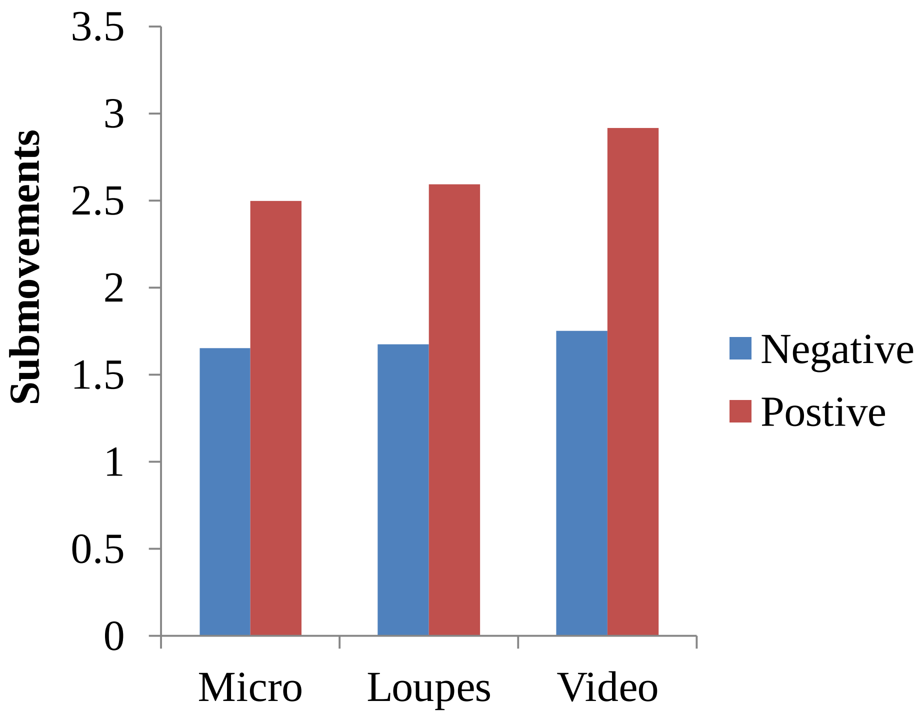
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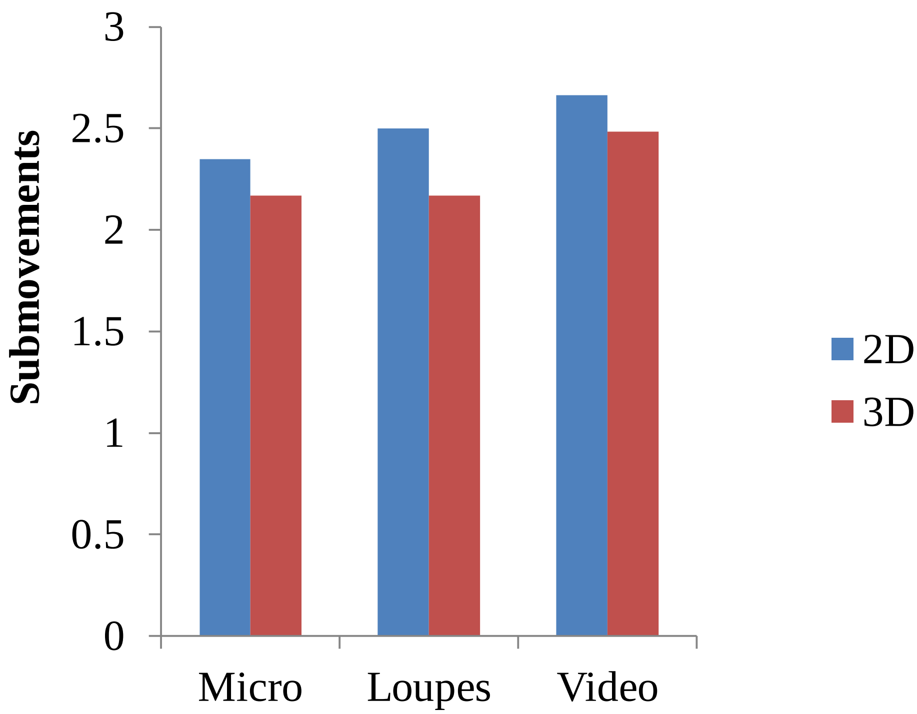
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CHAPTER 5

