UNIVERSITY OF CENTRAL OKLAHOMA

Edmond, Oklahoma

Jackson College of Graduate Studies

Comparative Analysis of Techniques for Shooting Trajectory Reconstruction

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

In partial fulfillment of the requirements

For the degree of

MASTER OF SCIENCE IN FORENSIC SCIENCE

University of Central Oklahoma

Forensic Science Institute

December 2012

Comparative Analysis of Techniques for Shooting Trajectory Reconstruction

Kiersten Finkle

A THESIS
APPROVED FOR THE W. ROGER WEBB FORENSIC SCIENCE INSTITUTE

December 2012

Dr. Mark R. McCoy Committee Chair

Mr. Deion Christophe Committee Member

Dr. Christopher O'Brien Committee Member

Dr. Thomas Jourdan Committee Member

Abstract

Shooting trajectory reconstruction is a common discipline in the field of crime scene reconstruction. This discipline, however, has minimal published history about the origin, the most valuable techniques and methods, or journal articles. In addition, this type of reconstruction is used on a daily basis by law enforcement, but there is no validation of its procedures or tools. This study advanced the knowledge of the discipline of shooting trajectory reconstruction by applying geometric principles and modern day crime scene reconstruction techniques to help with the history of the discipline. Through the use of comparative analysis, this project determined beneficial and hindering aspects of modern tools. This was accomplished by analyzing three shooting scene reconstruction tools; specifically use of the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper to determine the efficiency of each technique. This project examined data taken by participants and determined the accuracy, precision, and error rate for the three tools. The study provided law enforcement with research enabling them to choose the most effective tool for crime scene analysis based on the tools tested in this project. This research also began the process validating the discipline of shooting trajectory reconstruction.

A statistically significant difference in accuracy (mean bias) and precision (standard deviation) was found between the three tools. The difference between the accuracy and precision for the Smart Tool™ and angle finder was not statistically significant, however, the difference between those two tools and the digital caliper was significant. This difference between tools means that they cannot be averaged together when calculating results from a crime scene. No statistically significant difference in accuracy or precision was found between examiners and students, independent of the tools. Results indicate the angle finder was the most efficient tool tested. There was a statistically significant interaction found between the impact angles tested in this project. This interaction makes an overall error rate for the tools or discipline impossible.

Keywords: Shooting Trajectory Reconstruction, Crime Scene Reconstruction, Shooting Incident Reconstruction, Trajectory Rods, Smart Tool™, Angle Finder, Manual Calculations, and Digital Caliper.

Acknowledgements

I would like to thank my committee members, Dr. Jourdan and Dr. O'Brien, for having such wonderful suggestions and ideas to help better the thesis paper and project as a whole. You were both able to look at the thesis with a fresh perspective and spot areas for improvement.

A BIG thank you goes to Dr. Morris and Dr. Murray for all of your tireless efforts with the statistics for this project. They quickly became much larger than anyone anticipated, but you both stuck in there until the end. You worked with the committee and myself to make sure we had all of the information that we needed and that it was completely understood. I could not have asked for a better team to help with this part of the project. Thank you!

I want to thank Dr. McCoy for making sure I crossed all my t's and dotted all my i's. You were there to make sure the plans made were sound and that everything was followed through as planned. Mr. Christophe, I want to thank you for all of your wonderful support both academically and personally. You are someone who will always be there when help is needed. You were there every step of the way of this project, and ensured its success; without your help and knowledge this project would not have worked out as well as it did. To both of you, this thesis has been a wonderful project and experience. It has been a long journey that seemed to change constantly, so I thank you both for being with me through this entire process. You both kept me sane and calm and answered the thousands of questions I came up with along the way.

To my friends and family, thank you for putting up with me as I constantly talked your ear off with new information from the project and told you more than you ever wanted to know about ancient geometry and reconstruction!

To my loving parents, I can’t begin to thank you enough for all that you have done and given me over the years. I would not have accomplished all that I have or be the person I am today if it was not for you. You were there to congratulate me on the ups and push me through the downs. You have always been there for me, and I know you will always be there for me in the future. Thank you so much and I love you both!

TABLE OF CONTENTS

TABLE OF FIGURES AND TABLES

Introduction

Over the years, criminal activity and strategy have become increasingly complex and more frequent, leaving law enforcement striving to evolve and keep up (Felson, 2006). One of the many ways law enforcement combats crimes is through investigative analysis, aided by crime scene reconstruction. One area of reconstruction is shooting trajectory reconstruction. This discipline utilizes basic geometric theorems and postulates to help generate a model of what most likely occurred at the time of the incident. Shooting trajectory reconstruction has a myriad of techniques and tools available for reconstructing shooting scenes and determining bullet trajectories (Haag, 2006). Investigators use these techniques and tools to estimate shooter locations and bullet impact angles at crime scenes.

The use of trajectory rods and shooting trajectory reconstruction to find the approximate location of the shooter(s) is an established technique, but the discipline has limited history and validation for the basis of its daily procedures and techniques. Shooting trajectory reconstruction is not held to Daubert challenges, however, owing to the fact that the geometric principles used for reconstruction are proven. Due to the daily use of these principles, the courts recognize the reconstruction procedures (Hueske, 2006). These methods are used on a regular basis by law enforcement and criminalists to reconstruct shooting incidents, yet there have been few comprehensive studies to determine the accuracy, precision, and error rates of the discipline and its tools (Haag, 1976; Garrison, 1996).

Various studies have been completed in the area of shooting reconstruction, yet many have focused on isolated cases or single tools as opposed to the discipline as a whole (Houde, 1991; Warren, 1991). With the available literature lacking historical and validation studies, investigators have a difficult decision as to what is the most effective technique or tool. This has led some law enforcement officials to use multiple tools and average the results together, instead of relying on one tool (Parker, 2005).

By compiling reconstruction techniques in this manner, technicians lose valuable time, limit themselves from utilizing other resources, and sacrifice the accuracy and precision of using one tool. This study provides law enforcement and other investigators with data to assist in the selection of a trajectory reconstruction tool based on its efficiency and overall performance to save time and effort when reconstructing scenes.

Statement of the Problem

This study addressed three issues in shooting trajectory reconstruction. The first issue was the lack of history and foundation for shooting trajectory reconstruction. The second issue was to begin the validation process of this reconstruction area. The last issue was to find the most efficient tool for law enforcement and crime scene technicians.

The issues of a lacking foundation and validation for the discipline of shooting trajectory reconstruction go hand in hand. Validation comes from detailed testing of a process and knowing what the possible accuracy and precision rates are for that process, along with any known or potential error rates. This, however, is not possible if research has not been done on a large scale for the process; this is what has happened to shooting trajectory reconstruction. Without this research and foundation, those testifying to these methods in court may find it difficult to defend themselves and their actions at a scene.

The issue of inefficient tools being used by reconstructionists creates a waste of time and resources for the reconstruction team and department. The department may lose money due to the accumulation of expensive and often unnecessary tools. If reconstructionists do not value these tools or know the proper way to use them, then this could possibly lead to crime scenes being improperly analyzed. While talking to reconstructionists in the field, there is a common practice is to measure impact angles at a scene with multiple tools and average the results together. This process wastes time by redoing time consuming processes. More importantly, the impact angle measured is not going to be as accurate as a measurement taken by one tool. In addition, if there is one distant measurement taken from a tool in the group, this can skew the end determination and change the reconstruction of the scene significantly. This change could be the difference between two suspects of close heights or the distance between suspects to the victim.

Background of the Research

Shooting trajectory reconstruction is crucial for investigating crime scenes involving a firearm. By following the established protocols and using rudimentary geometry, the angle of the shot(s) and a range of the shooter's or shooters' location can be estimated (Haag, 1976; Trahin, 1987). Shooting trajectory reconstruction is used to demonstrate what may have occurred at a crime scene based on analysis of the physical evidence found (Garrison, 1993).

There are often misconceptions that shooting scene reconstruction can recreate an entire shooting incident, but in reality, a reconstruction can only be created for the instant that a projectile was fired. Incidents before and after the projectile was fired can be speculated, but only the instant of firing can be truly estimated. In order for an impact angle to be determined, a trajectory rod is placed through the impact hole and a measuring device is placed on the rod at the entrance of the impact hole. The impact angle can then be calculated by reading the instrument or using geometric principles to help recreate the incident. Also crucial in reconstruction is the taking of numerous photos and detailed measurements of all aspects of the scene.

Often in a scene, an impact hole does not completely go through a double paneled surface, leaving only one hole. In cases like this, a trajectory rod cannot be used; instead, measurements of the hole must be taken instead. The length and width of the impact hole are taken and inserted into the equation: "IMPACT ANGLE = arcsin (Width/Length)" (Fischer, in James 1999, p. 2). The measurements can then be collected using a ruler or caliper.

Shooting trajectory reconstruction requires exact measurements to occur in order to accurately depict the scene during the shooting incident. It is for this reason that criminalists need to be able to say with confidence that the tool they are using is the best possible choice. When a few degrees can change a scene completely, having a tool with high accuracy and precision rates and low error rates is crucial.

Purpose of the Research

The purpose of this study was to systematically test the accuracy, precision, and error rates for the Smart Tool™, angle finder, and manual calculations with a digital caliper when used by shooting reconstructionists, of varied experience, to determine shooting trajectories. The study will begin the process of validation for the discipline of shooting reconstruction and provide quantitative and qualitative data for practitioners to use in making decisions on which technique to use when calculating bullet trajectory angles.

Research Questions

This study proposed multiple hypotheses and questions to be answered.

H_0: There is no difference between the precision rates of the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper.

H_1: There is a difference between the precision rates of the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper.

H_0: There is no difference between the accuracy rates of the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper.

H_1: There is a difference between the accuracy rates of the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper.

H_0: There is no difference between the examiners and students using the Smart Tool™.

H_1: There is a difference between the examiners and students using the Smart Tool™.

H_0: There is no difference between the examiners and students using the angle finder.

H_1: There is a difference between the examiners and students using the angle finder.

H_0: There is no difference between the examiners and students using manual calculations utilizing a digital caliper.

H_1: There is a difference between the examiners and students using manual calculations utilizing a digital caliper.

What are the error rates for the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper?

What are the participants' experience and confidence levels with the tools?

What tool is preferred by the participants?

Significance of the Research

This study indicated the more efficient tool for law enforcement to help save time and resources when analyzing a crime scene. Reconstructionists will have the knowledge of whether the tool they are using is accurate, precise, and user-friendly. In addition, this study served as the beginning to validating this discipline of expertise. Recently, there has been a new push in forensic science to make every discipline and field of expertise validated, accredited, and carried out through sound scientific methods. This has been further emphasized by a study by the

National Academy of Sciences (NAS) on forensic science in the United States (Strengthening forensic science, 2009). Although this study did not examine crime scene reconstruction, it was found that the field of firearms had “no statistical foundation for estimation of error rates” (Strengthening forensic science, 2009, p. 154). The field was also found to have a lack of standard definitions and protocols. These findings directly apply to the discipline of shooting trajectory reconstruction. This study considered variations in measurement and comparative analysis coupled with statistical models to help aid in some of the errors found by the NAS report.

This study also provided a brief historical progression showing how crime scene and shooting trajectory reconstruction originated. The historical background addresses ancient geometric principles through 20th century geometry and shows the connection to the history of bloodstain pattern analysis. Difficulties arise in saying a technique is valid or should be trusted when limited data supports where or how that technique originated. This is especially crucial, yet troubling, when it comes to examiners testifying to reconstruction methods in court. This study allows reconstructionists to say with confidence that a certain technique came from a geometric law/principle or from the well tested and proven scientific principles of bloodstain pattern analysis.

Limitations of Study

The impact holes in this study were created by a power drill and bit of known diameter instead of a wall being fired upon by a gun. This change from a crime scene is crucial because the accurate measurement of a hole’s angle was utilized in order to determine the accuracy of the volunteers’ measurements. A ransom rest was not incorporated because in a similar study, unsteadiness in the shooter caused complications in determining the aiming point when the experiment was carried out at 100 meters (Nennstiel, 1991). In addition, if impacts in the walls were created through firing a gun, then the impact angle would be unknown at a specific level and would have to be determined by another method; thus adding another variable and human error into the project. With power-drilled holes, an exact and precise angle could be established and measured. Although, the variation in measurements would be small based on factors such as bullet composition and design or surface mediums, research indicated that studies of this nature will not work without a known angle to refer back to (Trahin, 1987).

In addition, the trajectory rods selected fit perfectly into the impact holes, so there was no chance of fluctuating or a misreading. This was not similar to fieldwork, but necessary to the project. If the participants were asked to place a poor fitting trajectory rod into the impact hole and read the angle, the project would then be testing the participants' ability to correctly place the trajectory rod and not the tool's ability to obtain the measurement.

Review of the Literature

There is minimal published literature for the discipline of shooting trajectory reconstruction, but there is ample history for geometry and bloodstain pattern analysis. The history and published studies associated with these two disciplines can be used to determine where various aspects and techniques of shooting trajectory originated. Both of these fields have a rich past and are the driving force behind the main aspects that make reconstruction possible.

The first section of the literature review looks back at those that started the field of crime scene reconstruction, showing how the field moved from theory to practice. The next section examines how the field of bloodstain pattern analysis began, from experiments at the beginning of the century to methods used today. This section also looks into geometric principles and theorems associated with both bloodstain pattern analysis and shooting trajectory reconstruction. This section follows the progression from ancient postulates to common day geometric principles. The last section gives a brief overview of the various aspects involved with shooting trajectory reconstruction.

Crime Scene Reconstruction

Reconstruction, as defined by the Association for Crime Scene Reconstruction (ACSR), is “the use of scientific methods, physical evidence, deductive and inductive reasoning, and their interrelationships to gain explicit knowledge of the series of events that surround the commission of a crime” (Bevel & Gardner, 2009, p. 1). Unlike most fields of science that work forward to solve a problem, reconstruction uses reductionism. This means the analysis of a scene works from the evidence backwards to the beginning of the incidence, a form of reverse engineering.

Crime scene reconstruction truly got its beginning with the “father of criminal investigations” (Bevel & Gardner, 2009, p. 4) Hans Gross in 1898. He was the first to talk about the analysis of a crime scene and look deeper into physical evidence and what it can tell investigators. He also stressed the dangers of relying on testimonies from witnesses and not on facts from the scene (Bevel & Gardner, 2009). In 1933, Luke May published *Scientific Murder Investigation* stating the importance of connecting the random pieces of scene together to make one incident. He also warned against developing a theory of what occurred at a scene and developing tunnel vision towards the evidence and other theories about the scene. May believed that to be a good investigator, one must have the ability to continue work until all possible pieces of evidence are collected and have the ability to change one's theory of what occurred at the scene as new evidence surfaces (May, 1933). Also printed that year was *Clues and Crimes* by Henry T. F. Rhodes. This book stressed the need to determine the order of events and how the crime occurred, putting special emphasis on the scientific method as the basis for investigation. These practices are the basics still followed today in any modern reconstruction (Bevel & Gardner, 2009). This thought was continued by Edward Oscar Heinrich, the "Wizard of Berkeley" (Bevel & Gardner, 2009, p. 6) throughout the early 1900's. Heinrich added to these beliefs and fully explained the theories of crime scene reconstruction.

The 1960's brought a change from theorists and general beliefs to police officers with specific facts and procedures. In 1965, Charles O'Hara published *Fundamentals of Criminal Investigation*, which included a detailed process for analysis of a scene based on the scientific method (O'Hara & O'Hara). In 1984, William Chisum and Joseph Rynearson published their book *Evidence and Crime Scene Reconstruction*. This book helped to bridge the gap between general theory and specific pieces of evidence found at crime scenes. Chisum and Rynearson stressed the making pathways and scenarios to help explain possible event steps for a scene (Rynearson & Chisum, 1989).

They identified three crime scene relationships:

1. Predictable effects
2. Unpredictable effects
3. Transitory effects

(Bevel & Gardner, 2009, p. 7)

Examples of predictable effects are those effects known to happen to the body after death, such as the three mortises. These effects follow established timelines, thus allowing the reconstructionist to have better knowledge of the timing for the events. Unpredictable effects are just that, they are those events that cannot be planned or foreseen. These can be effects to the scene by first responders or evidence destroyed or altered by evidence collectors. Lastly, transitory effects are those events or evidence that are fleeting. These can be as simple as the temperature in the scene at first arrival or smell like cigarette smoke or perfume. How these three effects and other events come together create great influence on how an analyst reconstructs a scene (Bevel & Gardner, 2009).

The change from general theories to actual methods of reconstruction continued into the 1990's with Dr. Henry Lee, Ross Gardner, and Tom Bevel. In 1992, Dr. Lee wrote *Crime Scene Investigation,* following that up in 1999 with *Henry Lee's Crime Scene Handbook.* In both of these writings, and through his work as a crime scene analyst, Dr. Lee stresses the importance of using the scientific method as a systematic way to move through a crime scene investigation (Lee, 2001). Bevel and Gardner created a new way to do this in 1997 with their "Event Analysis" (Bevel & Gardner, 1999, p. 8). This analysis was completed using the analogy "PhD etc" (Bevel & Gardner, 2009, p. 74). Investigative questions can be answered by finding the "Problem, Hypothesis, Data, Expectations, Test, and Conclusion" (Bevel & Gardner, 2009, p.

74). This process goes around cyclically until the ultimate solution becomes clear. To begin, it is important to identify the problem, what question is actually being answered. Next, a hypothesis is created that attempts to explain the events that have occurred. To complete the hypothesis, data is collected from the scene that relates back to the question being posed. Then the hypothesis is examined, seeing what would be expected and not expected if the hypothesis was true. When analyzing a scene, a reconstructionist must look at every angle, making sure to realize the cause and effect of the actions found in a scene. Once a hypothesis is selected, it is important to think about what factors should be found at the scene for the theory to be true. If these factors are not present, other directions for what occurred must be followed. Next, the hypothesis is tested against the data present at the scene to see if they match. Finally, a conclusion is created that says whether or not the question at hand has been answered, or if a new hypothesis must be created to explain the data present. This process has become a staple in the crime scene reconstruction process. It is especially crucial when a scene has multiple questions to answer, when the evidence does not have a clear meaning, or there is little evidence left behind (Bevel & Gardner, 2009).

Bloodstain Pattern Analysis

Shooting trajectory reconstruction inherited its techniques and procedures from the methodology associated with bloodstain pattern analysis. This analysis is a helpful tool in crime scene reconstruction; it seeks to determine what occurred in crime scenes by examining physical blood evidence left behind. Bloodstain pattern analysts are able to determine various aspects such as; type of weapon used, expected distance from the target to the first drop of blood, respective positioning of suspect(s) and victim(s), and the angle and direction the stain(s) was or were traveling (Bevel & Gardner, 2001). This similarity of information being obtained from the crime scene allows bloodstain pattern analysis to transfer its techniques and methods smoothly into shooting reconstruction.

Bloodstain pattern analysis has a long and rich history. "Perhaps one of the most impressive treatises written on the subject of bloodstain pattern analysis is…*Concerning Origin, Shape, Direction, and Distribution of Bloodstains Following Blow Injuries to the Head*, written by Eduard Piotrowski of the University of Vienna in 1895" (Bevel & Gardner, 2001, p. 5). Dr. Piotrowski reconstructed entire crime scenes, controlling different variables in order to determine the actions that transpired. He often used rabbits to recreate the bloodstain patterns he saw at a scene; assuring himself that all conceivable events and their effects were accounted for by numerous strikes against the rabbits. Through these experiments and reconstructions, he discovered basic concepts of bloodstain pattern analysis; including, using the tail end of a stain to determine its direction or origin, appearance and causes of cast-off, and how the parabolic arc affects a bloodstain pattern. Dr. Piotrowski compiled this information to determine the weapon used and what direction it was traveling (Bevel & Gardner, 2001).

The 1900's were a groundbreaking time for the field of bloodstain pattern analysis. In previous years, the science was just beginning and new theories and hypotheses were being tested, but in this new dawn, the basic laws and theories of this field were formed. Also emerging during this time-period are the fathers of bloodstain pattern analysis, such as Dr. Victor Balthazard, Dr. Paul Leland Kirk, and Herbert MacDonell.

In 1939, Dr. Victor Balthazard, R. Piedelievre, Henri Desolille, and L. Derobert changed bloodstain pattern analysis forever when they presented one of the most perceptive articles about the field. The article stated the main reason for "research was to pinpoint characteristic elements of a bloodstain which might 'give decisive hints' as to its origin" (Bevel & Gardner, 2001, p.

13). Balthazard et al. realized the need to understand the basic dynamics of blood droplets, such as exit manner, changes in flight, and trajectory. They also saw the importance of determining the point of origin of the incident for understanding what occurred at the time of the incident. He, like Dr. Piotrowski, often created real injuries like those experienced in crime scenes, through the use rabbits. In the end though, Balthazard's biggest addition to the field was the beginnings of bloodstain pattern analysis's and shooting trajectory's most basic law: that there is a connection between the angle of impact and a particular stain's length-to-width ratio. This meant a measurement of the stain could lead to the angle of impact.