DISCUSSION AND CONCLUSIONS

5.1. Summary of aims

This dissertation was organized into an Introduction and three Chapters that presented results and analysis from both field studies and human subject experiments. Each study was performed to address one or more of the three specific aims of this dissertation. The three specific aims were to:

Aim 1: Develop a taxonomy that systematically describe surgical procedures and the variations in surgeon technique in order to form hypotheses on best methods for surgical outcomes, performance, and musculoskeletal health

Aim 2: Test hypothesis on microsurgery factors that may affect musculoskeletal stresses in a laboratory setting. Specifically, measure the impact of visualization equipment on postures during simulated microsurgery skills tasks in order to quantify the benefits of alternative video displays to conventional microscope, and

Aim 3: Test hypothesis on microsurgery equipment and task conditions that may affect surgeon performance. Specifically, determine the impact of microscope, loupes, and video displays on performance during small-amplitude targeting tasks and the application of video displays during microsurgery.

This chapter will discuss the findings from each experiment as they relate to the specific aims and proposed framework (Figure 1.1), and as each chapter relates to the overall goal of this work**: to develop a framework that can be used to describe surgical procedures, measure performance, and identify ergonomic factors that affect surgical outcomes and musculoskeletal stresses.**

5.2. Discussion of findings

The taxonomy developed in Chapter 2 is integral to the proposed framework (Figure 1.1). It contributes towards the overall goal of this work by 1) addressing gaps in our ability to systematically describe and compare variations in surgery so that best techniques can be found, 2) drive the design of laboratory studies for testing surgeon performance and musculoskeletal stresses, and 3) linking laboratory findings with relevant tasks, work goals, and conditions to understand the impact of findings on microsurgery practice.

5.2.1. Tool for describing variations in surgeon technique

The developed taxonomy provides a tool for describing surgical procedures and formulating hypotheses on best methods based on clinical evidence to address challenges in surgical procedures and surgeon training. Although surgeons may perform the same procedure, e.g., microvascular anastomosis, different surgeons may choose different methods or techniques to complete the surgery (Gawande 2012). Previous investigators have suggested that tools in ergonomics has potential for addressing the complexity of surgical work and providing tools for evidence based change (Hignett et al. 2013; Lowndes & Hallbeck 2012). The taxonomy developed in Chapter 2 can be used to facilitate these goals.

Previous work had success with hierarchical task analysis on describing complex work environments and surgical procedures (Stanton 2006; MacKenzie et al. 2001; Sarker et al. 2008); however, a key contribution of this work was the integration of work attributes for describing variations to traditional hierarchical task analysis (Section 2.2.4). The flexibility and granularity provided by the taxonomy have immediate impact on improving our ability to describe procedures and variations in technique. For example, Chapter 2 showed that high-level description using subtasks can be used to distinguish variations in time among cases. More importantly, subtasks in the taxonomy allowed us to compare segments with similar work goals and under similar conditions among cases despite the length and complexity of the procedure (e.g., 52% of cases lasted 10 hours or longer).

Chapter 2 also demonstrated the granularity of the taxonomy through elements and attributes. Using elements and attributes, the taxonomy can quantify variations in techniques among surgeons (Table 5.1) and can provide a tool to address large variations among surgeons observed by Gawande (2012). For example, clamps hold and align vessels during suturing (Chapter 2); however, Surgeon 2 and 5 exclusively chose to suture arteries without clamps (Table 5.1). In addition, vessels can be configured end-to-end or end-to-side (Chapter 2). Although variations in configuration may be partially influenced by anatomical conditions, Surgeon 2-5 and 8 were observed to exclusively use end to end methods. Finally, several techniques have been published for stitch pattern and choice of first stitch location (Pederson 2010), and Surgeon 2, 4, and 5 were observed to predominantly use backwall first techniques (Table 5.1). These examples supports Gawande's (2012) statement concerning the large variations among surgeons. In addition to techniques, Table 5.1 also lists frequency of outcome metrics like "Anastomosis redo" and "Addition stitch required" described by the taxonomy. Using this taxonomy, observed variations among surgeons can be used to formulate hypotheses on outcome metrics in order to identify best methods and address the large variations among surgeons. However, it is important to note that many confounders and conditions affect both surgeons' choice in technique and outcomes. Although further work is needed to identify statistical methods for establishing associations and casual relationships, this work shows the application of the taxonomy for describing procedures, quantifying technique, and comparing variations among surgeons and cases.

Table 5.1: Comparison of technique among eight surgeons from Chapter 2. Surgeon ID and the number of artery anastomoses are shown in table. Percentages indicate the frequency that each tool and method was observed for all cases (n) by each surgeon. Highlighted cells are further discussed in the text.

		Surgeon ID (8 unique surgeons)							
		1 (n=2)	**2 (n=31)**	**3 (n=3)**	**4 (n=21)**	**5 (n=9)**	**6 (n=3)**	**7 (n=3)**	**8 (n=1)**
		%	**%**	**%**	**%**	**%**	**%**	**%**	**%**
Tool: Apposition	Freestyle	50%	100%	67%	81%	100%	33%	33%	0%
	Double clamp	50%	0%	33%	0%	0%	67%	33%	0%
	Frame clamp	0%	0%	0%	19%	0%	0%	33%	100%
Method: Configuration	End to end	50%	100%	100%	100%	100%	67%	67%	100%
	End to side	50%	0%	0%	0%	0%	33%	33%	0%
Method: Connection	Couple	0%	0%	0%	0%	0%	0%	0%	0%
	Suture	100%	100%	100%	100%	100%	100%	100%	100%
Method: First stitch location	120	0%	0%	0%	0%	0%	0%	0%	0%
	180	50%	0%	67%	19%	0%	67%	67%	100%
	Backwall	0%	100%	33%	81%	100%	33%	0%	0%
	Acute	50%	0%	0%	0%	0%	0%	33%	0%
Outcomes: Redo	Redo	0%	13%	0%	10%	11%	0%	0%	0%
	No redo	100%	87%	100%	90%	89%	100%	100%	100%
Outcomes: Add suture	Add suture	50%	26%	67%	24%	33%	67%	67%	0%
	No add sutures	50%	74%	33%	76%	67%	33%	33%	100%

In addition to providing a descriptive and comparative tool for surgical procedures (Table 5.1), the taxonomy has applications in surgeon communication and training. The structure and granularity of the taxonomy provide standard language and clear descriptions of steps that surgeons can use for communication during the procedures or during training. Furthermore, the methodology for creating the taxonomy can be extended to other surgical procedures.

5.2.2. Factors that affect surgeon performance and musculoskeletal stresses

The taxonomy helped drive the formulation and testing of hypotheses on ergonomic factors that may impact surgeon performance and musculoskeletal stresses (Figure 1.1). Application of the taxonomy (Chapter 2) demonstrated that time varied widely among microsurgery cases that, in addition to jeopardizing tissue survival, may affect the workload and fatigue of microvascular surgeons. From anecdotal reports and published studies, posture stresses due to microsurgery equipment were particular concerns in microsurgery, and musculoskeletal symptoms were prevalent among up to 81.5% microsurgeons (Liberman et al. 2005; Capone et al. 2010; Sivak-Callcott et al. 2011). As observed in the application of the taxonomy (Chapter 2), visualization equipment provided essential visual information to the surgeon in order to complete the tasks described by the taxonomy, e.g., visualization of adventitia during “strip adventitia” elements and visualization of the lumen during “drive needle” elements to avoid suturing the backwall. However, operating microscopes required surgeons to be fixated over optical eyepieces (Franken et al. 1995), which constrained the surgeon’s eye locations, reduced comfort (Franken et al. 1995), and forced surgeons to be in awkward positions (Ross et al. 2003). These observations from the proposed taxonomy and previous literature were used to (Figure 1.1): 1) formulate a laboratory study to test hypotheses on the impact of visualization equipment on musculoskeletal stresses, 2) design relevant tasks to simulate microsurgery skills based on elements (e.g., “support vessel,” “align vessels,”) and work objects attributes (e.g., using narrow silicon tubes and monofilaments to simulate vessels and sutures respectively), and 3) determine workplace layout (e.g., field of view).