Another major breakthrough for blood spatter reconstruction came with Dr. Paul Leland Kirk's affidavit in the *State of Ohio v. Samuel Sheppard* case in 1955 (James, 1999). Dr. Kirk was a professor of biochemistry and criminalistics. He used this knowledge to aid various law enforcement departments from 1935 to 1967. Two of his main areas of research were in studying the formation/causes of blood trails and drying time for bloodstains (Bevel & Gardner, 2001).

Also occurring in 1960 was the work of Dr. Jozef Radziki of Warsaw, Poland. His definitions are still used today in modern bloodstain pattern analysis.

> Dr. Radziki established three basic groups of bloodstains based on their mechanisms of creation.
>
> 1: Bloodstains resulting directly from extravasation – drops, gushes, and pools of blood
>
> 2: Bloodstains resulting from the application of various instruments
>
> 3: Bloodstains resulting from the wiping or removal of blood

Dr. Radziki also stressed the importance of looking at what surface the blood droplet hit due to the significant difference it made in a stain's appearance, size, and shape. (Bevel & Gardner, 2001, p. 15).

A revival of bloodstain pattern analysis was seen after Dr. Kirk's work in the 1960's and into the efforts of Herbert MacDonell following him. Many people see Mr. MacDonell as the "father of modern bloodstain pattern analysis" (Bevel & Gardner, 2001, p. 15). In fact, it was MacDonell with the help of Bialousz, in a 1971 paper, who found a repeatable correlation between the length-to-width ratio of a bloodstain and the angle at which the stain hit a fixed surface that could then be estimated. The equation they formulated for this correlation was: "IMPACT ANGLE = arcsin (Width/Length)" (Fischer, in James, 1999, p. 2). Now, the exact equation was found to calculate the angle of impact using only measurements of the stain and trigonometric functions.

Typically, the credit for discovering the relationship between the length to width ratio and how it is used to calculate the impact angle is given to Dr. Victor Balthazard. On the other hand, Herbert MacDonell is credited with continuing this theory and adding the math function sine to the equation; this allows geometric techniques to be used in the calculations (Bevel & Gardner, 2001). This equation is crucial to reconstructionists because with an impact angle they can estimate where an offender was during the crime (Fischer, in James, 1999). This equation can be readily applied to well-formed stains with ease. The definition of a well-formed stain is one that can be bisected length or width wise to form nearly perfect equal halves (Bevel & Gardner, 2001).

Bloodstain pattern methodology

While working a crime scene, it is possible to calculate the approximate origin of a bloodstain based on three variables:

I: Using the width to length ratio of various bloodstains

II: Measuring the distance to the intersection point, a universal point for the bloodstains

III: Measuring the distance to the point of origin for each bloodstain

(Fischer, in James, 1999).

Due to the trigonometric functions of sine, cosine, and tangent, and the association between a right triangle and its sides, reconstructionists are able to apply the impact angle formula and use right triangles to make calculations in their crime scenes, just as in shooting trajectory reconstruction (Bevel & Gardner, 2001). Analysts can estimate the angle of impact of a stain by creating a ratio of the measured width and length of the stain; the length being the long axis of the stain, where the width is the narrow axis of the stain. They will then use the simple "trigonometric formula: Sine of Impact Angle = Width of bloodstain/ Length of bloodstain" (Lee, 2001, p. 284 - 285). Bloodstain pattern analysts, looking at the diameter of a droplet, are able to determine the approximate height a blood drop fell due to one simple rule, "the diameter of the resulting circular stain will remain constant" (Lee, 2001, p. 284). Another method of determining the approximate angle of impact is to look at the overall shape of the droplets. The droplets will become more elliptical in shape as the angle of impact decreases to a more acute angle; this effect being identical to how trajectory angles work in firearms. The direction of travel is also aided by the drops for "the 'tail' of the bloodstain generally points to the direction of the travel of the blood drop" (Lee, 2001, p. 284). In addition, a tie can be made between the length of a bloodstain and the hypotenuse of right triangle, and the width of the bloodstain and the adjacent side (Bevel & Gardner, 2001).

Geometric Principles

Classic history

To better understand how the discipline of shooting trajectory reconstruction developed, it is necessary to delve into the past and discover how the basic geometric theorems and postulates were created in earlier times. Geometry has a diverse and rich history, which originated in 3100 B. C. within the Mesopotamian region. It was in this region around 3000 B.C., that the first documented evidence of early geometry was discovered in the form of engraved clay tablets. The Egyptians, however, are credited as being the true founders of modern day geometry, which they transformed into “scientific geometry” (Eves, 1963, p. 3). Ancient Egyptians understood “that a triangle having sides of lengths 3, 4, and 5 units is a right triangle” (Eves, 1963, p. 5). Additional data supporting the extent of Egypt’s contributions to geometry can be found thousands of years later in the Moscow and Rhind Papyri, dated roughly at 1850 B.C. and 1650 B.C., respectively. These two documents are sheets of papyrus containing mathematical problems and of the 110 combined problems, 26 are associated with geometric problems. It is believed that these mathematical problems were developed in response to the Egyptians’ commitment to better organize their land and storage systems (Eves, 1963).

The next influence on geometry was the Greek culture. The Greeks advanced the study process out of the testing rooms and into the research rooms; this change in thought processes created the “mathematical” (Eves, 1963, p. 10) geometry we know today. The majority of history from this time-period comes from the *Eudemian Summary* of Proclus. The *Eudemian Summary* begins its Greek history in early sixth century B. C. with Thales of Miletus. He became the first to use the deductive method, which forms the basis for geometry, when he journeyed to Egypt and brought back all he learned and applied the Greek philosophy of deductive thinking. Thales of Miletus was able to take geometry based on organizing lands and other functional purposes and transform them into arguable, provable theories. This application of deductive thinking and change of geometry purpose made geometry what it is today (Eves, 1963). The importance of Thales' work is best described by D. E. Smith when he says, "Without Thales there would not have been a Pythagoras – or such a Pythagoras; and without Pythagoras there would not have been a Plato – or such a Plato" (1958, p. 68).

The next name of interest in Greek history is the infamous Pythagoras. Born on Samos in 572 B. C., he continued the groundbreaking work of the Thales of Miletus with the creation of the Pythagorean School. This scholastic brotherhood focused on "the study of philosophy, mathematics, and natural science" (Eves, 1963, p. 11). This significant school influenced Plato and held an impact over the rest of Greek philosophy and mathematics (Wallace & West, 1992). It was this brotherhood that "developed the properties of parallel lines and used them to prove that the sum of the angles of any triangle is equal to two right angles" (Eves, 1963, p. 11). This basic concept is the crucial step for any shooting trajectory reconstruction to be possible.

A groundbreaking stride for geometry came in 300 B.C. with Euclid and his book *Elements.* This book is "a single deductive chain of 465 propositions neatly and beautifully comprising plane and solid geometry, number theory, and Greek geometrical algebra" (Eves, 1963, p. 12). The Greek civilization gave the world a multitude of intellect, but none more important and unprecedented than this collection. Sir Thomas L. Heath explains it best when he said, "Euclid's work will live long after all the text-books of the present day are superseded and forgotten. It is one of the noblest monuments of antiquity" (1956, pp. vi - vii). The magnitude of this collection does not come from Euclid's theorems, for none actually belong to him, but in his logical organization of all the known geometry for this time. Euclid's theorems for his system were established on facts, which he called "axioms or postulates" (Blumenthal, 1961, p. 2). He had no actual proof for any of them, but used these facts to build up his system.

The Elements book contains five postulates that Euclid based his deductive system on. His five postulates are as follows:

I: A straight line may be drawn from any point to any other point.

II: A finite straight line may be extended continuously in a straight line.

III: A circle may be described with any center and any radius.

IV: All right angles are equal to one another.

V: A finite straight line may be extended continuously in a straight line. If a straight line meets two other straight lines so as to make the two interior angles on one side of it together less than two right angles, the other straight lines, if extended indefinitely, will meet on that side on which the angles are less than two right angles.

- Meaning of Postulate 5: If two triangles have two sides equal to two sides respectively, and have the angles contained by the equal sides equal, they will also have their third sides equal, and their remaining angles equal respectively: in fact, they will be congruent triangles. (Coxeter, 1961, pp. 4 - 5).

It is the fifth postulate, which talks about parallel lines, right triangles, and congruent triangles that gives shooting trajectory reconstruction one of its main bases.

Most of the concepts and principles that the Greek nation gave us was already known or hypothesized by earlier cultures, such as the Babylonians, the Orient, and Egypt, but it was the

Greeks that advanced this knowledge and transitioned it into a more deductive style of thinking that we use today (Eves, 1963).

Modern history

The School Mathematics Study Group (SMSG) was created in the early 1960's to aid the United States in the worldwide competition of mathematics and science. While completing this task, they continued Euclid's work by adding on axioms to his collection. These axioms and additions are studied in classrooms around the United States and form the basis for calculations in shooting trajectory reconstruction (Wallace & West, 1992). Although the list compiled by the SMSG for Euclid's postulates and other geometric theorems is lengthy, there are a few that stand out above the rest as the main foundation for the field of reconstruction:

THEOREM 3.4.1: *Alternative Interior Angle Theorem.* If two lines are intersected by a transversal such that a pair of alternate interior angles formed are congruent then the lines are parallel.

COROLLARY 3.4.4: If two lines are intersected by a transversal such that a pair of interior angles on the same side of the transversal are supplementary, then the lines are parallel.

THEOREM 3.4.9: The Euclidean parallel postulate is equivalent to the following statement. Given Δ PQR and any line segment AB, there exists a triangle having a side congruent to AB that is similar to Δ PQR.

THEOREM 3.6.18: The Euclidean parallel postulate is equivalent to the following statement: The angle sum of every triangle is 180˚. (Wallace & West, 1992, pp. 95 - 96).

A complete list of geometric additions related to Euclid and the geometry principles associated with shooting trajectory reconstruction is listed in the appendix.

Shooting Trajectory Reconstruction

Shooting trajectory reconstruction is crucial for investigating crime scenes involving a firearm. By following the established protocols and using rudimentary geometry, the angle of the shot(s) and a range of the shooter's/shooters' location can be estimated (Haag, 1976; Trahin, 1987). Shooting trajectory reconstruction is used to demonstrate what may have occurred at a crime scene based on analysis of the physical evidence found there (Garrison, 1993).

Difficulties arise in reconstructing a scene involving moving people. It is sometimes difficult to say, with certainty, where an individual moved to or from within a scene. Shooting trajectory reconstruction assists with this difficulty by determining where a person was at a certain point in time during the scene. With an estimated trajectory, reconstructionists can consider whether the shooter or victim was standing, sitting, or walking away, but only at the time the weapon was fired. Information about what happened before or after this time cannot be determined, only estimated (Clemens, 1998; Garrison, 1993).

Shooting trajectory reconstruction is best applied to find the impact angles and approximate locations of people present within a crime scene. The process generally starts with trajectory rods being inserted through impact sites throughout a scene.

> By marking the trajectory rod at the entry surface and at the exit surface, the distance the bullet traveled through the object may be measured. This distance then forms the hypotenuse of an imaginary right triangle used to calculate the associated angle desired.
>
> (Hueske, 2006, pp. 69 - 70)

This concept becomes useful when the shooting crosses through multiple areas, surfaces, or enters objects such as doors or walls. A good reconstructionist knows, trajectory rods are crucial to reconstructing and investigating crimes scenes that involve shooting incidents

(Garrison, 1996). In addition, when there is one bullet hole or trajectory rods are not available, the use of a mathematical equation is best to obtain the angle of impact. An investigator can estimate the angle of impact by using a ratio of the width of a bullet hole to its length in the equation:

$$\text{Sine of the impact angle} = \frac{\text{Width}}{\text{Length}}$$

(Hueske, 2006, p. 72)

Accurate angles of impact may not be determined from photographs of placed trajectory rods alone. Measurements can be taken from the scene and medical examiner reports to help aid in reconstruction. From scene drawings and autopsy reports, the use of geometric equations can assist reconstructionists in evaluating and substantiating the findings at a crime scene of proposed shooting trajectories (Trahin, 1987; Hueske, 2006). Reconstruction at this point becomes critical, and by using scaled drawings, reconstructionists can support/refute evidence in cases (Molner, 1970). Above all, “a cardinal rule in shooting reconstruction is that theories must be subjected to physical testing. It is never adequate to rely on theoretical information without ever testing it” (Hueske, 2006, p. 89). For this reason it is crucial to substantiate case findings with test fires using the same ammunition and weapon(s) found in the crime scene, whenever possible.

Although a forensic report cannot be completed on sight alone, it is possible to get a general feeling of a scene based on the repeated angles of projectiles. A bullet hole shaped as a nearly perfect round circle will indicate a 90˚, or nearly 90˚ angle of impact. On the other hand, an elliptical indentation indicates an acute impact angle, with the longer and thinner the elliptical imperfections indicating an impact angle of a smaller degree. When a bullet impacts the target surface, it will generally expand, to a various degree, based on the surface medium. This impact diameter will be larger than the bullet itself, with the difference in size being more distinct when the impact surface is more unyielding. This becomes more obvious with target surfaces, such as car doors, which are double paneled. Due to hitting two panels and the internal structures that may be present, exit holes will often be considerably larger and more irregular with expansion and exiting of fragments. Exit holes, compared to entry holes, will not have a shoulder when a bullet strikes through metal or wood (Hueske, 2006).

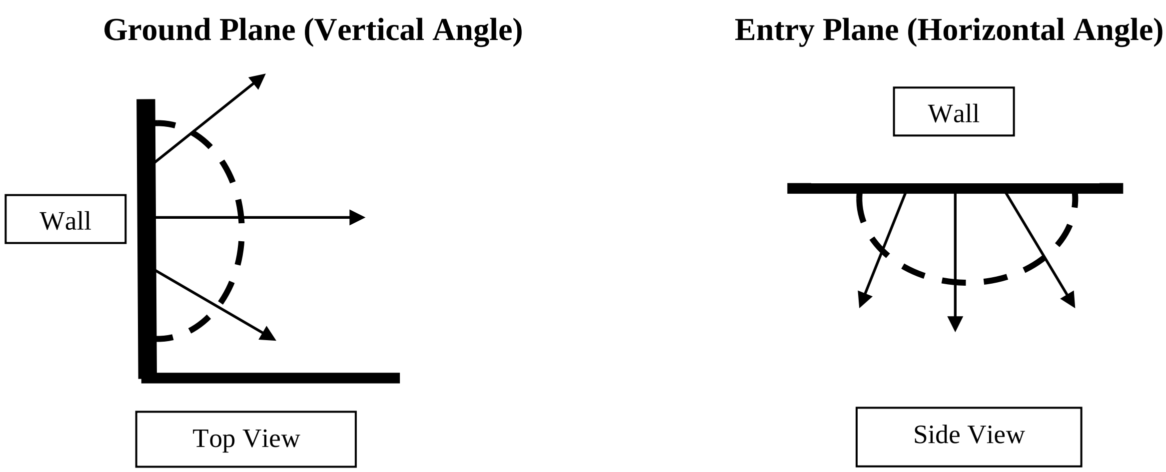
There are different paths for a projectile to take when striking a surface. They can "perforate (go all the way through an object), penetrate (enter and stay inside) an object, or ricochet off the surface they impact" (Noedel, in Bevel & Gardner, 2009, p. 152). Ricochets are also possible and are more common when the bullet comes into contact with a hard, non-elastic surface with a small degree of impact angle. Although a ricochet may cause difficulties in deciding the trajectory of the bullet and its origin, ricochets can sometimes help determine direction or class characteristics, such as a barrel rotation pattern or other patterns that show the travel direction (Noedel, in Bevel & Gardner, 2009).

Planes

Shooting trajectory reconstructionists break shooting incidents into two planes for calculation purposes: the ground plane and the entry plane, also known as the vertical and horizontal plane respectively. The ground plane is the angle of the shot in relationship to the ground, determining the height of the muzzle during the impact shot. There are three possible options for the shot angle: it can be downward from the shooter, upward, or parallel to the ground surface. This is commonly reported as the vertical angle. The second plane is the entry plane, which is the angle at which the projectile strikes the target surface. This determines the shooter location, to the right or left, of the impact hole. Again, there are three possible options for this angle, moving right to left, left to right, or straight on, which is horizontal with the ground. This is commonly reported as the horizontal angle (Trahin, 1987; Noedel, in Bevel & Gardner, 2009). Figure 1 below demonstrates how the planes appear in relationship to the floors and walls of a crime scene.

Figure 1

Reconstruction Planes



Calculations

There are a number of mathematical equations and terms that allow reconstructionists to complete their tasks for determining facts in a crime scene reconstruction. The equations use basic geometry in explaining how angles are determined and compute them into right triangles for further computations.

Impact angles are crucial to the set up and calculation of data from a crime scene, therefore it is important to know how to classify the angles found. A list of the angles used in reconstruction is found on the Definitions of Terms page. Trigonometric functions allow reconstructionists to relate the side lengths of a triangle to its internal angles. There are two constants allow reconstructionists to work with triangles: the internal angles of every triangle will equal to 180˚ and no matter the composition made, there will be a known ratio between the angles and sides of a triangle.

Three trigonometric functions allow reconstructionists to calculate the unknown elements at a crime scene and they are Sine, Cosine, and Tangent. The equations for calculating the functions involved with triangles are located in the Definition of Terms page. The inverse of sine, cosine, and tangent are called secant, cosecant, and cotangent, respectively (Trahin, 1987). These factors are purely mathematical and are not based on any data from a crime scene (Bevel & Gardner, 2001).

Trajectory rods

As previously stated, trajectory rods play a crucial role in obtaining the angles necessary for calculations used in shooting trajectory reconstruction. Trajectory rods are available in a wide range of compositions that are tailored to their usage. Aluminum and stainless steel rods are used by medical examiners to denote the path of a wound. Metal rods allow for easy care and cleaning, due to their direct contact with bodily fluids, but occasionally have too much weight to stay in a wound track by themselves. Glass rods can take care of this weight issue, but may be difficult to visualize when photographed and are fragile. It is not uncommon to see arrow shafts, tent poles, or other fiber glass (often colored) in a reconstructionist's tool bag. These rods are all light, strong, and readily available. Another common trajectory rod is a wooden dowel rod. Their commonality comes from the ease of use, wide array of diameters, and ability to be painted and water sealed to fit any situation that may arise. Reconstructionists also carry a number of accessories to assist them at crime scenes. There are centering cones (for when the hole is larger than the trajectory rod), connectors (allowing multiple rods to be attached for longer trajectories), and pointed tips (for ease of insertion in difficult objects, such as car seat backs). Usually, a crime scene technician will have a combination of these rods and others with various accessories to make sure they are prepared for any scene that may arise (Garrison, 1996; Lee, 2001; Hueske, 2006).

A wide assortment of trajectory rods is crucial because target surfaces can present various obstacles. Splintering may occur in the exit hole of plywood and certain other laminates. Metal and glass due to their structure can create irregular or sometimes oversized impact holes; where tires can, depending on caliber size, minimize the size of the impact hole. Padded items such as upholstered furniture and car seat backs can obscure holes from view. The most serious of these incidents, however, occurs with double paneled surfaces such as walls and car doors, which, due to internal structure and mechanisms, can change the course of the bullet from entry hole to exit hole (Hueske, 2006).

Techniques to obtain data

There are several methods for collecting the angles necessary to complete a reconstruction. One of the more common tools and methods utilized is a protractor and trajectory rod. To measure the horizontal angle (left/right component) the trajectory rod is place through both the entry and exit holes and the center of a standard protractor is placed at the bottom of the trajectory rod where it meets the surface and the angle is then read and recorded. To measure the vertical angle (up/down component) the trajectory rod is kept through the entry and exit holes, while the protractor is turned vertically, with the center at the point where the rod connects with the plane surface, the angle is then read and recorded (Noedel, in Bevel & Gardner, 2009). Also, as previously mentioned, when there is only one impact hole or trajectory rods are not available, an investigator can estimate the angle of impact by using a ratio of the width of a bullet hole to its length in the equation:

$$\text{Sine of the impact angle} = \frac{\text{Width}}{\text{Length}}$$

(Hueske, 2006, p. 72)

Known sources of error

There are many sources of error to be taken into account while working a crime scene. One of the main sources of error, deflection, occurs when an object passes through another object. There are various factors involved that determine the severity of the degree of deflection. These factors may be associated with the projectile, such as solidity, form, mass, momentum and stability in flight. There are also factors associated with the type of surface the projectile encounters, such as strength, characteristics of the surface, diversity level of materials in the surface and their orientation, along with their ability to give. These factors all play major roles in determining what the degree of deflection will be (Lee, 2001).

The largest sources of error, however, come from simply performing the tests needed to evaluate the crime scene. No matter how careful a reconstructionist performs their work, a degree of uncertainty exists when it comes to taking measurements. A reconstructionist's capability of repeating a measurement is called precision, where accuracy deals with the confidence level given to a measurement. Measurements with higher precision are those that can be repeated in the same manner multiple times and these are affected by the procedure used to carry out the measurements. A higher accuracy level comes from those measurements with lower levels of uncertainty and these are affected by the object itself that is being measured (Bevel & Gardner, 2009). It is often easier to understand accuracy and precision in the context of a target. Precision is the ability to hit the same place on the target repeatedly, where accuracy is how close the hit is to the actual target. An experiment with high accuracy and precision has values that were close to the target value and close to each other. An experiment with low accuracy and precision will have scattered values significantly away from the target value.

Summary

The forefathers of crime scene reconstruction truly brought the scientific method processes along with deductive and inductive reasoning into the process of analyzing crime scenes. Crime scene reconstruction exists today due to their tireless efforts and groundbreaking work. It was through these early strides that bloodstain pattern analysis was born. This allowed crime scene technicians to actually work through the bloodstains found at a crime scene as opposed to simply guessing at what occurred or ignoring them completely. Through the ancient postulates and theorems of geometry with the methods of bloodstain pattern analysis, was born shooting trajectory reconstruction.

Research Methodology

This study analyzed three reconstruction methods utilizing volunteers with practical knowledge levels from novice crime scene technicians to proficient shooting reconstruction examiners. Participants performed shooting trajectory analyses utilizing a Smart Tool™, angle finder, and manual calculations utilizing a digital caliper. The reconstruction was done similar to that in the field, as lined out by Trahin (1987), Parker (2005), Haag (2006), and Hueske (2006). Each hole was a different impact angle, encompassing large to small impact angles. The participants measured each impact hole three separate times for each method. The participants measured the five impact holes with one tool and then switched to the next tool. The process was then repeated until all five impact holes had been measured three times for each tool. Comparative analysis was then performed on the data compiled. This data was then statistically analyzed to establish error rates for the three tools and to determine which tool was most efficient for use in the field, based on accuracy and precision rates.

This study proposed multiple hypotheses and questions to be answered.

H_0: There is no difference between the precision rates of the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper.

H_1: There is a difference between the precision rates of the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper.

H_0: There is no difference between the accuracy rates of the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper.

H_1: There is a difference between the accuracy rates of the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper.

H_0: There is no difference between the examiners and students using the Smart Tool™.

H_1: There is a difference between the examiners and students using the Smart Tool™.

H_0: There is no difference between the examiners and students using the angle finder.

H_1: There is a difference between the examiners and students using the angle finder.

H_0: There is no difference between the examiners and students using manual calculations utilizing a digital caliper.

H_1: There is a difference between the examiners and students using manual calculations utilizing a digital caliper.

What are the error rates for the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper?

What are the participants' experience and confidence levels with the tools?

What tool is preferred by the participants?

Reconstructionists

This project utilized 17 students and 31 examiners. The participants' experience levels ranged from just beginning to learn the techniques of shooting trajectory reconstruction to 10 years of execution. Those that had experience with these tools have applied them in crime scenes, bloodstain pattern analysis, and traffic accidents. The use of participants with varying levels of experience had two benefits in this experiment. The first benefit was to ensure the tools' ease of use translates across the board and not just for experts or new trainees. The second benefit in using numerous participants was to generate larger data pools. These large data pools have rarely been done in experiments on this subject. Large data pool samples lead to better generalization of the population and serve as the building blocks for validating these techniques and this discipline.

The examiners were taken from local police departments and law enforcement agencies. They were employed in a wide array of positions including: investigators, state troopers, crime scene investigators, lieutenants, law enforcement officers, detectives, and patrolmen. The novice crime scene technicians were students from the University of Central Oklahoma's Forensic Science Analysis class, led by Mr. Deion Christophe. Participation from this class was voluntary and not a requirement for the class, nor was incentive given to participate. Although the novice examiners were all students, a few had previous experience with these tools due to past classes or jobs.

The identities of the participants were unknown to the researcher. A random number was assigned to be an identifier on data sheets. The researcher of this study was placed in the novice group and participated in the study as a blind volunteer. The angle values of the impact holes were unknown to the researcher, and volunteers, until the testing was complete. The researcher completed their testing before the other volunteers so data could be taken from the volunteers without biasing the researcher.

Experiment Tools

The Smart Tool™ and angle finder allow the user to estimate the angle of bullet impact, when there are two impact holes present. These tools were chosen because they are two of the most commonly used tools by examiners for reconstruction. In addition, both tools are available at many hardware stores.

The Smart Tool™ is a digital level that displays the angle in question in degrees, inches per foot, and percentage slope. According to the company, MD Building Products, the Smart Tool™ "is accurate to 1/10 of a degree and holds the best accuracy of any digital level on the market that MD has tested" ("Smarttool").

An angle finder is an instrument that allows for the measurement of an angle in a full 360˚. Unlike a compass, an angle finder does not relate to the earth's magnetic fields to determine the direction of travel, but instead rotates around to show the angle of the incline in degrees. It reads in four 90˚ sections as opposed to a full 360˚. The angle finder for this experiment was the EVI – PAQ™ Level and Angle Finder.

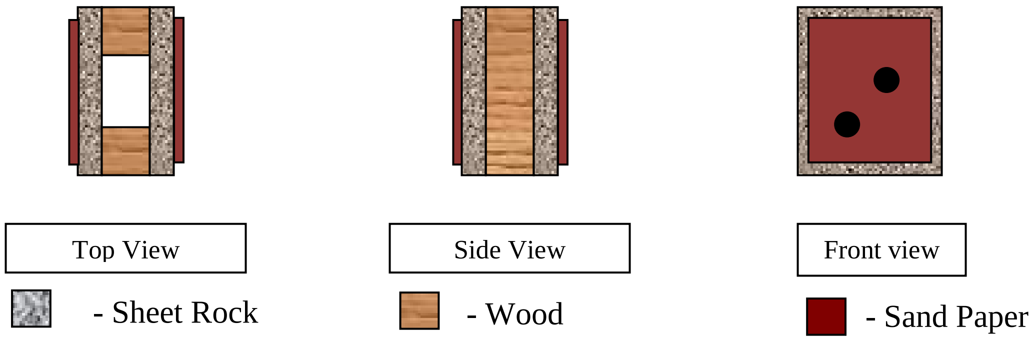
The manual calculation aspect of this study will be tested due to the incidents that arise where only one impact hole is made at a scene. Calipers are tools used to measure opposing sides of an object. They can be digital or analog, and can be simple tools or highly calibrated and accurate for extremely detailed work. A digital caliper was chosen for this project based on their ease of use and digital read out. The digital caliper used for this project was a Mitutoyo™ 700-126. The caliper has buttons to turn the device off, on/zero, and it has a button to change from inches to millimeter. Another feature of this caliper is the double edge, which allows the measurement of the outside and inside of objects. According to the company, Mitutoyo, the caliper has an accuracy rating of ± 0.005 inches ("Caliper").

Wall and Impact Angle Construction

The shooting trajectory reconstruction occurred on faux sheet rock walls with holes made by a power drill. These walls were 12" x 12" and constructed by layering a 2 x 4 (widthwise) between two pieces of sheet rock. The sheet rock pieces were covered by adhesive sand paper sheets to give the drilled holes structure and protection. Figure 2, below, more adequately demonstrates the walls' construction from all sides.

Figure 2

Wall Construction



This project used scientific principles and methods to show its application in casework. The project used faux walls, instead of floors or other surfaces, due to their commonality for reconstructionists at crime scenes. The faux walls were used versus real walls to compensate for the large number of impact holes being tested and the number of volunteers analyzing those impact holes.

The impact holes were created by a member of the University of Central Oklahoma's Physical Plant. He drilled two holes of the same angle into each of the five walls, for a total of 10 holes and 5 impact angles. A number was put next to one of the two holes to indicate order and which hole was to be tested. This ensured all the participants used the same hole and labeled their measurements with the same number. The impact holes were made by cutting a 2 x 4 with a table saw set to a specific angle and then drilling the holes with a power drill held next to the board. The impact angles were selected by the plant worker and were unknown to the researcher and volunteers. Both the researcher and participants conducted measurements on "unknown" angles and were not allowed to know the measurements calculated by the other volunteers, making this a blind study for all involved.

In order for the tools to measure the impact angle of each hole a trajectory rod will be used to aid in the process. The trajectory rods chosen for this project were aluminum arrow shafts. These were chosen for their durability over the entire project and ability to withstand bending or alteration. The holes were drilled with a diameter of .25 inches to accommodate the width of the arrow shaft selected. To minimize error, the trajectory rods were the same diameter as the holes drilled. This allowed for a tight fit without fluctuation, which can cause a false reading of the angle of impact. In the field, a reconstructionist may not have a trajectory rod the same diameter as the impact hole, so this aspect was not identical to field work. This change, however, was crucial to the statistical data of this project. The trajectory rods used must be the same size as the impact hole to minimize user error. This allowed the focus of the data to be on the error rates of the methods being tested and not the human error of rod placement by the reconstructionists. This error would not only show in the statistical data for the three methods, but also in the statistics between the examiners and student examiners.

Procedure for Collecting Data

The participants completed the examinations by following the method outlined in Trahin's article (1987), *Bullet Trajectory Analysis,* and guidelines from Mr. Deion Christophe's class "Forensic Science Analysis," found at the University of Central Oklahoma in Edmond, Oklahoma. The method used was as follows:

Step 1: The participant carefully placed the trajectory rod through the entry and exit holes.

Step 2: The participant then placed the measuring device (Smart Tool™ or angle finder) on the trajectory rod, on the entrance hole's side. They then recorded the tool's displayed value on the worksheets provided. Care was taken to wait until the tools had leveled out before recording the value.

Manual calculations: the participant set the digital caliper to inches. They then placed the caliper just into the edge of the impact hole horizontally and slid the caliper open until it reached the edges of the hole. The measurement was read off the caliper and recorded. The process was then repeated for the vertical measurement. The entrance hole was the only hole measured; the exit hole was ignored as if there was only one impact hole found. As previously mentioned the data taken will then entered into the impact angle equation to estimate the angle of the impact hole: “IMPACT ANGLE = arcsin (Width/Length)” (Fischer, in James, 1999, p. 2).

Step 3: The participant repeated steps 1 – 2 for each for each hole until each tool had been repeated in triplicate for all five walls.

The participants were given a worksheet by the researcher to fill in their measurements of the impact angles on the five faux walls. After all five walls were measured, the worksheet was given back to the researcher and a new worksheet given back to the participant. The participants were asked to wait around a minute before starting the next worksheet to help stop bias towards the impact hole angles. This process continued until all five walls had been measured in triplicate by all three tools. Three trials (Trial 1, Trial 2, and Trial 3) were completed using the process below for collecting measurements:

Trial: Smart Tool™ - Hole #1 – Hole #5 (One measurement for each hole)

Angle Finder – Hole #1 – Hole #5 (One measurement for each hole)

Digital Caliper – Hole #1 – Hole #5 (Three measurements for each hole)

This process gave the Smart Tool™ and angle finder five measurements per trial and 15 measurements overall per participant. The digital caliper had 15 measurements per trial and 45 measurements overall per participant.

Due to the uncertainty of the digital calipers that was known before the project started, the digital calipers were not only measured in triplicate for all angles, like the other two tools, but also triplicate measurements were taken for each angle tested. This means that each hole was measured three times and all five walls were measured in triplicate as well in each trial.

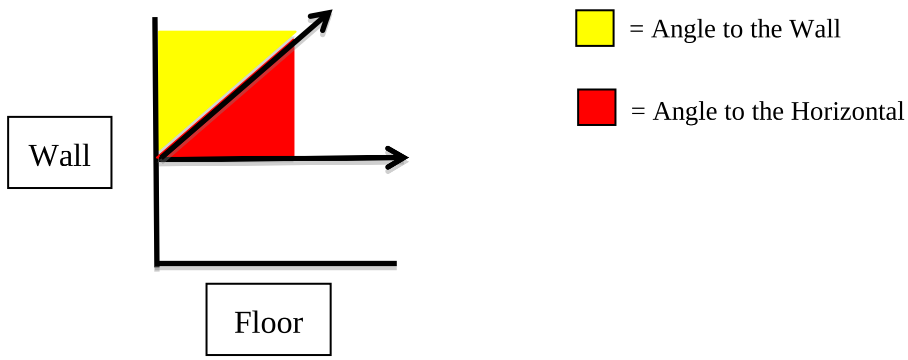
The holes were measured in triplicates for each tool to create better statistical data. When data is collected in triplicate, it allows small errors to be averaged into the values and to not throw off the data values. Collecting data in triplicates is an easy control; if two values are close together and one is far off, then immediately it is clear that the results are skewed and the measurements need to be repeated; this is true for casework as well.

Normally, the horizontal angle of impact angle is also collected at scenes, but due to the use of the power drill, all holes will be drilled head on with a 0˚ horizontal angle. This also allowed the measurements taken by the Smart Tool™ and angle finder to match the manual calculations taken by the digital caliper. Digital calipers can only measure impact angles in one direction at a time. If the impact hole is vertical (up and down direction), digital calipers can measure the vertical impact angle. If the impact hole is horizontal (left or right direction), the tool measures the horizontal impact angle.

Two angles can be determined while conducting shooting trajectory reconstruction: the angle to the wall and the angle to the horizontal. For ease during the project, the volunteers were asked to only find the angle to the wall. In Figure 3, below, the participants located the yellow space as opposed to the red. The Smart Tool™ and angle finder have a long side and a short side. The participants were asked to use the short side of both tools to allow them to calculate the angle to the wall. (Trahin, 1987; Parker, 2005)

Figure 3

Wall Angles



After the participants finished measuring the angles of the impact holes, they were given a short questionnaire to fill out. The names and organizations for the participants were not known in order to protect their identity and not bias the project. For this reason, it was important to gain information through the questionnaire. Questions pertaining to this type of information were their occupation, their experience levels with the tools, and the confidence levels with the tools. The questionnaire also asked which tool the participant felt was more accurate and which tool they preferred. This part of the questionnaire was important to see what actual participants felt about the tools, and not what the statistics said about the tools' performance. The full questionnaire is located in the appendix.

Procedure for Assessing Data

The participants entered their calculations of the impact hole angles onto worksheets created by the researcher. The data collected from the worksheets was entered in to Excel™ spreadsheets in order to track the angle of impact each participant reported for each of the walls and trials. Each tool had its own spreadsheet to ensure that data was not crossed between the tools. Statisticians, Dr. Tracy Morris and Dr. Cynthia Murray, from the University of Central Oklahoma statistically analyzed the values and compared them to see which tool was more efficient. The data was analyzed on SAS by calculating the accuracy (mean bias), precision (standard deviation), and error rate (percent error) of each of the three tools.

To address the five hypotheses, a three-factor (tool, hole, group) analysis of variance, ANOVA, for both accuracy and precision was performed with two repeated factors (tool and hole) assuming a heterogeneous compound symmetry structure. An ANOVA allows for the determination of variation between multiple means. This was then followed by Tukey's pairwise multiple comparisons, where appropriate. The term heterogeneous compound symmetry structure allows for a common correlation between measurements, but different variances. An ANOVA assumes items being tested will have the same variance among the various factors. In this case, the various factors were the tool used, impact angle, and the group being tested. When there was a statically significant difference in the variances between these factors, Tukey's multiple comparisons were used to locate the significant differences.

It was crucial to analyze the data statistically because in reconstruction a large effect exists on calculations with just a few degrees of difference between measurements. The data collected was analyzed to see if there was a statistically significant difference between the values of the three tools tested in this project and to see if there was a difference between examiners and students.

Results

The results from this study came from information taken from 17 students and 31 examiners (N = 48). The participants performed shooting trajectory reconstruction on faux sheet rock walls with five impact angles drilled into them. The participants analyzed the impact angles using a Smart Tool™, angle finder, and manual calculations using a digital caliper. The data collected was reported on worksheets provided by the researcher and statistically analyzed by Dr. Tracy Morris and Dr. Cynthia Murray of the University of Central Oklahoma using SAS (version 9.1).

Analysis of the data from this study included accuracy, which was reported using mean bias. As previously mentioned, accuracy is the measure of how far away the recorded value for an angle was from the actual value of the angle. This means that if an angle is 30˚ and it is calculated to be 31.4˚ there is a bias of + 1.4 degrees. A mean bias was computed for the three measurements for each group, hole, and tool. Precision was computed using the standard deviations of the three trials. This value is a measure of the variability of the measurements of an angle. A *p*-value was also reported to determine the statistical significance of a value. A *p*-value is the probability of being wrong if the word significant was used with regard to differences. The cutoff point for this project was a *p*-value of 0.05; anything less than 0.05 will lead to a rejection of the null hypothesis (H_0). A rejection of the null hypothesis means there was a significant difference between the factors being analyzed.

This study proposed multiple hypotheses and questions to be answered.

H_0: There is no difference between the precision rates of the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper.

H_1: There is a difference between the precision rates of the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper.

H_0: There is no difference between the accuracy rates of the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper.

H_1: There is a difference between the accuracy rates of the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper.

H_0: There is no difference between the examiners and students using the Smart Tool™.

H_1: There is a difference between the examiners and students using the Smart Tool™.

H_0: There is no difference between the examiners and students using the angle finder.

H_1: There is a difference between the examiners and students using the angle finder.

H_0: There is no difference between the examiners and students using manual calculations utilizing a digital caliper.

H_1: There is a difference between the examiners and students using manual calculations utilizing a digital caliper.

What are the error rates for the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper?

What are the participants’ experience and confidence levels with the tools?

What tool is preferred by the participants?

Analysis

The analysis of the data was compared based on three factors: tool used, examiner vs. student, and the impact angle of the hole. Table 1 shows the summary statistics for the tools based on (A) Accuracy, (B) Precision, and (C) Error. All of the following values are in degrees.

Table 1

Summary Statistics for Tools

(A) Accuracy (Bias)

Tool	*n*	Mean	Median	Std. Dev.	Range
Angle Finder	240	0.12	0.00	2.71	-7.33 – 9.33
Smart Tool™	240	-0.30	0.37	2.15	-10.20 – 9.17
Digital Caliper	240	-5.87	-2.55	13.33	-37.79 – 24.47

(B) Precision (Standard Deviation)

Tool	*n*	Mean	Median	Std. Dev.	Range
Angle Finder	240	1.86	1.15	2.14	0 - 11.85
Smart Tool™	240	1.22	0.69	1.75	0 - 12.67
Digital Caliper	240	3.19	2.32	3.17	0 - 22.43

(C) Error (|Bias|)

Tool	*n*	Mean	Median	Std. Dev.	Range
Angle Finder	240	2.05	1.67	1.78	0 - 9.33
Smart Tool™	240	1.69	1.40	1.36	0 - 10.20
Digital Caliper	240	11.69	8.71	8.66	0.11 - 37.79

Precision

For each participant, the standard deviation of the three measurements was calculated. These standard deviations were then averaged to obtain the following results. The precision for the examiners and students is found in Table 2 and graphically represented in Figure 4.