A key contribution of Chapter 3 is the quantitative measurements on posture and posture patterns among displays. Previous work comparing displays and postures were largely based on qualitative observations on microscope postures and suggestions that video displays can reduce musculoskeletal stresses (Statham et al. 2010; Franken et al. 1995; Ross et al. 2003). Findings from Chapter 3 showed that subjects using video displays had 1) 9-13° more erect neck postures, 2) 13% higher duration in time spent at neck extension, and 3) 3.2x more neck posture adjustments (Aim 2). These observed posture patterns suggest that applications of video displays may lead to more neutral postures that may reduce biomechanical loads and muscle exertions. In addition, video displays do not require microscope eyepieces that constrain surgeon posture constraints, and this may explain the higher number of posture changes that have been reported as a key mechanism for reducing fatigue during surgery (Park et al. 2010). However, subjects needed 66-110% more time to complete the skill tasks using the 3D video display than the conventional microscope (Chapter 3).

Although video displays improved postures, the performance trade-off may be unacceptable in the operating room. As a surgeon collaborator suggested, performance on the video display must be at least 80% as good as the microscope in completing the tasks described by the taxonomy. Microsurgery tasks described in the taxonomy was varied widely in terms of work goals and the necessary motion and visual feedback needed to accomplish these goals. For example, surgeons emphasized that driving the needle requires precise placement of the needle on the vessel (however, placement techniques may vary Table 5.1) and smooth arc motion to prevent tears to vessel walls (Pederson 2010). In contrast, tasks like “irrigate the field” that are frequently performed by the assisting surgeon may not require as much visual precision. Thus, a laboratory study (Chapter 4) was conducted to further determine the impact of visualization displays, task factors, and performance to identify the impact of displays in microsurgery tasks described by the taxonomy and identify strategies for implementing video displays in microsurgery practice.

Findings from Chapter 4 were observations that differences in performance times on video were only 6-12% slower for targets on the x (left/right) and y (fore/aft)-axes than the microscope; however, video was 26% slower than microscope for large for targets on the vertical z-axis (Aim 3). In addition to movement time, Chapter 4 also compared other performance metrics (i.e., distance moved, overshoot, and submovements) that may reflect mechanical stress of tissues. Specifically, video displays were better or not significantly different than loupes or microscope for other performance metrics like overshoot for targets on all axes and movement distance and submovements for targets on the x and y-axes. This illustrates that video displays perform comparably with other displays for targets on x and y-axes. However, key performance tradeoffs were observed from targets in the vertical z-axis. Subjects required more time per distance moved and more time per submovement to complete the targeting task while maintaining similar overshoot distances. Although findings on the impact of displays on posture and performances were limited to a laboratory setting (Chapters 3 and 4), the developed taxonomy (Chapter 2) may provide insight on how the laboratory findings apply in microsurgery practice (Figure 1.1).

5.2.3. Application of video displays in microsurgery practice

Findings from the studies in this work (Figure 1.1) identified both benefits and strategies to overcome limitations for the application of video displays into microsurgery practice. Linking the effect of movement axis with the tasks decomposed with the taxonomy (Figure 1.1), specific elements are predicted to have comparable performance on video displays as microscope. For example, “irrigate the field” and “evacuate” elements were frequently observed to not require precise movements in the vertical axis, and thus, may not be affected by the performance tradeoffs observed on the video displays for targets on the vertical z-axis. In contrast, the taxonomy can also be used to identify several elements that may be adversely impacted by video displays. For example, “drive needle” elements required complex motion in 3D space (e.g., the arc motion when driving the needle) and precise assessment of depth (e.g., distance to the vessel’s backwall) to successfully complete the suture. In addition, “align” vessel elements require precise positioning in 3D space of two vessels or vessel and needle drive together. Findings from the taxonomy and laboratory studies (Figure 1.1) suggest several potential strategies to overcome limitations of video displays.