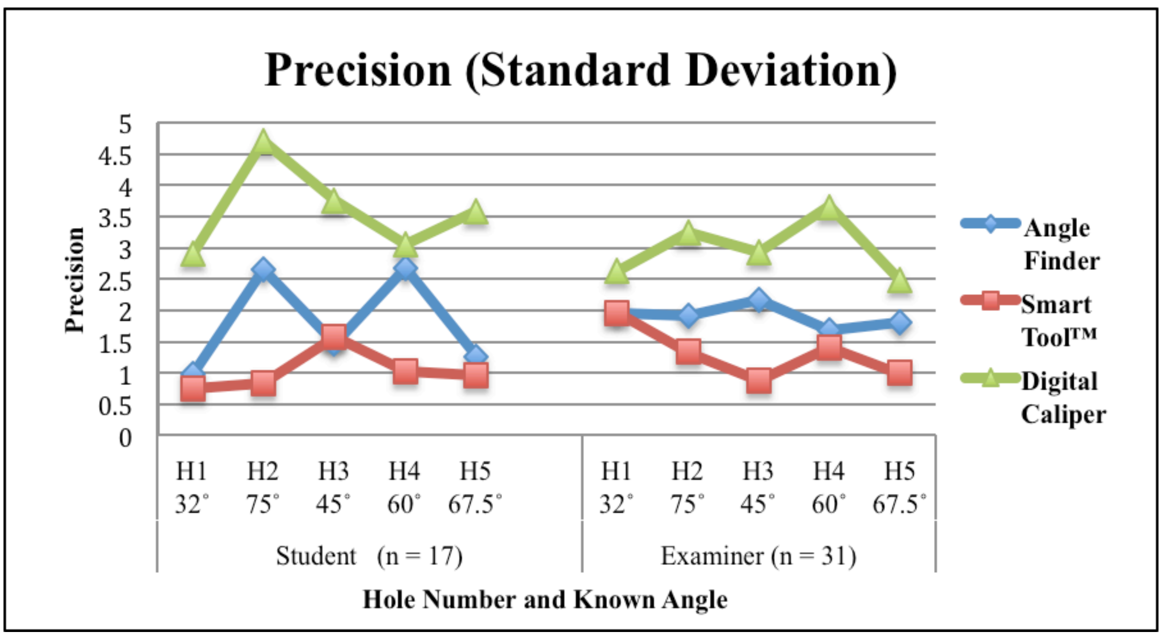
Table 2

Precision for Examiners and Students

Participant	Hole	Angle Finder	Smart Tool™	Digital Caliper
Student (*n* = 17)	Hole 1 - 32˚	0.98˚	0.74˚	2.90˚
	Hole 2 - 75˚	2.64˚	0.83˚	4.69˚
	Hole 3 - 45˚	1.46˚	1.57˚	3.74˚
	Hole 4 - 60˚	2.66˚	1.03˚	3.04˚
	Hole 5 - 67.5˚	1.26˚	0.96˚	3.57˚
Examiner (*n* = 31)	Hole 1 - 32˚	1.94˚	1.96˚	2.62˚
	Hole 2 - 75˚	1.91˚	1.33˚	3.24˚
	Hole 3 - 45˚	2.16˚	0.88˚	2.92˚
	Hole 4 - 60˚	1.67˚	1.41˚	3.65˚
	Hole 5 - 67.5˚	1.80˚	0.99˚	2.47˚

Figure 4

Graph of Precision for Examiners and Students



Tables 3 - 8 were based on the results of a 3-factor (tool, hole, group) ANOVA with 2 repeated factors (tool and hole) assuming a heterogeneous compound symmetry structure.

Table 3 displays the mean precision by group. The *p*-value for this factor was found to be $p = 0.812$, making the difference between the students and examiners not statistically significant.

Table 3

Mean Precision by Group

Student	Examiner
2.14˚	2.06˚

Table 4 contains the mean precision by tool. The *p*-value for this factor was $p < 0.001$, meaning there was a statistically significant difference among the tools.

Table 4

Mean Precision by Tool

Angle Finder	Smart Tool™	Digital Caliper
1.86˚	1.22˚	3.19˚

Table 5 displays the mean precision by hole. The *p*-value for this factor was $p = 0.204$, indicating there was no statistically significant difference between the holes.

Table 5

Mean Precision by Hole

Hole 1 - 32˚	Hole 2 - 75˚	Hole 3 - 45˚	Hole 4 - 60˚	Hole 5 - 67.5˚
1.95˚	2.36˚	2.08˚	2.24˚	1.82˚

Table 6 presents the mean precision by tool and group. The *p*-value of this interaction was p = 0.187, meaning there was not a significant interaction between these two factors.

Table 6

Mean Precision by Tool and Group

	Angle Finder	Smart Tool™	Digital Caliper
Student	1.80˚	1.03˚	3.59˚
Examiner	1.90˚	1.32˚	2.98˚

Table 7 contains the mean precision by tool and hole. The *p*-value of this interaction was p = 0.652, meaning there was not a statistically significant interaction between these two factors.

Table 7

Mean Precision by Tool and Hole

	Angle Finder	Smart Tool™	Digital Caliper
Hole 1 - 32˚	1.60˚	1.53˚	2.71˚
Hole 2 - 75˚	2.17˚	1.15˚	3.75˚
Hole 3 - 45˚	1.91˚	1.26˚	3.21˚
Hole 4 - 60˚	2.02˚	1.28˚	3.43˚
Hole 5 - 67.5˚	1.61˚	0.98˚	2.86˚

Table 8 shows the mean precision by group and hole. The *p*-value of this interaction was p = 0.307, meaning there was not a significant interaction between these two factors.

Table 8

Mean Precision by Group and Hole

	Student	Examiner
Hole 1 - 32˚	1.54˚	2.17˚
Hole 2 - 75˚	2.72˚	2.16˚
Hole 3 - 45˚	2.26˚	1.99˚
Hole 4 - 60˚	2.24˚	2.24˚
Hole 5 - 67.5˚	1.93˚	1.75˚

There were no significant interactions (tool and hole, tool and group, group and hole, and then all three, tool and group and hole), but for the sake of completeness, p-values for the following interactions are provided. Table 9 displays the *p*–values for 2 – tailed t – tests to determine statistically significant differences between mean precision of groups by tool and hole.

Table 9

P-values for Differences among the Factors

p - values	Angle Finder	Smart Tool™	Digital Caliper
Hole 1 - 32˚	0.094	0.030	0.713
Hole 2 - 75˚	0.232	0.183	0.397
Hole 3 - 45˚	0.197	0.268	0.212
Hole 4 - 60˚	0.319	0.441	0.489
Hole 5 - 67.5˚	0.194	0.943	0.320

The highlighted cell shows that the Smart Tool™ on Hole #1 was the only combination of tool and hole for which there was a statistically significant difference in the mean precision of the groups.

Table 10 displays the *p*–values for ANOVAs to determine significant differences between mean precision of tools by group and hole

Table 10

P-values for Differences in Tools

	Hole	*p* - value	Significance
Student (*n* = 17)	Hole 1 - 32˚	< 0.001	DC - AF, ST
	Hole 2 - 75˚	0.026	DC - ST
	Hole 3 - 45˚	0.002	DC - AF, ST
	Hole 4 - 60˚	0.042	DC - ST
	Hole 5 - 67.5˚	0.004	DC - AF, ST
Examiner (*n* = 31)	Hole 1 - 32˚	0.445	None
	Hole 2 - 75˚	0.003	DC - AF, ST
	Hole 3 - 45˚	< 0.001	ST - AF, DC
	Hole 4 - 60˚	0.002	DC - AF, ST
	Hole 5 - 67.5˚	0.005	DC - ST

Again, the highlighted cells show statistical significance. The only combination of group and hole that was not statically significant was Hole #1 for the examiners. The last column shows how the tools related to each other based on significance. A " - " symbol represents that those two tools are significantly different, where a " , " means the tools were not significantly different. For example in the first cell, with regard to the students at Hole #1, the digital caliper was significantly different from the angle finder and Smart Tool™. The order of the tools in the significance column is based on the magnitude of the means.

Table 11 contains the SAS output for the Tukey's multiple comparisons among the tools.

Table 11

Results of Tukey's Multiple Comparisons among the Tools

(A) Difference of Least Squares Means

Effect	Type - Group 2	Type - _Group 2	Estimate	Standard Error	DF	t value
Type	Angle Finder	Digital Caliper	-1.4344	0.2501	266	-5.73
Type	Angle Finder	Smart Tool™	0.6777	0.173	360	3.92
Type	Digital Calipers	Smart Tool™	2.112	0.2442	210	8.65

(B) Difference of Least Squares Means

Effect	Type - Group 2	Type - _Group 2	Pr > |t|	Adjustment	Adj. *p* - value
Type	Angle Finder	Digital Caliper	< 0.0001	Tukey - Kramer	< 0.0001
Type	Angle Finder	Smart Tool™	0.0001	Tukey - Kramer	0.0003
Type	Digital Calipers	Smart Tool™	< 0.0001	Tukey - Kramer	< 0.0001

(C) Tests of Effect Slices

Effect	Type	Number DF	Den. DF	F value	Pr > F
Type * Group 2	Angle Finder	1	88.4	0.07	0.7851
Type * Group 2	Digital Caliper	1	81.7	1.29	0.2588
Type * Group 2	Smart Tool™	1	87.7	1.02	0.3159

Accuracy

For each participant, measured values for Trials 1 through 3 were averaged and biases were calculated. These biases were then averaged to obtain the following results. The mean biases for the examiners and students by tool and hole are found in Table 12 and graphically represented in Figure 5.

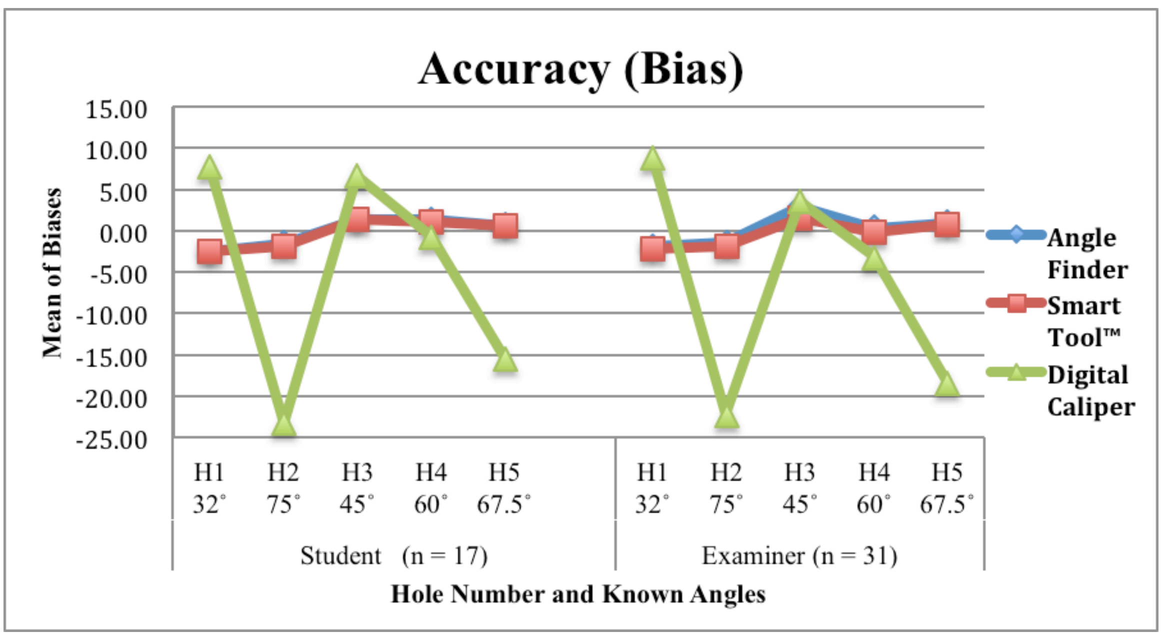
Table 12

Mean Bias for Students and Examiners

Participant	Hole	Angle Finder	Smart Tool™	Digital Caliper
Student (n = 17)	Hole 1 - 32˚	-2.50˚	-2.49˚	7.69˚
	Hole 2 - 75˚	-1.43˚	-1.78˚	-23.24˚
	Hole 3 - 45˚	1.37˚	1.45˚	6.60˚
	Hole 4 - 60˚	1.39˚	1.14˚	-0.73˚
	Hole 5 - 67.5˚	0.70˚	0.64˚	-15.49˚
Examiner (n = 31)	Hole 1 - 32˚	-1.85˚	-2.17˚	8.76˚
	Hole 2 - 75˚	-1.39˚	-1.86˚	-22.27˚
	Hole 3 - 45˚	2.99˚	1.56˚	3.52˚
	Hole 4 - 60˚	0.42˚	-0.09˚	-3.23˚
	Hole 5 - 67.5˚	1.01˚	0.78˚	-18.40˚

Figure 5

Graph of Mean Bias for Examiners and Students



Tables 13 - 18 were based on a 3-factor (tool, hole, group) ANOVA with 2 repeated factors (tool and hole) assuming a heterogeneous compound symmetry structure.

Table 13 displays the mean bias of the participants. The *p*-value for this factor was found to be $p = 0.264$, making the difference between the students and examiners not statistically significant.

Table 13

Mean Bias of Participants

Student	Examiner
-1.78°	-2.15°

Table 14 contains the mean bias of the three tools. There was a statistically significant difference, so further testing at each hole was done to determine which tools were significantly different.

Table 14

Mean Bias of Tools

Angle Finder	Smart Tool™	Digital Caliper
0.12°	-0.30°	-5.87°

Table 15 displays the mean bias for each hole. Again, there were statistically significant differences, but because of a significant interaction with the tools, further testing at each tool was done to determine which holes were significantly different.

Table 15

Mean Bias of Holes

Hole 1 - 32°	Hole 2 - 75°	Hole 3 - 45°	Hole 4 - 60°	Hole 5 - 67.5°
1.34°	-8.62°	2.85°	-0.41°	-5.25°

Table 16 presents the mean bias of the three tools by group. The *p*-value of this interaction was $p = 0.085$, meaning there was not a statistically significant interaction between these two factors.

Table 16

Mean Bias of Tools by Participant

	Angle Finder	Smart Tool™	Digital Caliper
Student	-0.09°	-0.21°	-5.03°
Examiner	0.24°	-0.36°	-6.33°

Table 17 contains the mean bias of the three tools by hole. The *p*-value of this interaction was $p < 0.001$, meaning there was a statistically significant interaction between these two factors.

Table 17

Mean Bias of Tools by Hole

	Angle Finder	Smart Tool™	Digital Caliper
Hole 1 - 32°	-2.08°	-2.28°	8.38°
Hole 2 - 75°	-1.41°	-1.83°	-22.62°
Hole 3 - 45°	2.42°	1.52°	4.61°
Hole 4 - 60°	0.76°	0.35°	-2.35°
Hole 5 - 67.5°	0.90°	0.73°	-17.37°

Table 18 shows the mean bias for the groups by hole. The *p*-value of this interaction was $p = 0.087$, meaning there was not a statistically significant interaction between these two factors.

Table 18

Mean Bias of Participants by Hole

	Student	Examiner
Hole 1 - 32°	0.90°	1.58°
Hole 2 - 75°	-8.81°	-8.51°
Hole 3 - 45°	3.14°	2.69°
Hole 4 - 60°	0.60°	-0.97°
Hole 5 - 67.5°	-4.72°	-5.54°

Due to the statistically significant interaction between the tools and holes, as shown in Table 17, further tests (simple effects) were needed to determine what tools were significantly different at each hole, Table 19 and Table 20, and what holes were significantly different at each tool, Table 21 and Table 22.

Table 19

P – values Between Tools at Each Hole

Hole	*p*-value
Hole 1 - 32˚	< 0.001
Hole 2 - 75˚	< 0.001
Hole 3 - 45˚	< 0.001
Hole 4 - 60˚	0.014
Hole 5 - 67.5˚	< 0.001

Table 20

P –values Between Pairs of Tools at Each Hole

Hole	AF - ST	AF - DC	ST - DC
Hole 1 - 32˚	1.000	<0.001	<0.001
Hole 2 - 75˚	1.000	<0.001	<0.001
Hole 3 - 45˚	0.908	0.022	<0.001
Hole 4 - 60˚	0.998	0.177	0.373
Hole 5 - 67.5˚	1.000	<0.001	<0.001

Table 21

P – values Between Holes at Each Tool

Angle Finder	< 0.001
Smart Tool™	< 0.001
Digital Caliper	< 0.001

Table 22

P –values for Pairs of Holes at Each Tool

	Angle Finder	Smart Tool™	Digital Caliper
H1 - H2	0.977	0.994	<0.001
H1 - H3	<0.001	<0.001	0.153
H1 - H4	<0.001	<0.001	<0.001
H1 - H5	<0.001	<0.001	<0.001
H2 - H3	<0.001	<0.001	<0.001
H2 - H4	<0.001	<0.001	<0.001
H2 - H5	<0.001	<0.001	<0.001
H3 - H4	0.175	0.025	<0.001
H3 - H5	0.107	0.127	<0.001
H4 - H5	1.000	1.000	<0.001

Table 23 displays the *p* – values for 2 – tailed t – tests to determine significant differences between the mean biases of the students and examiners at every tool and hole.

Table 23

2 – Tailed T – Test for Statistical Significance for the Participants based on Tool and Hole

p - values	Angle Finder	Smart Tool™	Digital Caliper
Hole 1 - 32˚	0.214	0.550	0.513
Hole 2 - 75˚	0.962	0.789	0.531
Hole 3 - 45˚	0.025	0.775	0.037
Hole 4 - 60˚	0.112	0.005	0.194
Hole 5 - 67.5˚	0.527	0.682	0.056

The highlighted cells show that all three tools have one statistically significant difference between the groups. The angle finder and digital caliper at Hole #3 and the Smart Tool™ at Hole #4 are the only combinations of tool and hole that were found to be statistically significant.

Table 24 displays the p-values for an analysis of variance (repeated measure design) to determine statistically significant differences between mean biases of the three tools at each group and hole combination.

Table 24

Analysis of Variance for the Tools based on Group and Hole

	Hole	*p* - value
Student (n = 17)	Hole 1 - 32˚	< 0.001
	Hole 2 - 75˚	< 0.001
	Hole 3 - 45˚	< 0.001
	Hole 4 - 60˚	0.129
	Hole 5 - 67.5˚	< 0.001
Examiner (n = 31)	Hole 1 - 32˚	< 0.001
	Hole 2 - 75˚	< 0.001
	Hole 3 - 45˚	0.054
	Hole 4 - 60˚	0.004
	Hole 5 - 67.5˚	< 0.001

Again, the highlighted cells show statistical significance based on *p* – values. All combinations aside from students at Hole #4 and the examiners at Hole #3 were found to have statistically significant differences.

As a separate analysis of the bias, a one-factor analysis of variance for tool was performed. The actual SAS output is presented in Table 25.

Table 25

SAS Output for the Bias

(A) Least Squares Means

Effect	Type	Estimate	Standard Error	DF	t-value	Pr > |t|
Type	Angle Finder	0.1194	0.1771	47	0.67	0.5034
Type	Digital Caliper	-5.8664	0.5959	47	-9.84	< 0.0001
Type	Smart Tool™	-0.3031	0.08107	47	-3.74	0.0005

(B) Differences of Least Squares Means

Effect	Type	Type	Est.	Std. Error	DF	t-value	Pr > t	Adjustment	Adj. P
Type	Angle Finder	Digital Caliper	5.9859	0.6217	55.2	9.63	< 0.0001	Tukey - Kramer	< 0.001
Type	Angle Finder	Smart Tool™	0.4225	0.1948	65.9	2.17	0.0337	Tukey - Kramer	0.0855
Type	Digital Caliper	Smart Tool™	-5.5634	0.6014	48.7	-9.25	< 0.0001	Tukey - Kramer	< 0.001

The results further demonstrated that, if the effects of group and hole are not considered, the digital caliper had a statistically significant variance between the other two tools, but the Smart Tool™ and angle finder had no statistically significant differences from each other.

Table 26 contains the mean bias for each combination of tool and hole. The *p*-values indicate there was a significant difference between the mean biases of the tools at each hole. The results of the Tukey's multiple comparisons at each hole are displayed in the bottom row of the table. Groups separated by a comma are not significantly different and groups separated by a hyphen are significantly different.

Table 26

Mean Bias for Each Combination of Tool and Hole

Tool	Hole 1 - 32˚	Hole 2 - 75˚	Hole 3 - 45˚	Hole 4 - 60˚	Hole 5 - 67.5˚
Angle Finder	-2.17˚	-1.41˚	2.18˚	0.91˚	0.85˚
Digital Caliper	8.23˚	-22.76˚	5.06˚	-1.98˚	-16.94˚
Smart Tool™	-2.33˚	-1.82˚	1.51˚	0.53˚	0.71˚
p - value	< 0.0001	< 0.0001	< 0.0001	0.0136	< 0.0001
Multiple Comp.	ST, AF - DC	DC - ST, AF	ST, AF - DC	None	DC - ST, AF

Error Rates

The error rates for this project will be reported as percent error and were calculated using the formula:

$$\% \text{ Error} = \frac{|\text{ Known Value} - \text{Experimental Value }|}{|\text{ Known Value }|} \times 100$$

The percent errors were calculated using the error rates by hole. These were calculated by taking the mean of the absolute value of the bias for each combination of tool and hole; these are displayed in Table 27. The percent error for each tool used in this project by hole number are displayed in Table 28. The *p*-values in Table 27 indicate there was a significant difference between the mean of the absolute value of the biases of the tools at each hole. The results of the Tukey's multiple comparisons for each hole are displayed in the bottom row of the table. Groups separated by a comma are not significantly different and groups separated by a hyphen are significantly different.

Table 27

Error (|*Bias*|) *by Hole and Tool*

Tool	Hole 1 - 32˚	Hole 2 - 75˚	Hole 3 - 45˚	Hole 4 - 60˚	Hole 5 - 67.5˚
Angle Finder	2.65˚	2.36˚	2.28˚	1.26˚	1.47˚
Digital Caliper	8.23˚	22.76˚	5.63˚	4.29˚	17.20˚
Smart Tool™	2.70˚	1.85˚	1.54˚	1.14˚	1.08˚
p - value	< 0.0001	< 0.0001	< 0.0001	0.0003	< 0.0001
Multiple Comp.	AF, ST - DC	ST, AF - DC	ST, AF - DC	ST, AF - DC	ST, AF - DC

Table 28

Percent Error by Hole and Tool

Tool	Hole 1 - 32˚	Hole 2 - 75˚	Hole 3 - 45˚	Hole 4 - 60˚	Hole 5 - 67.5˚
Angle Finder	8.28%	3.15%	5.07%	2.10%	2.18%
Digital Caliper	25.72%	30.35%	12.51%	7.15%	25.48%
Smart Tool™	8.44%	2.47%	3.42%	1.90%	1.60%

Figure 6 is the graphical representation of Table 28. The graph was created in order of increasing impact angles to demonstrate the change of percent error as the impact angle changes. Added for each of the lines is a trend line that estimates the percent error at lower and higher angles than were tested in this project.

Figure 6

Percent Error by Hole and Tool in Order of Impact Angle with Trend Lines

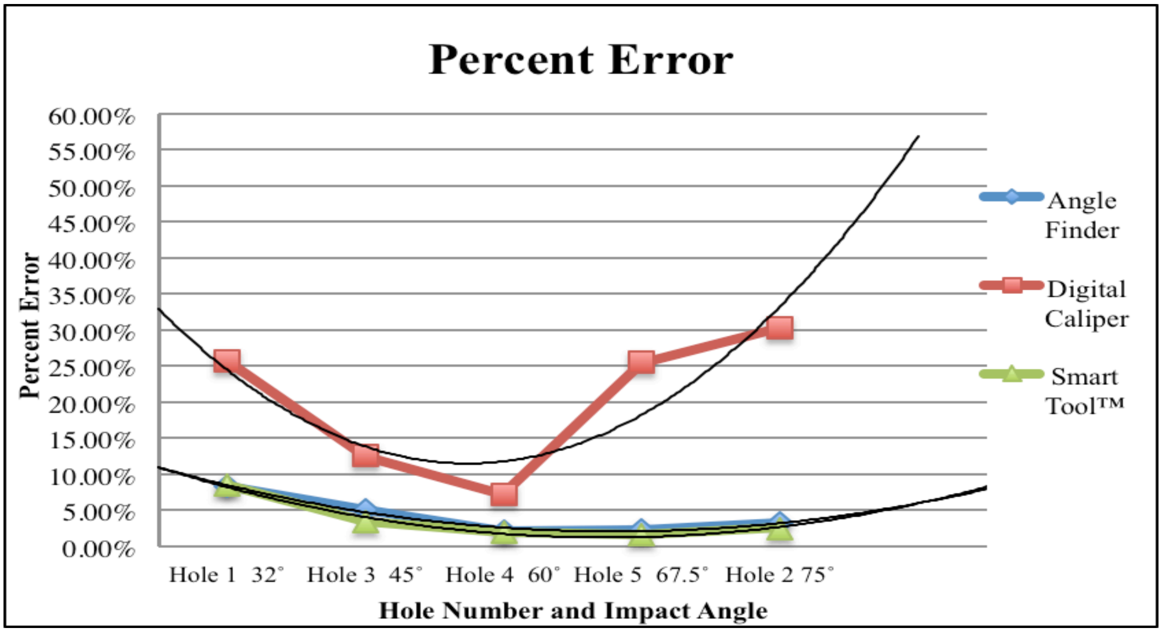


Figure 6 demonstrate the increase in percent error as the angle of impact becomes more acute or obtuse. This trend can be seen at a drastic level for the digital calipers, and to a lesser extent, the angle finder and Smart Tool™.

As a separate analysis of the error, a one-factor analysis of variance for tool was performed. The actual SAS output is presented in Table 29.

Table 29

SAS Output for the Error

(A) Least Squares Means

Effect	Type	Estimate	Standard Error	DF	t - value	Pr > |t|
Type	Angle Finder	2.0486	0.1389	47	14.75	< 0.0001
Type	Digital Caliper	11.6927	0.3726	47	31.38	< 0.0001
Type	Smart Tool™	1.6898	0.1053	47	16.05	< 0.0001

(B) Differences of Least Squares Means

Effect	Type	Type	Estimate	Std. Error	DF	t - value	Pr > t	Adjustment	Adj. P
Type	Angle Finder	Digital Caliper	-9.6441	0.3977	59.8	-24.25	< 0.0001	Tukey - Kramer	< 0.001
Type	Angle Finder	Smart Tool™	0.3588	0.1743	87.6	2.06	0.0425	Tukey - Kramer	0.1061
Type	Digital Caliper	Smart Tool™	10.0029	0.3872	54.5	25.83	< 0.0001	Tukey - Kramer	< 0.001

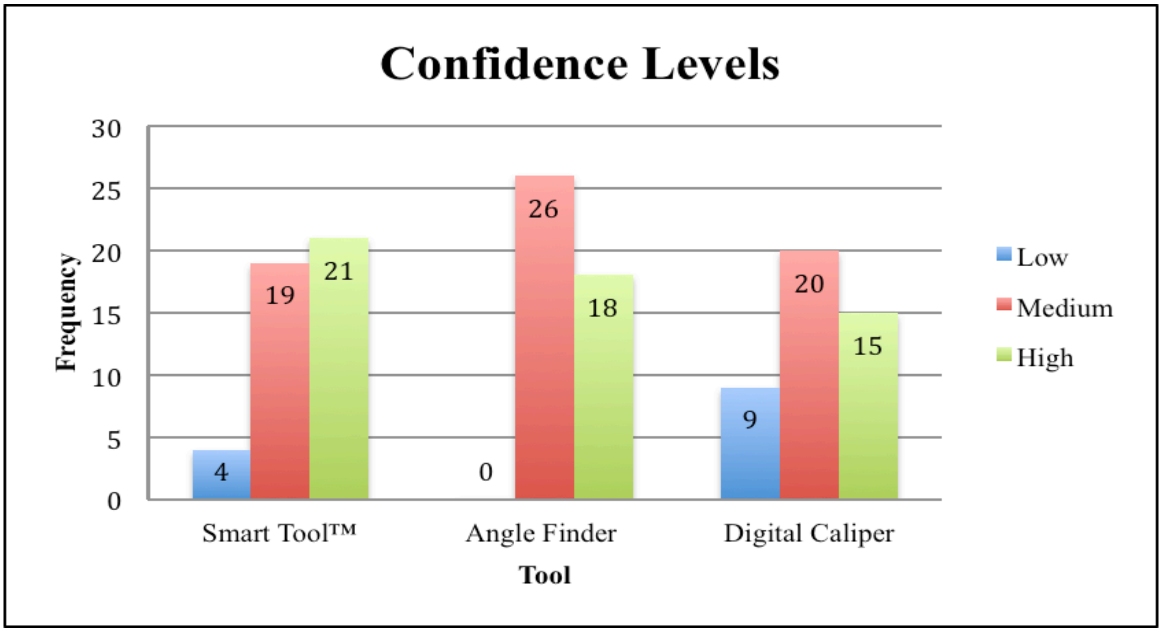
Questionnaire

The following information is from a short questionnaire the participants were asked to fill out after their participation in the study; of the 48 examiners that participated, 43 filled out the questionnaires.

The confidence levels for the participants with each of the tools after completing the project are graphically represented in Figure 7.

Figure 7

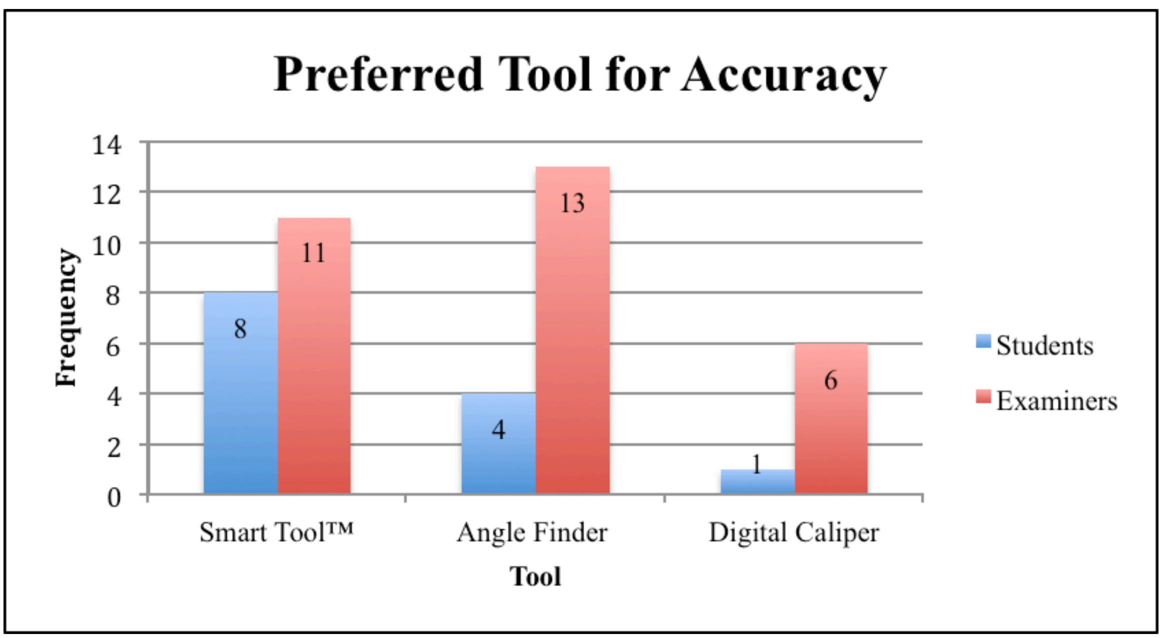
Confidence Levels with Tools



The participants were also asked which tool they felt to be more accurate and why they thought that about the tool. These results are displayed in Figure 8.

Figure 8

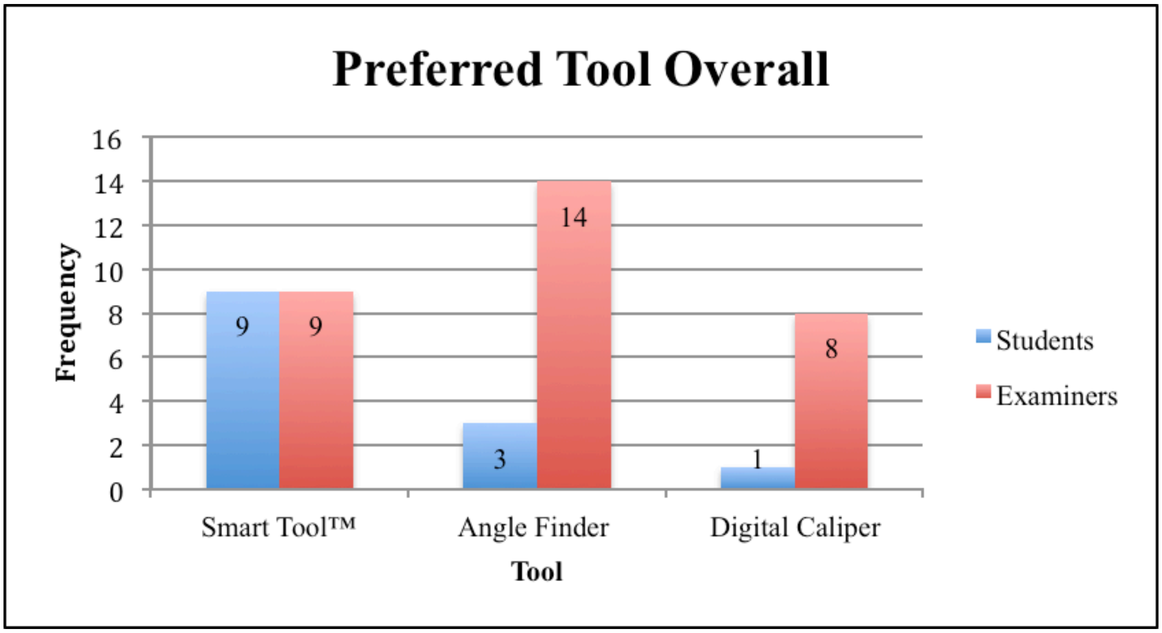
Participants' Preferred Tool for Accuracy



The participants were also asked which tool they preferred overall to use everyday; these choices are graphically shown in Figure 9.

Figure 9

Preferred Tool Overall



Discussion

Introduction

Although shooting trajectory reconstruction is used daily to aid in the reconstruction of crime scenes involving shooting incidents, the tools used and their methods are not validated. The courts allow reconstruction testimony due to the fact that it is based on right triangles and trigonometric functions that are proven and have a history stretching as far back as 3,000 B.C.. Shooting trajectory reconstruction also gains its methods and procedures from the field of bloodstain pattern analysis, which helps its ability to be used in court.

Studies of a large magnitude are limited for shooting trajectory reconstruction, and there are limited estimated error rates for the tools used in this discipline. This study used novice and experienced reconstructionists to obtain the accuracy, precision, and error rates for three of the tools used in this discipline on a large scale. This project looked at the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper when only one entrance hole was present.

Summary Statistics

Table 1

Summary Statistics for Tools

(A) Accuracy (Bias)

Tool	*n*	Mean	Median	Std. Dev.	Range
Angle Finder	240	0.12˚	0.00˚	2.71˚	-7.33˚ – 9.33˚
Smart Tool™	240	-0.30˚	0.37˚	2.15˚	-10.20˚ – 9.17˚
Digital Caliper	240	-5.87˚	-2.55˚	13.33˚	-37.79˚ – 24.47˚

(B) Precision (Standard Deviation)

Tool	*n*	Mean	Median	Std. Dev.	Range
Angle Finder	240	1.86˚	1.15˚	2.14˚	0˚ - 11.85˚
Smart Tool™	240	1.22˚	0.69˚	1.75˚	0˚ - 12.67˚
Digital Caliper	240	3.19˚	2.32˚	3.17˚	0˚- 22.43˚

(C) Error (|bias|)

Tool	*n*	Mean	Median	Std. Dev.	Range
Angle Finder	240	2.05˚	1.67˚	1.78˚	0˚ - 9.33˚
Smart Tool™	240	1.69˚	1.40˚	1.36˚	0˚ - 10.20˚
Digital Caliper	240	11.69˚	8.71˚	8.66˚	0.11˚ - 37.79˚

Table 1 shows the summary statistics for the tools based on (A) Accuracy, (B) Precision, and (C) Error. All of the above values are in degrees. It is clear from Table 1 that there was a difference between the three tools with respect to accuracy, precision, and error. When looking at Table 1A, the angle finder and Smart Tool™ were very close in accuracy when looking at their means of 0.12˚ with a standard deviation of 2.71˚ and a mean of -0.30˚ with a standard deviation of 2.15˚, respectively. The angle finder reported values just over the known values, where the Smart Tool™ came in just under the known values for the impact angles. The angle finder had a slightly smaller range than the Smart Tool™. The digital caliper had a mean 5x larger than the other two tools at -5.87˚ with a standard deviation of 13.33˚. Not only is the mean bias for the digital calipers larger than the other two tools, but also the standard deviation and range are both approximately 5.5x and 3.5x larger, respectively.

Table 1B shows the precision of the angle finder and Smart Tool™ are very close with means of 1.86˚ with a standard deviation of 2.14˚ and 1.22˚ with a standard deviation of 1.75˚, respectively. The standard deviation of the precision for the angle finder was larger than that of the Smart Tool™, but with a smaller range, just as in Table 1A. The digital caliper was much closer to the Smart Tool™ and angle finder when it came to precision, coming in at only double range.

Table 1C is the error of these three tools. This was calculated by taking the mean of the absolute value of the bias. The table shows how far from the known value each of the tools were overall. This time, the digital calipers had a mean roughly 6x higher than that of the angle finder and Smart Tool™, while the range was about 4x higher. This table shows that the angle finder was on average 2.05˚ from the known value with a standard deviation of 1.78˚ this is compared to the Smart Tool™ with a difference of 1.69˚ from the known value and a standard deviation of 1.36˚. The error values are not double the value of the accuracy values due to the fact that the range of negatives and positives was not equal; there may have been more negative values than positives for a tool, and vice versa.

Table 1 demonstrates the abilities of these tools in comparison to each other. The angle finder and Smart Tool™ were very close through Table 1A, 1B, and 1C. There was not a consistency between the three tables on which had a smaller mean bias or standard deviation between the two tools. Aside from Table 1B, standard deviation, the digital caliper came in significantly higher than the angle finder and Smart Tool™ on all measurements for accuracy and precision. These tables also demonstrate that the digital caliper has not only a larger margin for its distance away from the known value, but also in its range of results calculated for the various measurements.

Hypotheses

Hypothesis 1: H_0: There is no significant difference between the precision rates of the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper.

After a 3 - factor (tool, hole, group) ANOVA with 2 repeated factors (tool and hole) assuming a heterogeneous compound symmetry structure was completed, no interactions were significant and only one main effect was significant; this was for the tools. Based on the *p* – value of $p < 0.001$, there was a statistically significant difference between the mean precisions of the three tools (Smart Tool™, angle finder, and digital caliper), thus rejecting the null hypothesis. The mean precision for each tool is displayed in Table 4.

Table 4

Mean Precision by Tools

Angle Finder	Smart Tool™	Digital Caliper
1.86˚	1.22˚	3.19˚

Specifically, the Smart Tool™ had a significantly lower mean standard deviation than that of the angle finder, which had a significantly lower mean standard deviation than that of the digital caliper.

Even though none of the interactions were significant, an additional analysis of variance was completed to look at the significance between the tools based on the holes and groups. All but one hole had a statistically significant difference between the mean precision of the tools. These results are displayed in Table 10.

Table 10

P – Values for Differences in Tools

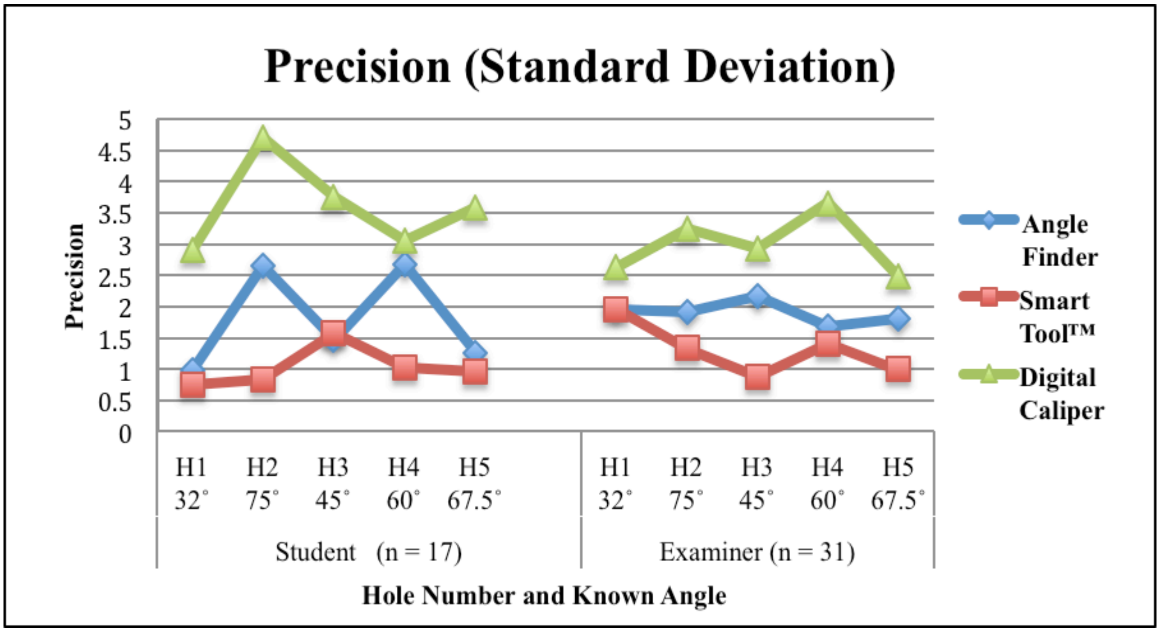
	Hole	*p* - value	Significance
Student (n = 17)	Hole 1 - 32˚	< 0.001	DC - AF, ST
	Hole 2 - 75˚	0.026	DC - ST
	Hole 3 - 45˚	0.002	DC - AF, ST
	Hole 4 - 60˚	0.042	DC - ST
	Hole 5 - 67.5˚	0.004	DC - AF, ST
Examiner (n = 31)	Hole 1 - 32˚	0.445	None
	Hole 2 - 75˚	0.003	DC - AF, ST
	Hole 3 - 45˚	< 0.001	ST - AF, DC
	Hole 4 - 60˚	0.002	DC - AF, ST
	Hole 5 - 67.5˚	0.005	DC - ST

The only combination of group and hole that was not statically significant was Hole #1 for the examiners. The last column shows how the tools related to each other based on significance. A “ - ” symbol represents that those two tools are significantly different, where a “ , ” means the tools were not significantly different. For students, Holes #1, #3, and #5 had a significant difference between the digital calipers and both of the other tools. Holes #2 and #4 had a significant difference between the digital caliper and Smart Tool™. For examiners, Holes #2 and #4 had a significant difference between the digital caliper and both of the other tools. For Hole #3, the Smart Tool™ was significantly different than both of the other tools. For Hole #5, the digital caliper and Smart Tool™ were significantly different. This analysis shows that the statistical difference between the tools is mainly between the digital caliper and the other two tools and rarely between the Smart Tool™ and angle finder. The only statistical significance was between the three tools, and not the holes or groups, which indicates that this project tested the tools' abilities and not that of the groups and was not dependent on the holes' construction.