First, tools can be designed or implemented to arrange the surgical worksite along the right/left and fore/aft planes where video performance is comparable to microscopes. In particular, the frame clamp discussed previously (Table 5.1) may be used to hold two vessel ends on the same plane and reduce the need for vertical maneuvers during “align” vessel elements. Second, microsurgery motions, vessel placement, or surgeon position can be adjusted to minimize motions in the vertical axis, and it is important to note that video displays may provide surgeons flexibility in selecting positions and also for improving comfort and performance. Third, tasks tested in Chapter 4 required movement from one hand; however, proprioception strategies (i.e., location of one hand in respect to the other) can provide additional cues that may further improve video performance. Finally, camera location and design warrants further investigation to identify whether oblique angles or other camera positions can further improve video performance. Although additional research is needed to investigate these strategies, this work provides a framework (Figure 1.1) for formulating and testing hypotheses on surgical outcomes and musculoskeletal stresses that can be used to improve microsurgery practice, posture stresses, and performance.

5.3. Future research directions

Building on the findings from this dissertation, several basic research areas are proposed: 1) extending the hierarchical task analysis to incorporate task flow among the surgical team in order to improve safety, reliability, and training of surgical procedures, 2) identifying additional surgical workplace risk factors, e.g., posture constraints and workplace layouts, that contribute to discomfort, fatigue, and musculoskeletal injuries for the surgical team, and 3) designing, implementing, and evaluating new equipment, workflow changes, and workplace redesigns that improve performance and prevent harm in the operating room.

Continuing with work in the operating room domain, the taxonomy developed in this dissertation (Chapter 2) can be extended to include patient factors and concepts from healthcare error analysis for improving the safety and reliability in surgery. For example, researchers have reported success categorizing workflow disruptions in cardiac surgery using the Human Factors Analysis Classification System (HFACS) to healthcare and systematically identify causes of surgical errors (Diller et al. 2013; ElBardissi et al. 2007). The categories of workflow disruptions and the HFACS framework can be integrated into the taxonomy developed during this dissertation to 1) systematically quantify and compare actions, methods, techniques, and other workplace factors that may affect the reliability and safety of surgical procedures and 2) link work factors to surgical outcomes and errors. In addition, the flexibility of the taxonomy may provide opportunities for looking beyond individual surgeons and extend to interactions in the surgical system that include the assisting surgeon, residents in training, scrub and rotating nurses, and anesthesiologist. This will extend the capability of the taxonomy to examine how interactions in the system can impact surgeon choices and potential for adverse events. The proposed research can lead to the identification of best practices, provide clinical evidence for surgical training, simulation, and assessment, and contribute towards the standardization of surgical procedures. The proposed research can have broader impacts for improving the safety and reliability in other surgical disciplines and extend beyond the operating room to other environments (e.g., hospitals, clinics, nursing homes) that can benefit from the identification of factors that impact performance and health.

In addition to investigating surgical techniques, it is also necessary to continue addressing the high prevalence of acute injuries, overuse injuries, and muscular fatigue among medical practitioners in the operating rooms and further investigate workplace solutions that may improve surgeon performance and surgical outcomes. Findings in this dissertation focused on alternative video displays and showed that video display improved surgeon postures, which may lead to reduce postural stresses during microsurgery (Chapter 3). Although video displays improved postures, task performance using the video display was significantly worse under task conditions where view targets line up with the viewing axis (Chapter 4). Based on these findings, further research is needed to investigate depth perception differences between video and microscope equipment and systematically test depth cues like convergence and occlusion on video displays to improve the performance of stereoscopic displays for surgery. In addition, work is needed to explore other equipment and workplace redesigns to reduce the physical work demands and factors that impact performance of the surgical team.

The long term goal of this research direction is to further expand and improve the framework for describing surgical procedures, measuring performance, and identifying ergonomic factors that can affect outcomes and musculoskeletal stresses. Application of this work can be used to improve outcomes for both patients and medical practitioners during surgical procedures.

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