Figure 4 graphically shows the difference in the mean precision of the tools by group and hole.

Figure 4

Graph of Mean Precision by Tool



This graph shows how inconsistent, with regard to precision, each tool was from hole to hole, for both the students and examiners. The values of mean precision are also inconsistent from tool to tool; this can be seen in the fact that highest mean precision of one tool only barely touches the lowest mean precision of another tool. This demonstrates how the tools can be statistically significantly different from each other. Again, with the Smart Tool™ being significantly lower than the angle finder, which was statistically significantly lower than the digital caliper. Another interesting note is that although there was not a large difference in patterns of precision between the students and examiners, the students were slightly more consistent from hole to hole for all three tools. The examiners had more fluctuation for the angle finder and digital caliper than the students.

Hypothesis 2: H_0: There is no significant difference between the accuracy rates of the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper.

After a 3 - factor (tool, hole, group) ANOVA with 2 repeated factors (tool and hole) assuming a heterogeneous compound symmetry structure was completed, it was found there was a significant interaction between tools and holes. All other interactions of tool, hole, or group came back with no statistically significant differences. The three-way interaction was not significant at $p = 0.2876$, but the two-way interaction for tool and hole was significant at $p < 0.0001$ indicating that differences between the tools must be analyzed separately for each hole.

An additional analysis of variance was performed to look at the significance between the tools based on the holes and groups. All but two holes, Hole #4 for examiners and Hole #3 for students, had a statistically significant difference between tools with regard to mean bias. These results are found in Table 20.

Table 20

Analysis of Variance for the Tools based on Group and Hole

	Hole	*p* - value
Student (n = 17)	Hole 1 - 32˚	< 0.001
	Hole 2 - 75˚	< 0.001
	Hole 3 - 45˚	< 0.001
	Hole 4 - 60˚	0.129
	Hole 5 - 67.5˚	< 0.001
Examiner (n = 31)	Hole 1 - 32˚	< 0.001
	Hole 2 - 75˚	< 0.001
	Hole 3 - 45˚	0.054
	Hole 4 - 60˚	0.004
	Hole 5 - 67.5˚	< 0.001

All highlighted cells indicate a statistically significant difference between the tools. In each case, the digital caliper was significantly different from the angle finder and Smart Tool™.

To further analyze the significant interaction between tools and holes, tests for simple effects were performed. Table 26 contains the mean bias for each combination of tool and hole. The *p*-values indicate there was a significant difference between the mean biases of the tools at each hole. The results of the Tukey's multiple comparisons for each hole are displayed in the bottom row of the table. Groups separated by a comma are not significantly different and groups separated by a hyphen are significantly different.

Table 26

Mean Bias for Tools at each Hole

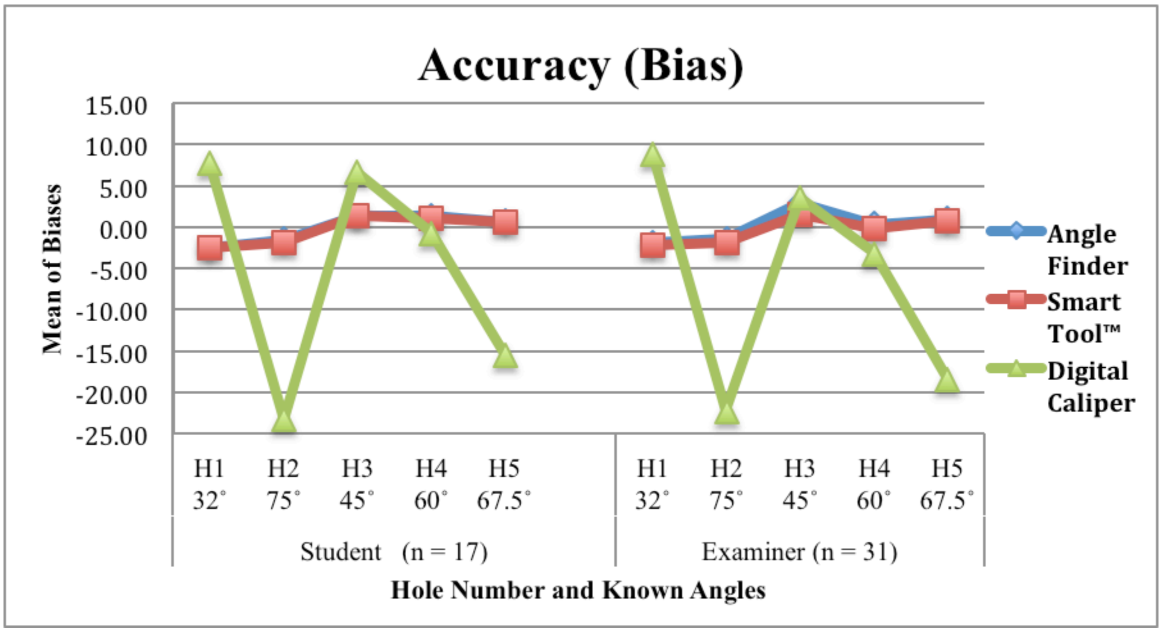
Tool	Hole 1 - 32˚	Hole 2 - 75˚	Hole 3 - 45˚	Hole 4 - 60˚	Hole 5 - 67.5˚
Angle Finder	-2.17˚	-1.41˚	2.18˚	0.91˚	0.85˚
Digital Caliper	8.23˚	-22.76˚	5.06˚	-1.98˚	-16.94˚
Smart Tool™	-2.33˚	-1.82˚	1.51˚	0.53˚	0.71˚
p - value	< 0.0001	< 0.0001	< 0.0001	0.0136	< 0.0001
Multiple Comp.	ST, AF - DC	DC - ST, AF	ST, AF - DC	None	DC - ST, AF

The difference between the mean bias for the Smart Tool™ and angle finder was very close for all five holes. The difference between those two tools and the digital caliper, however, was significantly larger. A mean bias for the digital caliper on Hole #2 was -22.76˚. This means that the hole was read an average of 22.76˚ below the hole. For Hole #2 and Hole #5, there was a large difference between the digital caliper and other two tools. This difference demonstrates the need for examiners and students to be trained with digital calipers. Although this tool has a large margin for error, it is still necessary when there is only one impact hole found at a scene, and therefore cannot be overlooked in investigations. Examiners must be trained on the sources of error that are possible with this tool. They should understand the ability of digital calipers to be zeroed at a number below zero, thus skewing future measurements. Examiners should also understand how sensitive the tool can be in regards to how far it is inserted into the impact hole and how far it is opened; and realize that a change even in the thousandths place can make a large difference in the calculation of the impact angle.

Figure 5 graphically shows the difference in the mean bias for the tools by group and hole.

Figure 5

Graph of Mean Bias for Tools by Group and Hole



This graph demonstrates how consistent the angle finder and Smart Tool™ were to each other and from hole to hole, for both the students and examiners. The mean bias lines for these two tools were nearly identical for the students. For the examiners, only a slight difference for the angle finder at Hole #3 was the major difference in the mean bias lines. The digital caliper was extremely inconsistent from hole to hole in their mean biases and in how large the mean bias was from hole to hole. The mean biases for the digital caliper ranged from 8.76˚ to -23.24˚, this is a range of 32˚. This range is drastic in size, especially when compared to the range of 5.49˚

for the angle finder and 4.05˚ for the Smart Tool™. These ranges of mean biases confirm the rejection of the null hypothesis, proving there is a statistically significant difference in the accuracy rates of the three tools.

As a separate analysis, a one-factor analysis of variance for tools, with regard to mean bias, was performed. Tukey – Kramer multiple comparisons were run on the Least Squares Means of the three tools and found that the digital calipers were significantly different from the other two tools with a *p* – value of $p < 0.0001$, but the Smart Tool™ and angle finder were not significantly different from each other with a *p* – value of $p = 0.0855$.

Hypothesis 3-5: H_0: There is no significant difference between the examiners and students using the Smart Tool™, angle finder, or digital caliper.

Table 30 contains the *p*-values for groups using each tool to determine significance between the students and examiners.

Table 30

Significance Levels between Participants for Each Tool

	Smart Tool™	Angle Finder	Digital Caliper
Accuracy (Mean Bias)	0.5156	0.2997	0.1032
Error (|Bias|)	0.3116	0.2284	0.5208
Precision (Standard Deviation)	0.3159	0.7851	0.2588

Table 30 shows that there was no statistically significant difference between the students and examiners for any tool based on the accuracy, error, and precision rates, thus confirming the null hypothesis. This data shows that on all three aspects the examiners and students performed similar for all the tools. This is encouraging because it indicates that experience does not play a role in using these tools. As long as the proper use of the tools is explained and understood, the tools are just as effective in the hands of a novice investigator as an experience investigator. The basic principles behind reconstruction and using the tools are simple and can easily be learned. The benefit of experience will come into play when a reconstruction scene is complicated or has conflicting information, but not when it comes to using the tools.

Error Rates

What are the error rates for the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper?

The error rates for this project are reported in percent error. A percent error allows you to calculate the percentage that a measurement will be off from the actual value.

The percent errors are reported in Table 22. They were created by using the formula:

$$\% \text{ Error} = \left| \frac{\text{Known Value} - \text{Experimental Value}}{\text{Known Value}} \right| \times 100$$

Table 28

Percent Error by Hole and Tool Using Error (|*Bias*|) *by Hole and Tool*

Tool	Hole 1 - 32˚	Hole 2 - 75˚	Hole 3 - 45˚	Hole 4 - 60˚	Hole 5 - 67.5˚
Angle Finder	8.28%	3.15%	5.07%	2.10%	2.18%
Digital Caliper	25.72%	30.35%	12.51%	7.15%	25.48%
Smart Tool™	8.44%	2.47%	3.42%	1.90%	1.60%

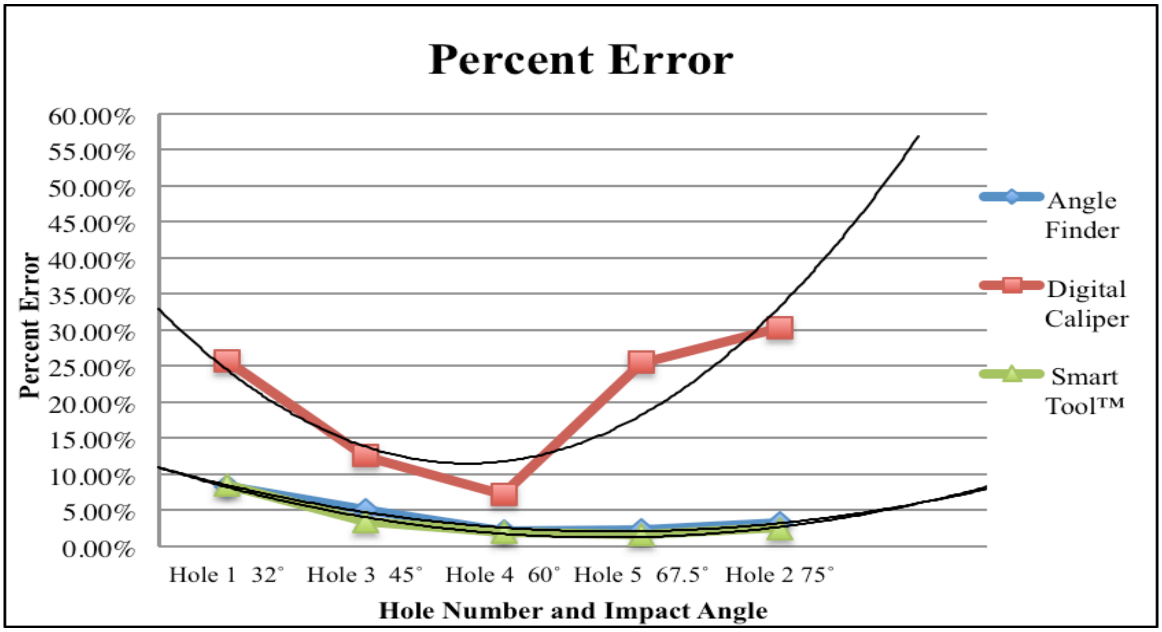
Just as with the mean bias for the tools by hole, the percent errors for the Smart Tool™ and angle finder were consistent from hole to hole and were very close to one another. The percent error for the angle finder ranged from 2.10% to 8.28%, while the Smart Tool™ ranged from 1.60% to 8.44%. The digital caliper, however, had percent errors that ranged from 7.15% to 30.35%. The digital caliper percent error does not start until just under the high end of error for the other two tools. Not only was the percent error higher, but it also had a wider range of error, compared to the Smart Tool™ and angle finder. It was interesting to note that the 45˚

impact angle did not have the lowest percent error; this suggests that the testers were not biased toward the angles read from the tools based on what they visually saw with the trajectory rods.

Figure 6 is the graphical representation of Table 28. The graph was created in order of increasing impact angles to demonstrate the change of percent error as the impact angle changes. Applied on top of the lines for each of the tools is a trend line that estimates the percent error at lower and higher angles than were tested in this project.

Figure 6

Percent Error by Hole and Tools in Order of Impact Angle with Trend Lines



This graph further shows the difference between the percent errors for the digital calipers compared to the Smart Tool™ and angle finder. With the walls in order of increasing impact angle, it is easier to see a pattern of error between the holes. As the impact angles get more obtuse and more acute, the percent error increases. Trend lines have been placed over the graph to indicate the trend if the angles were tested at lower and higher angles that were not tested in this project. The lines show that this pattern of increasing error significantly increases from 67.5˚ and higher. Although the trend for the Smart Tool™ and angle finder was at a lesser extent than the digital caliper, it was still increasing at the lower and higher angles tested. This phenomenon has also been seen in other studies such as Barr (2001a) and Barr (2001b).

Haag (2008), Barr (2001a), Barr (2001b), and others performing similar projects have tried to set a standard error range to be applied to all measurements. This study tried to create a standard range of error for the tools, but one range could not be established overall because there were statistically significant differences between the tools. A separate range would have to be set for each tool individually. This too was not possible due to the significant interaction found between the holes themselves; this is why the percent errors were calculated using the absolute biases for each hole. As previously mentioned, the increase of error as the impact angle became more obtuse and acute show that one error rate cannot be created for a tool. There is too much variance over all angles to have one determined error rate overall.

As mentioned earlier, there are a number of law enforcement departments that take multiple measurements with various tools; these measurements are then averaged together. This process has been unchallenged until now, but the error rates in this project, along with the significant difference found between the digital caliper and the other two tools, reveal that this process can no longer occur. There is too much interaction and variance between the holes and tools for the results to be averaged together. When the tools are averaged together, the results can be skewed wildly. This skewing of results can alter the reconstruction that might not happen if one tool was used.

Questionnaire

The following information is from a short questionnaire the participants were asked to fill out after their participation in the study; of the 48 examiners that participated, 43 filled out the questionnaires.

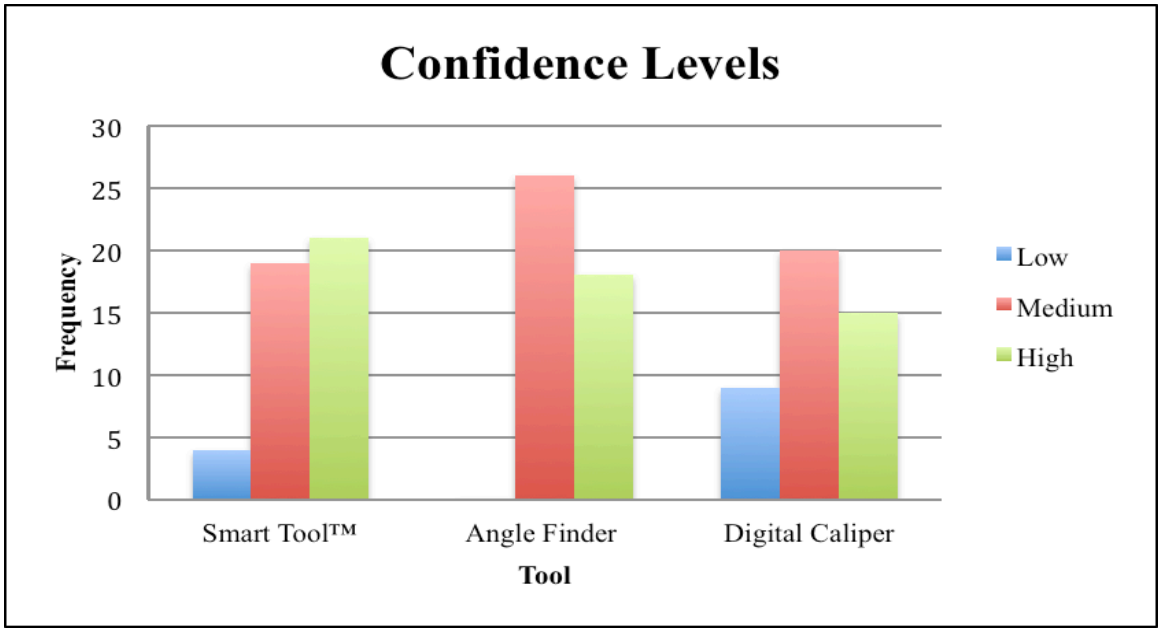
What are the participants' experience and confidence levels with the tools?

The participants were asked what previous experience they had with each of the tools. The Smart Tool™ had few participants with experience using this tool. The digital caliper and angle finder had moderate levels of experience. It was not surprising that there were not many participants experienced with the Smart Tool™; this tool is not standard to a general reconstruction kit and is considerably more expensive than other reconstruction tools. When asked where the participants felt their experience levels were the majority felt they were at a novice level, with 14 feeling they were experience and four said mid-level experience.

The confidence levels for the participants with each of the tools after completing the project are graphically represented in Figure 7.

Figure 7

Confidence Levels with Tools



It important to note that although the participants had limited experience with the tools in this project, the participants felt at least medium to high confidence levels after the project was completed; this demonstrates the ease with which these tools can be learned. Not only is the ability to learn these tools simple, but also the education of these tools. Teaching reconstructionists about these tools, their pros and cons, and the geometric equations that go along with reconstructing a scene is not a difficult task and should not be skipped due to a belief that using these tools is a skill set that can simply be learned without the proper instruction.

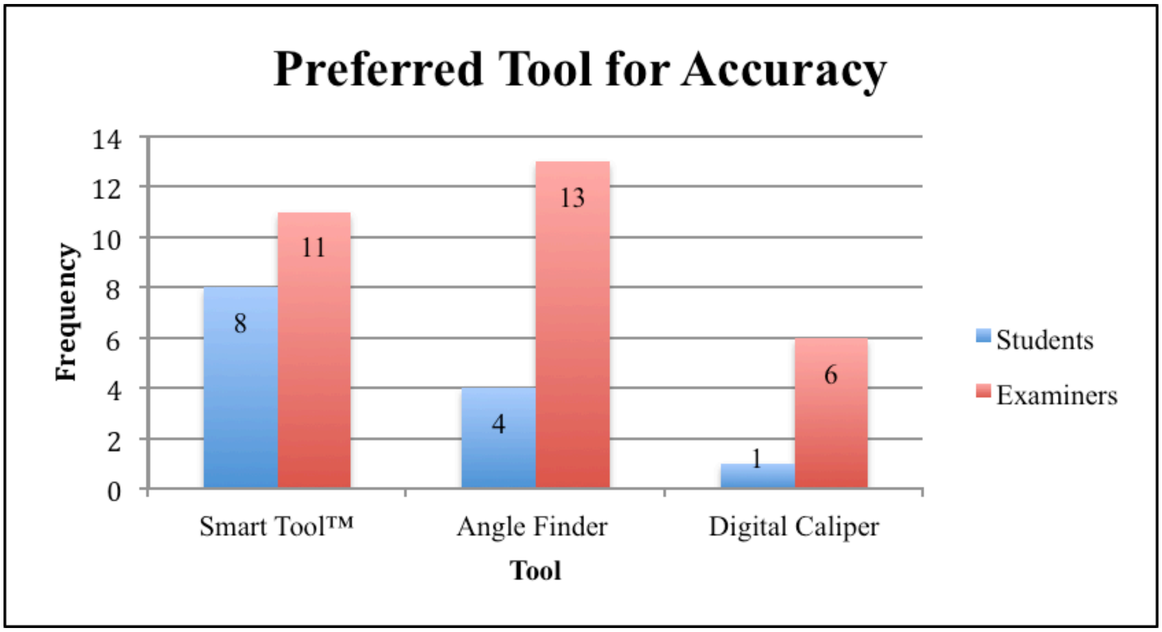
What tool is preferred by the participants?

When it came to which tool was felt to be more accurate the examiners chose the angle finder because it was easier to use. The Smart Tool™ was heavy and made the trajectory rod wobble and the digital caliper lends itself to be more subjective in measurements and error. The angle finder held better to the rod without shifting, and this was well received. The Smart Tool™ was chosen because it was easier to read, gave you an exact measurement, read in more detail than the angle finder, and its simplicity in use. The digital caliper was not chosen often, but it was chosen because the math does not have error.

The students chose the angle finder for its ease of use. The Smart Tool™ was chosen because of its easy to read display, similar measurements each time, and easier measurement of the impact angle. No reason was given by the one person that chose the digital caliper. The frequency at which each of the tools was chosen is in Figure 8.

Figure 8

Participants' Preferred Tool for Accuracy



It is interesting to note the significant difference between the examiners and students when it came to the frequency of the angle finder and digital caliper being chosen. The examiners were fairly close from tool to tool on which was preferred, while the students had a clear difference between the tools. There was an obvious preference for the Smart Tool™ by the students and the angle finder by the examiners.

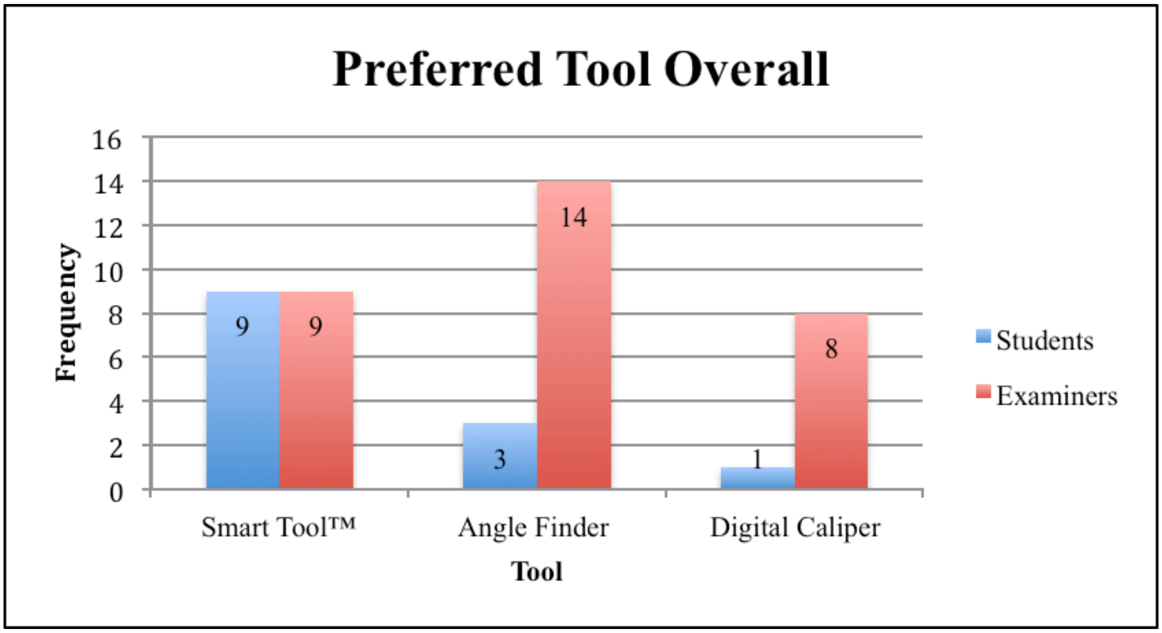
When it came to which tool preferred overall the examiners chose the angle finder because it was found to be less cumbersome and easier to use. The examiners liked the ridge at the bottom of the tool that allowed it to sit on the trajectory rod. The examiners felt there was less subjectivity an error compared to the digital calipers. Unlike the Smart Tool™, the angle finder was light enough to rest on the rod without making it wobble and did not require batteries or protection. These last two facts were very important to the examiner since they could put it into their trucks and no matter how many scenes they needed to go to they would not have to worry about its physical condition or whether it has enough battery power to work. The Smart Tool™ was chosen because it was quick, easy to use, had less of a chance for error, and easy read display. It was also chosen because it was easy to know when the tool was tilting and providing a wrong measurement. The digital calipers were chosen because they can be used in spaces and situations when a Smart Tool™ or angle finder cannot fit or work and you can take the measurements and average them together. One examiner also chose the digital calipers because it is important to be familiar with trigonometric calculations because they are necessary in every investigation.

The students chose the angle finder for ease of use and because it didn't need batteries. The Smart Tool™ was chosen because it felt more accurate than the manual calculations, the quickest method, and had a low level of difficulty. Again, no response was given for the one person that chose the digital calipers.

The frequency numbers of the participants' choices for which tool was preferred overall for use everyday are graphically shown in Figure 9.

Figure 9

Preferred Tool Overall



Although the Smart Tool™ was selected with a higher frequency over the digital caliper for the more accurate tool by examiners, both tools were chosen with almost as much frequency when it came to preferred tool overall. This spoke to the examiners' knowledge that the digital caliper may contain more error than the Smart Tool™, but their preference to having more solidity in their angle calculations. Those that chose the digital calipers liked knowing that the math does not contain error and that they can rely on this when constructing a scene. If asked how or what they performed in reconstructing the scene, they would have the math to back up their statements. This change in preference from Smart Tool™ to digital caliper was not seen in the students. This may be due to their knowledge that the digital calipers have significant error possibilities and their lack of backing up reconstruction statements the examiners have to do with their positions in law enforcement. It is also very clear from both Figure 8 and 9 and the descriptions given by the participants for their preferences that there was not one consistent thought for which tool was more accurate or their favorite overall. This demonstrates that if a reconstructionist has a favorite tool that is different from someone else that this is not bad, each person simply needs to know the pros and cons and sources of error for the tool they use.

Implication of Study

Court

Many aspects in this project have a direct correlation to how reconstruction will have to be conducted and reported in the future to have the correct results for court. This project began the validation process for this discipline on a large scale and highlighted areas that require further examination. One such area is concerning the concept of one overall error rate for the entire discipline. There was too much variance and interaction found between not only the tools tested in this project, but also between the angles tested to have an error rate for each tool, let alone the entire discipline. It has been suggested by various papers that an error rate of +/- 5 – 10 degrees should be added to all measurements taken by digital calipers or angle finders (Barr, 2001a; Barr, 2001b; Haag, 2008). These error rates only apply to those two tools and cannot be applied to the discipline in general. In addition, due to data collected from this project concerning the interaction impact angles play into error rates, the error rates presented in these papers do not apply for those tools across all angle measurements. There is an increase in error at the low and high ends of impact angles that make singular error rates for individual tools impossible. The closest the tools can get to a standard error rate is a general statement about their error as calculated by taking the absolute value of their mean biases across this project. It can be said that in the most general sense of error, the Smart Tool™ has an error rate of 1.69˚ ± 1.36˚, the angle finder of 2.05˚ ± 1.78˚, and the digital caliper of 11.69˚ ± 8.66˚.

Through this project, it has been learned that there are a number of law enforcement departments that take multiple measurements with various tools; these measurements are then averaged together. This process has been unchallenged until now, but the error rates in this project, along with the significant difference found between the digital caliper and the other two tools, reveal that this process can no longer occur. There is too much interaction and variance between the holes and tools for the results to be averaged together. When the tools are averaged together, the results can be skewed wildly. This skewing of results can alter the reconstruction that might not happen if one tool was used. The Smart Tool™ and angle finder were not found to be statistically significantly different from each other, this means that an examiner can measure with one tool and double check the findings with the other tool, but the examiner can still not average the values together due to the accuracy and precision rates.

Digital Calipers

Although the digital caliper had a percent error that was considerably higher than that of the Smart Tool™ and the angle finder for some holes, this tool cannot be eliminated from crime scene investigations. It is one of the only ways to estimate the impact angle when there is only one impact hole. Shooting incidents that only leave one impact hole cannot be ignored due to issues with the digital caliper; instead, their results need to be understood as a rough estimate of the impact angle.

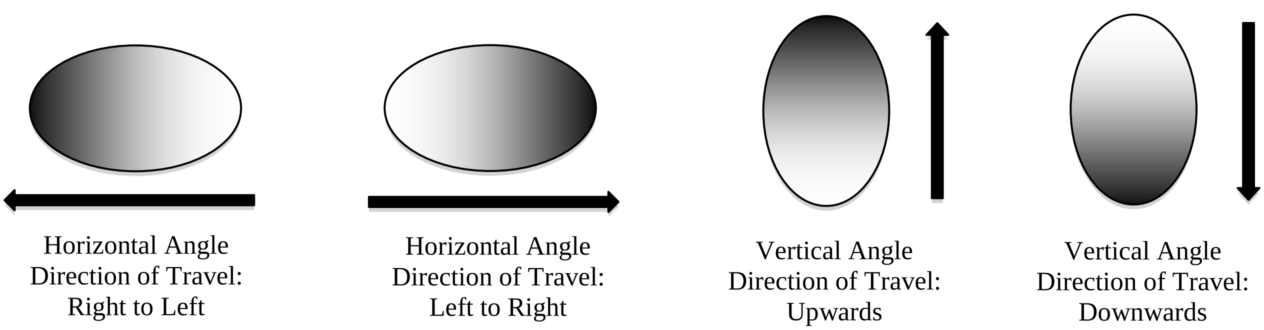
It is clear from the error rates and inconsistent accuracy and precision rates that the digital caliper has many problems, so it is important that examiners that use this tool understand not only its flaws, but also ways to combat them. The first error is simply with the tool itself.

With the model tested in this project, it was possible to push the tool past zero. If it was zeroed at this point it would be off by how far past zero it was set when measuring impact angles. Examiners that use this tool need to be aware of this problem and ensure that the tool is closed when zeroed, but no further pressure is applied to allow it to go past zero. Another way to help with this problem is by buying better quality digital calipers, which will not move past zero.

Digital calipers and manual calculations can also have error based on the knowledge level reconstructionists have with the process. Throughout the process of working on this project, it became clear that there might be a slight confusion in the understanding what angle is actually being measured by the digital calipers. This confusion may also be impacting case files and published papers. Digital calipers can only measure impact angles in one direction at a time. If the impact hole is vertical, upward and downward directionality, digital calipers can measure the vertical impact. If the impact hole is horizontal, left or right directionality, the tool measures the horizontal impact angle. The angles are further demonstrated in Figure 10.

Figure 10

Horizontal and Vertical Impact Angles



Another issue with the digital caliper is that a small math error can be exasperated into a major problem. The digital caliper uses measurements to use the equation: “IMPACT ANGLE =

arcsin (Width/Length)" (Fischer, in James 1999, p. 2) to calculate the impact angle. Due to the use of ratios and inverse sine, a small error can quickly become a large error**.**

An example of this situation is if measurements are taken as the following:

$\frac{\text{Width: } .340 \text{ in}}{\text{Length: } .458 \text{ in}} = .742$ Impact angle = $\sin^{-1}$ (.742) = 47.90˚

$\frac{\text{Width: } .345 \text{ in}}{\text{Length: } .458 \text{ in}} = .753$ Impact angle = $\sin^{-1}$ (.753) = 48.85˚

It is clear from just this simple change of .340 in to .345 in changes the impact measurement by nearly a degree. The difference of a degree may not appear to be a drastic change, but what is important is the small change that made this alteration. The difference in the measurements was only a change of five thousandths of an inch and only in the width and not the width and length. The difference in impact angles grows exponentially when you add in changes in the width and the length. This math error moves from the ratio of width to length on to the inverse sine and then again in the change from impact angle to the length in question at the scene.

Another math error occurs when entering the data into the calculator. There are many times that the collection of the data was done correctly, but is entered into the calculator incorrectly, causing a wrong impact angle. Examiners must be sure to double check the data entered into the calculator to ensure that not only the numbers are entered properly, but also that the numbers are rounded appropriately and the right trigonometric function is used. These problems show that even when the digital calipers are used correctly, there is still a chance for error.

There are steps that can be taken to further assist the digital caliper in making the best measurements. The first step is to use at least triplicates when measuring. Since there is an issue with consistency of measurements with this tool, measuring in triplicates helps to even out the measurements. If there was a measurement in the set that was further away from the actual measurement, it would get closer through averaging the measurements. An added benefit of using a digital caliper in triplicates is that if there are inconsistencies in the measurements or a largely different value, this will become obvious to the examiner and indicate an error and that other measurements need to be made.

Another step to help improve caliper accuracy and precision is to understand possible issues with the impact holes at a crime scene. If the impact hole is damaged then measurement of its true width and length can be difficult. Damage can happen to a bullet hole depending on the angle of the impact and the surface it strikes. There are multiple surfaces, like wood, that splinter and alter the shape of the impact hole. There are also substances, like metal, that stretch the hole, making the impact hole longer or larger than a normal impact hole at that angle.

In addition, manual calculations using trigonometric functions work with holes that are elliptical in shape. Often crime scenes do not have ideal elliptical or oval shapes. The shape can be altered not only by what the substance struck, but simply by the shape of the bullet itself. Most bullets, with the exception of wadcutter bullets, have a rounded nose and cause the elliptical shape of the impact hole to be lost to the rest of the bullet hitting the surface. Examiners need to learn how to recognize issues with bullet holes at crime scenes and how deal with the phenomenon (Barr, 2001a). It is crucial that examiners understand how to see the true oval of the impact hole and measure this shape and not the entire impact hole. There have been a few studies that have proposed methods to help visualize the true elliptical shape of an impact hole. These methods include photographing the hole and superimposing an elliptical shape over the impact hole in the computer, using transfers, and altering how the measurements are taken

(Barr, 2001a; Barr, 2001b; Cashman, 1986). These methods found similar error rates to this project and show that with knowledge of the possible errors associated with manual calculations with trigonometric functions, these problems can be lessened.

A last step to help with working with digital calipers is using the crime scene to assist. It is imperative with the error rates and inconsistencies that digital calipers have that evidence from the scene help verify the reconstruction. After the impact angles are calculated and a reconstruction is made, it is important to look back at the scene and see if the reconstruction fits with the scene dimensions and plausible scenario.

Smart Tool™ and Angle Finder Comparisons

It was found through statistical analysis of data in this study that the Smart Tool™ and angle finder were not statistically significantly different from each other based on their mean biases. There was, however, a significant difference between the two tools based on their mean standard deviations. Since there was such a small margin between these tools, it is important to look past the data and towards the tools themselves. The Smart Tool™ was found to have the best standard deviation, but it has a few design issues that can interfere with its use in crime scene reconstruction. First, the Smart Level™ is heavy, which if placed at the end of the trajectory rod can weigh down the rod and alter the impact angle. The angle finder is extremely light and even when placed at the very end of the trajectory rod will not alter the trajectory rod or impact angle reading. The Smart Tool™ is digital, so this means it requires batteries and must be kept in a protective case; on the other hand, the angle finder does not require batteries and can be carried anywhere without risk of damage to the tool. In addition, the Smart Tool™ does not have a slot to sit on the trajectory rod; this means it must be held in place by the examiner and the impact angle changes as the Smart Tool™ wobbles on the trajectory rod. This leads to an additional element of human error and uncertainty. The angle finder has a ridge that allows it to sit without assistance on the trajectory rod. The Smart Tool™, unlike the angle finder, has a clear, easy to read display that does not require an examiner to read between degrees to calculate the impact angle. It was because of these differences that the angle finder was chosen as the preferred tool by this study.

Although the Smart Tool™ and angle finder had very good accuracy and precision rates, these rates were created by averaging the measurements together; this means that there could have been larger measurements above and below the hole. In order to combat this change in accuracy and precision it could be helpful to measure in triplicates like with the digital calipers. Measurements should be taken in at least doubles to ensure that the tool was read correctly and the trajectory rod was placed correctly. This small change in protocol will ensure that these two tools maintain their small accuracy and precision rates in crime scenes.

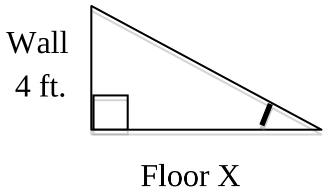
Mathematical Examples

The below examples are single situations worked out for one instance and not overall conditions. The examples will change as the angles and distances are changed.

All of the data in this project has been presented in changes of various degrees. Figure 11 displays the change in feet in a reconstruction if the impact angle is changed by 5˚ increments. This example is used to demonstrate the importance of the mean biases and standard deviations of the tools used in this project. Any tool can be used to work through this example. Figure 11, below, demonstrates a reconstruction scenario common to crimes scenes.

Figure 11

5˚ Change Scenario



This reconstruction uses the equation Tan (Angle) = Opposite/Adjacent. With the known values put in the equation then becomes: Tan (Angle) = $\frac{X}{4}$ or if rearranged: 4 • Tan (Angle) = X.

Figure 12

Alterations in Feet by 5˚ Changes

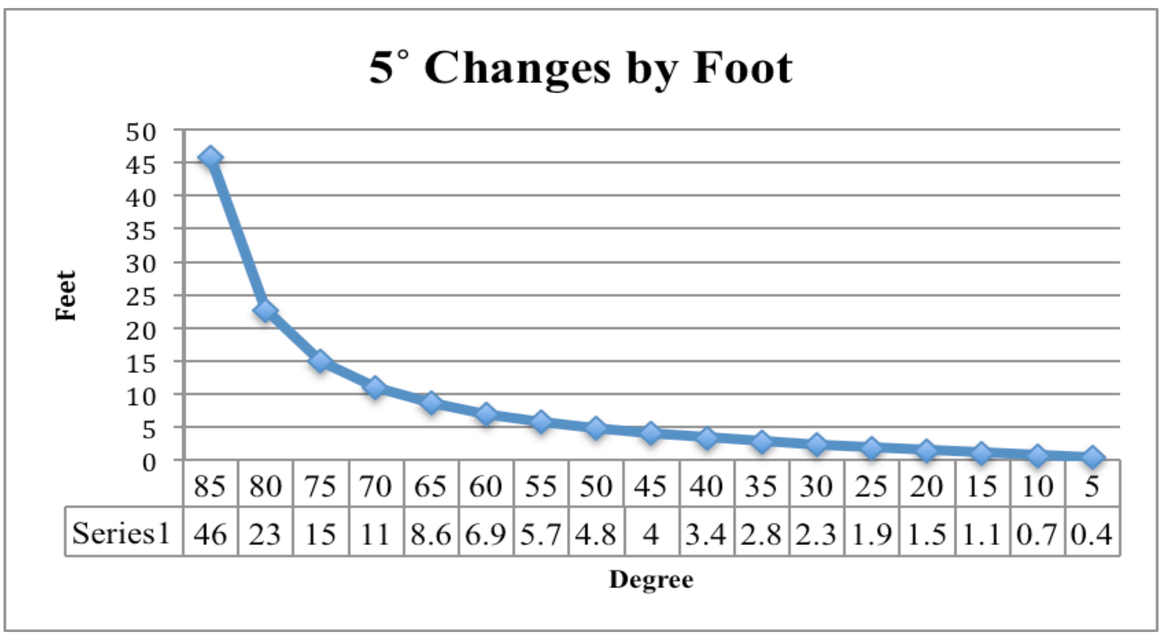


Figure 12 shows the substantial change in feet as the impact angle is changed from 5˚ up to 85˚ for the floor measurement (X). Up to 60˚, the change between 5˚ intervals was minimal. The change grew from 0.4 feet to just over one foot in between the intervals. After 60˚, however, the change became drastic, nearly doubling at every interval. This significant change at around 60˚ aligns with the increase in error at obtuse and acute angles found in this project.

This curve also stresses the inability to have a standard error rate for the tools used in reconstruction. With this large change of results over the range of angles, one error range is not practical. Any error range calculated would work for only a portion of angles measured and not the full range possible. This curve also emphasizes the need to be extremely careful and diligent when measuring angles, especially when at larger angles. The smallest change or error can make a large impact on the reconstruction. This example was completed using calculations with tangent; the curve for changes over the range of angles would change if the math were performed with a cosine or sine curve. The results would still show a change in values as the angles change, but the curve would follow a different pattern.

The digital caliper had a percent error of 12.51% at the impact angle of 45˚. This means that a measurement taken with a digital caliper could be off from the true mark by 12.51% above and below the known value. This would change a measurement of 45˚ by 5.625˚, making the measurement as low as 39.375˚ or as high as 50.625˚. When placed in the same reconstruction scenario as above, in Figure 12, a true measurement of 45˚ yielded a distance of 4 feet for the answer. When the range of values is entered into the equation, the 4-foot value changes to 3.28 feet at 39.375˚ and 4.87 feet at 50.625˚. This range of around .70 feet above and below the actual measurement may not sound significant, but it becomes very important to the reconstruction when a reconstructionist is asked to place the suspect in the crime scene using the horizontal angle. This range becomes extremely important if the foot and a half difference means the difference between the suspect being able to make the shot in question or not.

Limitations of Study

The impact holes in this study were created by a power drill and bit of known diameter instead of a wall being fired upon by a gun. This change from a crime scene is crucial because the accurate measurement of a hole's angle was utilized in order to determine the accuracy of the volunteers' measurements. A ransom rest was not incorporated because in a similar study, unsteadiness in the shooter caused complications in determining the aiming point when the experiment was carried out at 100 meters (Nennstiel, 1991). In addition, if impacts in the walls were created through firing a gun, then the impact angle would be unknown at a specific level and would have to be determined by another method; this adds another variable and human error into the project. With power-drilled holes, an exact and precise angle could be established and drilled. Although, the variation in measurements would be small based on factors such as bullet composition and design or surface mediums, research indicated that studies of this nature will not work without a known angle to refer back to (Trahin, 1987).

The trajectory rods fit perfectly into the impact holes, so there was no chance of fluctuating or a misreading. This was not similar to fieldwork, but necessary to the project. If the examiners were asked to place a poor fitting trajectory rod into the impact hole and read the angle, the project would then be testing the volunteer's ability to correctly place the trajectory rod and not the tool's ability to obtain the measurement.

There was a small chance of bias in this project concerning the participants remembering what an impact angle was found to be and changing their answer to match a previous measurement. To minimize this possibility, the participants measured all five impact holes before moving onto another tool. This was an attempt to eliminate bias toward the next tool's results. In addition, each participant turned in their data sheet for the method they were working on for that round of five impact holes once the measurements were completed. The participants were not able to keep the data on what angle they found the impact holes to be. This again was an attempt to minimize the bias toward changing answers for a method or impact angle to match previous measurements. The participants were asked to wait one minute between measurements as an attempt to insure that no impact angle measurements were remembered before starting the next tool. It is believed, however, due to the amount of numbers the volunteers were working with that there was little chance of remembering measurements from previous trials and tools, however the potential limitation is apparent and possible.

It was mentioned by a few of the participants that one or two of the walls tended to shift from back to front. This shifting may have altered some of the measurements, but it is not believed that these alterations were significant. Another possibility that may have had the potential to slightly alter measurements was the fact that some participants held the Smart Tool™ on the arrow shafts, while others let them rest on the trajectory rods. There was some weight associated with the Smart Tool™ not found in the angle finder and this may have effected the measurements slightly.

In crime scene work, the horizontal angle of impact is collected to assist reconstruction. This project, however, due to the use of the power drill, had holes drilled straight on with a 0˚ horizontal angle. This means only the vertical angle was collected and there was no horizontal angle measured.

Recommendations for Future Research

Future studies should include repeating this same study with a wider range and number of impact angles. This wider range of impact angles should include very acute angles all the way to near 90˚. It would also be interesting to test if there was a difference between participants' abilities to measure accurately an acute angle versus a larger angle. Future studies should include these angles to be able to fully judge participants' abilities. Protractors are one of the most common tools used by reconstructionists in the field. Unlike the tools used in this study, there is no mechanical aspect to the protractor; it is held to the trajectory rod and simply read. Future projects should include this tool so crucial to the field of shooting trajectory reconstruction.

If the researcher repeated this study, the project would be done similarly, but with a few alterations. The project would include the same tools, but with the addition of the protractor. This project was done utilizing sheet rock walls to help maintain its connection to actual crime scenes, but to ensure that there are no issues with hole deformation in the sheet rock, wood should be used in the future project. The wood walls would be constructed in the same manner as the faux sheet rock walls in this project, but with medium density fiberboard (MDF) instead of sheet rock. In addition, since there was significant variation among the holes found in this project, a future project should include five impact angles of the same measurement and then continue this process for a full range of impact angles (5˚ - 85˚); this would mean 5 holes at 5˚, 5 holes at 10˚, 5 holes at 15˚, and so on. This would allow for comparisons with the same angle and then comparisons to see the difference between the various angles. The future projects should also include a larger data pool of participants. This will help to move validation of the study and discipline forward. In addition, although there was not a statistical significant difference found between the examiners and students, a future project should include participants from only one group, either students or examiners, so statistical analysis does not have to be preformed to test their effect on the study.

Other projects should be constructed containing just the digital caliper. It is clear from the data found in this project that the digital calipers have a significant level of error. The error associated with this tool needs to be further investigated. This can be tested in two further projects. The first project should focus on testing the effect various calibers of ammunition have on the ability for manual calculations using digital calipers to measure the impact angle. The impact angles would be created with a firearm in a ransom rest, however, instead of the drill press as with this project. The holes should be created by various calibers ranging from .22 to .50. Also tested would be a wide range of calibers of wadcutter bullets. This range of calibers allows for ogives in shapes that are rounded, truncated, and flat, to test if the shape of the ogive is playing a factor in the creation or measurement of impact angles at a crime scene. This project should include the same impact angle construction from the previously suggested project, with the repeated angles over a wide range of angles.

The second project using digital calipers alone should test their ability to measure vertical angles with various horizontal angles. This project will look into if the severity of the horizontal angle can reach a point that it affects the elliptical shape of the impact angle enough to alter the vertical angle measurement. This project would have the holes drilled into MDF with a drill press to have better control over the angles and consistency.

Conclusion

Overall, this project sought to establish the most efficient tool for shooting trajectory reconstruction among the Smart Tool™, angle finder, and manual calculations utilizing a digital caliper. Efficiency was determined by the accuracy (mean bias), precision (standard deviation), and error (percent error) rates of the three tools.

The first hypothesis looked to see if there was a significant difference in the precision rates of the three tools and the null hypothesis was rejected. A statistically significant difference was found between the three tools. The precision rate for the Smart Tool™ was significantly lower than that of the angle finder, which was significantly lower than the digital caliper. When the data was broken down in pairs, the difference in standard deviations between the participants and holes were not significant. This indicates the project truly tested the tools abilities and not that of the participants or the holes' construction.

The second hypothesis looked to see if there was a significant difference in the accuracy rates of the three tools and the null hypothesis was rejected. A significant difference was found between the digital caliper and the other two tools. The Smart Tool™ and angle finder were not found to be statistically different from each other. The Smart Tool™ and angle finder were also consistent from hole to hole; where the digital caliper varied widely. This demonstrates that although math does not have errors, using digital calipers requires reconstructionists to be taught to use them properly and practice with various situations. In addition, digital calipers should only be used when necessary; when there is only one impact hole, and not on a regular basis.

Hypotheses 3 – 5 examined if there was a difference between the examiners and students performances with the three tools. All three hypotheses were accepted; there was no statistically significant difference between the examiners and students based on any of the tools. This data shows that the tools used in this project, with instruction, can be used with ease and proficiency. Experience did not play a factor in the participants' abilities to use these tools. Experience does come into play when it comes to difficult scenes with damaged holes or conflicting information.

This project tested to see if an error rate for the angle finder, Smart Tool™, and digital caliper could be calculated. The error rates were calculated as percent error. The percent error for the angle finder ranged from 2.10% to 8.28%, while the Smart Tool™ ranged from 1.60% to 8.44%. The digital caliper, however, had percent errors that ranged from 7.15% to 30.35%. Not only was the percent error higher, but it also had a wider range of error, compared to the Smart Tool™ and angle finder. It was interesting to note that the 45˚ impact angle did not have the lowest percent error; this suggests that the testers were not biasing the angles read from the tools based on what they visually saw. A single error rate for each of the tools could not be calculated due to significant interaction from angle to angle. Another issue with one error rate was an increase in error found, as the impact angle is closer to an acute or obtuse angle. The closest these tools can get to a standard error rate is a general statement about their error as calculated by taking the absolute value of their mean biases across this project. It can be said that in the most general sense of error, the Smart Tool™ has an error rate of 1.69˚ ± 1.36˚, the angle finder of 2.05˚ ± 1.78˚, and the digital calipers of 11.69˚ ± 8.66˚.

There are a number of law enforcement departments that take multiple measurements with various tools and then average together the results. This process has been unchallenged until now, but the error rates in this project, along with the significant difference found between the digital caliper and the other two tools, reveal that this process can no longer occur. There is too much interaction and variance between the holes and tools for the results to be averaged together. When the tools are averaged together, the results can be skewed wildly. This skewing of results can alter the reconstruction that might not happen if one tool was used.

The participants had varied experience between just learning the reconstruction techniques up to 10 years. After completing the project, the participants reported at least a medium level of confidence with the tools, with a high frequency of high confidence levels. It is encouraging to see that even with low levels of experience, that the participants reported such favorable confidence levels; this speaks to the tools' abilities to be easily taught and learned.

When the participants were asked which tool they preferred the students chose the Smart Tool™. This was chosen for its technological aspect, clear easy to read display, and a feeling that it was more accurate overall and consistent from trial to trial. The examiners chose the angle finder. This tool was chosen because it is lightweight, consistent, and its ability to rest on the trajectory rod. The examiners also appreciated that it did not require protection or batteries like the Smart Tool™; they could put the angle finder in with the rest of the reconstruction equipment and not worry about its condition or ability to work. Only a few volunteers selected the manual calculations using a digital caliper for the most accurate tool. Those participants did so because they believed the math would not be false compared to reading other tools.

It was determined by this project that the statistical data between the Smart Tool™ and angle finder was close, but due to the ease of use, the angle finder was the most efficient tool tested in this project. It was also determined that neither an overall error rate for the discipline or for an individual tool is possible due to the change in error as the impact angle becomes more obtuse or acute. A side consequence of this finding is that tools can no longer be averaged together at scenes to get a better measurement; one tool must be used for all measurements. Another tool can be used to check on readings, but must not be averaged into the results. This project also found that although shooting trajectory reconstruction does not have validation of its processes or tools or a strong history of its beginning, the discipline has firm roots going back to bloodstain pattern analysis and geometric principles dating back to 3,000 B.C., ensuring that it is using proper methods to perform reconstructions. In addition, this project began the validation process for this discipline on a large scale and highlighted areas that require further examination.

References

Barr, D. (2001a). Modification to the common trigonometric method of bullet impact angle determination. *Association of Firearm and Tool mark Examiners Journal*, *33*(2), 116 - 121.

Barr, D. (2001b). The trig-elliptical method of bullet impact angle determination. *Association of Firearm and Tool mark Examiners Journal*, *33*(2), 122 - 124.

Bevel, T., & Gardner, R. M. (2001). *Bloodstain pattern analysis with an introduction to crime scene reconstruction*. (2nd ed.). (pp. 3, 5, 13, 15; pp. 1 – 17, 159 – 191). Boca Raton, FL: CRC Press.

Bevel, T., & Gardner, R. M. (2009). *Practical crime scene analysis and reconstruction.* (pp. 1, 4, 7, 8, 74). Boca Raton, FL: CRC Press.

Blumenthal, L. M. (1980). *A modern view of geometry.* (p. 2; pp. 1 - 18) New York: Dover Publications, Inc.

Caliper. (n.d.) Retrieved from http://www.mitutoyo.com/TerminalMerchandisingGroup.aspx?group=1386

Cashman, P. J. (1986). Projectile entry angle determination. *Journal of Forensic Sciences*, *31*(1), 86 - 91.

Clemens, D. W. (1998). Introduction to crime scene reconstruction. *MAFS Newsletter*, 27(2), para. 1 – 11.

Coxeter, H. S. M. (1961). *Introduction to geometry.* (pp. 3 – 5). New York: John Wiley & Sons, Inc.

Eves, H. (1963). *A survey of geometry.* (Vol. 1). (pp. 3, 5, 10, 11, 12; 1 – 19). Boston, MA: Allyn and Bacon, Inc.

Felson, M. (2006). *Crime and Nature.* Thousand Oaks, CA: Sage Publications, Inc.

Fetisov, A. I. (1963). *Proof in geometry.* (p. 6; pp. 1 – 7). Chicago, IL: The University of Chicago.

Fischer, W. C. (1999). Defining the “address” of bloodstains and other evidence at the crime scene & utilizing bloodstains in accident reconstruction. In S. H. James (Ed.), *Scientific and legal applications of bloodstain pattern interpretation* (p. 2; pp. 1 – 14, 33 - 46). Boca Raton, FL: CRC Press.

Garrison, D. H. (1993). Shooting reconstruction vs. shooting reenactment. *AFTE Journal,* 25(2), 125 – 27.

Garrison, D. H. (1996). The effective use of bullet hole probes in crime scene reconstruction. *AFTE Journal*, 28(1), 57 - 61.

Haag, L. C. (1976). The use of ballistic calculations in the solution of a crime. *AFTE Journal*, 8(4), 45 – 51.

Haag, L. D. (2006). *Shooting incident reconstruction.* London, UK: Academic Press.

Heath, T. L., (1956). *The thirteen books of Euclid’s elements.* (Vol. 1). (pp. vi – vii). New York: Dover Publications, Inc.

Houde, J. (1991). Short – range bullet trajectory computer program for MS – DOS computers. *AFTE Journal*, 23(3), 784 – 90.

Hueske, E. E. (2006). *Practical analysis and reconstruction of shooting incidents.* (pp. 69 – 70, 72, 89; pp. 21 – 44, 65 – 96, 161 – 196). Boca Raton, FL: Taylor & Francis Group.

James, S. H. (1999). Preface. In S. H. James (Ed.), *Scientific and legal applications of bloodstain pattern interpretation* (pp. iii – vi). Boca Raton, FL: CRC Press.

Lee, H. C. (2001). *Henry Lee's crime scene handbook*. (pp. 284 – 285; 281- 298, 305 - 315). London, UK: Elsevier Academic Press.

May, L.S. (1933). Scientific Murder Investigation*. Institute of Scientific Criminology,* 9.

Molnar, S. (1970). Use of scale drawings to establish facts in shooting cases. *AFTE Journal*, 6, 24.

Nennstiel, R. (1991). Determination of the line of sight angle through firing experiments. *AFTE Journal*, 23(4), 919 – 23.

Noedel, M. (2009). Shooting scene processing and reconstruction. In Bevel, T. & Gardner, R. M. *Practical crime scene analysis and reconstruction.* (pp. 152; 131 – 173). Boca Raton, FL: CRC Press.

O'Hara, C. E., & O'Hara, G. L. (1965). *Fundamentals of criminal investigations.* Springfield, IL: Charles C Thomas Publisher, LTD.

Parker, L. (2005). *Workbook on crime scene reconstruction of shooting incidents.* Bloomington, IN: Author House.

Rynearson, J. M., & Chisum, W. J. (1989). *Evidence and crime scene reconstruction*. JM Rynearson.

Smarttool. (n.d.). Retrieved from http://www.mdteam.com/index.php/products/smarttool

Smith, D. E., (1951). *History of mathematics.* (Vol. 1). (p. 68). New York: Dover Publications, Inc.

(2009). *Strengthening forensic science in the United States: A path forward*. Washington, D.C.: The National Academies Press.

Trahin, J. L. (1987). Bullet, trajectory analysis. *AFTE Journal*, 19(2), 124 – 53.

Wallace, E. C., & West, S. F. (1992). *Roads to geometry.* (pp. 95 – 6, 377 – 78; 1-4, 27 – 64, 94 – 184). Englewood Cliffs, NJ: Prentice-Hall.

Warren, G. (1991). Simple measurement of angles of elevation. *AFTE Journal*, 23(3), 869.

Definition of Terms

Right Angle: angle measuring exactly 90˚

Acute Angle: angle measuring less than 90˚

Obtuse Angle: angle measuring more than 90˚

Complementary Angles: two angles whose sums total to 90˚

Supplementary Angles: two angles whose sums total to 180˚

Right Triangle: a triangle that has one of its three angles equal to 90˚

(Trahin, 1987)

Hypotenuse: the triangle side opposite of the 90˚ internal angle

Opposite Side: the triangle side opposite of the internal angle in question

Adjacent Side: the triangle side adjacent to the internal angle in question, while not being the hypotenuse

Sine: Opposite side/Hypotenuse

Cosine: Adjacent side/Hypotenuse

Tangent: Opposite side/Adjacent side

(Bevel & Gardner, 2001).

Appendix

List of Geometric Principles Relating to Shooting Trajectory Reconstruction

Taken directly from the School Mathematics Study Group (SMSG)

(Wallace & West, 1992, pp. 95, 96, 377, 378)

- Postulate 11: *The angle Measurement Postulate:* To every angle <ABC there corresponds a unique real number between 0 and 180.
- Postulate 14: *The Supplement Postulate*: If two angles form a linear pair, then they are supplementary.
- Postulate 15: *The SAS Postulate:* Given a correspondence between tow triangles (or between a triangle and itself). If two sides and the included angle of the first triangle are congruent to the corresponding parts of the second triangle, then the correspondence is a congruence.
- THEOREM 3.2.3: Supplements (and complements) of the same or congruent angles are congruent.
- THEOREM 3.2.7: *Isosceles Triangle Theorem.* If two sides of a triangle are congruent, then the angles opposite those sides are congruent.
- THEOREM 3.3.1: *Angle-Side-Angle (ASA) Triangle Congruence theorem.* If the vertices of two triangles are in one-to-one correspondence such that two angles and the included side of one triangle are congruent, respectively, to two angles and the included side of the second triangle, then the triangles are congruent.
- THEOREM 3.3.3: *Angle-Angle-Side* (AAS) *Congruence Theorem. If the vertices of two triangles are in one-to-one correspondence such that two angles and the side opposite one of them in one triangle are congruent to the corresponding parts of the second triangle, then the triangles are congruent.*
- THEOREM 3.3.9: *Side-Side-Side (SSS) Triangle Congruence Theorem.* If the vertices of two triangles are in one-to-one correspondence such that all three sides of one triangle are congruent, respectively, to all three sides of the second triangle, then the triangles are congruent.
- THEOREM 3.4.1: *Alternative Interior Angle Theorem.* If two lines are intersected by a transversal such that a pair of alternate interior angles formed are congruent then the lines are parallel.

- COROLLARY 3.4.2: Two lines perpendicular to the same line are parallel.
- COROLLARY 3.4.3: If two lines are intersected by a transversal such that a pair of corresponding angles formed are congruent, then the lines are parallel.
- COROLLARY 3.4.4: If two lines are intersected by a transversal such that a pair of interior angles on the same side of the transversal are supplementary, then the lines are parallel.
- THEOREM 3.4.5: Euclid's fifth postulate is equivalent to the Euclidean parallel postulate.
- THEOREM 3.4.6: The Euclidean parallel postulate is equivalent to the converse of the alternate interior angle theorem
- THEOREM 3.47: The Euclidean parallel postulate is equivalent to the following statement: if a line intersects one of two parallel lines, then it intersects the other.
- THEOREM 3.4.8: The Euclidean parallel postulate is equivalent to the following statement: if a line is perpendicular to one of two parallel lines then it is perpendicular to the other.
- THEOREM 3.4.9: The Euclidean parallel postulate is equivalent to the following statement. Given and Δ PQR and any line segment AB, there exists a triangle having a side congruent to AB that is similar to Δ PQR.
- THEOREM 3.5.1: *Saccheri-Legendre Theorem*. The angle sum of any triangle is less than or equal to 180˚.
- THEOREM 3.6.18: The Euclidean parallel postulate is equivalent to the following statement: The angle sum of every triangle is 180˚.

Data Worksheet

EXAMINER #		METHOD	
HOLE #		TEST # (1 , 2, 3)	
ENTRY ANGLE		EXIT ANGLE	
START TIME		FINISH TIME	

EXAMINER #		METHOD	
HOLE #		TEST # (1 , 2, 3)	
ENTRY ANGLE		EXIT ANGLE	
START TIME		FINISH TIME	

EXAMINER #		METHOD	
HOLE #		TEST # (1 , 2, 3)	
ENTRY ANGLE		EXIT ANGLE	
START TIME		FINISH TIME	

Examiner Survey

Please note that this survey is for student research purposes and is not in any way affiliated with your employer. Your answers will contribute to research being conducted on shooting trajectory reconstruction methods and your time is greatly appreciated!
What is the nature of your occupation? (What, specifically, is your title and duties?)
How long have you been working with the methods tested today?
Have you ever done this type of work before? What capacity? (Work, class, etc.)
What is your experience level with this type of work? (Novice or Experienced)
Experience with Smart Tool? (Yes or No) If yes, how long and what capacity?
Experience with Angle Finder? (Yes or No) If yes, how long and what capacity?
Experience with Manual Calculations? (Yes or No) If yes, how long and what capacity?
What is your confidence level with each method? (low, medium, high)
Smart Level :
Angle Finder :
Manual Calculations :
Which method felt more accurate? (Smart Level, Angle Finder, Calculations) Why?
Which method do you prefer? Why?
Thank you for your time! Please feel free to use the space below to write any additional comments pertaining to your experience today.