1-1-2011

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Christopher Blackledge

Recommended Citation

Blackledge, Christopher, "A Motion Capture Based Analysis of the Effects of Body Armor on Shooting Posture" (2011). *Theses and Dissertations*. 192.
https://scholarsjunction.msstate.edu/td/192

A MOTION CAPTURE BASED ANALYSIS OF THE EFFECTS OF BODY ARMOR ON SHOOTING POSTURE

By

Christopher Blackledge

A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Masters of Science
in Industrial Engineering
in the Department of Industrial and Systems Engineering

Mississippi State, Mississippi

December 2011

A MOTION CAPTURE BASED ANALYSIS OF THE EFFECTS OF BODY ARMOR ON SHOOTING POSTURE

By

Christopher Blackledge

Approved:

Lesley Strawderman
Assistant Professor of Industrial and
Systems Engineering
(Faculty Advisor/Chair)

Kari Babski-Reeves
Associate Professor of Industrial and
Systems Engineering
(Committee Member)

Daniel Carruth
Associate Director of Center for Advanced
Vehicular Systems
(Committee Member)

John Usher
Professor of Industrial and Systems
Engineering
(Graduate Coordinator)

Sarah A. Rajala
Dean of the Bagley College of
Engineering

Name: Christopher Blackledge

Date of Degree: December 9, 2011

Institution: Mississippi State University

Major Field: Industrial Engineering

Major Professor: Dr. Lesley Strawderman

Title of Study: A MOTION CAPTURE BASED ANALYSIS OF THE EFFECTS OF BODY ARMOR ON SHOOTING POSTURE

Pages in Study: 59

Candidate for Degree of Masters of Science

Body armor designs that limit the range-of-motion required for vital law enforcement tasks, such as shooting may be dangerous. Therefore, a posture based biomechanical analysis was performed to determine if upper body joint angles can be used to assess the effects of armor designs on assumed shooting. Participants (n=8) completed a battery of simulated duty tasks for three armor configurations (no armor, concealable, and tactical armor) while motion capture was used to compute included joint angles of the upper extremity and neck. In general, joint angles were impacted by armor configuration, and law enforcement experience (measured in years) significantly impacted their shooting posture. It was also found that the types of tasks performed interacted with shooting stance. This research is a first step at developing a method to analyze body armor designs and their impact on wearers, so that mobility may not need to be sacrificed for additional protective coverage.

ACKNOWLEDGEMENTS

The author would like to acknowledge the research assistants and graduate students in the Human Performance Lab at the Center for Advanced Vehicular Systems for their tremendous efforts in collecting and processing the motion capture data used for this study. Special thanks go to Steven Slater who spent countless hours extracting and compiling snippets of shooting postures over hundreds of trials. Thanks also go to police officers of the Starkville Police Department for their cooperation, and willingness to be thoroughly put to the test. Without their volunteered time this study could not have been completed. Finally, extreme gratitude goes to the author's advisor and committee for showing endless patients and enthusiasm, even over long distances.

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CHAPTER I

INTRODUCTION

Law enforcement and military personnel wear protective vests while on duty to help prevent fatal injuries from projectiles, such as bullets or shrapnel. These personal body armor vests are designed to cover the torso of the body with a ballistic projectile penetration resistant material that will disperse the energy from a projectile so that it does not enter the body. Unfortunately, the materials needed to protect against a high-velocity-projectile impact are often heavy and not very flexible. When these materials are used to construct personal body armor, a trade off must be made between the vest's ballistic protection and the comfort or range of motion of the person wearing the armor. Due to this trade-off restriction, body armor can become a hindrance to the wearer, especially when the armor worn is meant to protect against high powered rifle rounds and is constructed with multiple layers of material and rigid protective plates. According to an article in *Police Magazine*, 40 percent of police officers will elect not to wear their body armor with the prime reason being discomfort (O'Brien, 2008).

The work done by law enforcement and military personnel consists of a wide range of tasks in a constantly changing environment. Tasks can range from sitting in a patrol car for several consecutive hours, to chasing after a suspect and having to climb fences or crawl in low over-head spaces. Task demands, as well as the threat level, are constantly changing for this population, and it is of paramount importance to keep them protected at all times. The body armor worn needs to protect against any projectiles that the wearer might encounter, but it also needs to provide the flexibility to perform tasks such as reaching equipment on the duty belt or firing a weapon. Thick layers of material and inflexible plates become a hindrance when trying reach or move around, and can cause pinching or chafing when worn for extended periods of time. Important tasks; such as quickly accessing gear on the duty belt, getting in and out of a car, or firing a weapon; can be uncomfortable or even impossible.

Problem Statement

As the materials used to construct body armor improve, the variations in design may increase. One of the current trends in armor design is to extend the coverage in areas such as the arm holes, the collar, and along the bottom edge. An example of this would be the San Diego Concealable Vest from International Body Armor Corporation, which has expanded front panels to wrap around the sides, a higher collar, and an extended torso length (International Body Armor Corporation, 2005). There is also a trend in placing semi-flexible panels, called trauma plates, over vital organs in the torso to provide extra protection in specific areas (American Body Armor, 2009). A recent article analyzing police and body armor observed that close to 80 percent of documented body armor failures were the result of bullets circumventing the armor panel of the vest, but there was only a single case of the armor panel failing when hit with a bullet it was designed to stop (LaTourrette, 2010). These type of statistics highlight how important it is to extend the armor panels to cover as much of the body as possible. As body armor design further evolves, it will be important to understand how changes, such as extended coverage, affect the balance between performance, protection, and comfort so that wearers are protected and able to accomplish their duties. A body armor developer that can empirically prove that its design protects more of the body and is still comfortable to wear will have a market advantage. This study and additional studies will be needed to develop the methodology and metrics to better understand the ergonomic impact of body armor on the performance of law enforcement and military personnel.

History of Body Armor

As long as humans have been in conflict, the technology of weapons has driven the evolution of protection. Bone and leather protected against stone blades and sharpened wooden spears; chainmail protected against swords and short-bow fired arrows; and steel plate protected against blades, battle axes, and long-bow fired arrows. Modern day “bullet-proof” vests have their beginnings in layered silk garments that were invented to protect against early, low-velocity pistols and rifles. These garments were created because the medieval plate armor was heavy, bulky, and largely ineffective against guns. It was discovered that layers of strong silk fiber were able to stop the penetration of muzzle loaded shot and maintain the flexibility provided by cloth. But, as firearms moved into the industrial age, the projectile velocities increased and the bullets became more pointed. These innovations quickly overcame protection provided by silk and new type of armor was needed.

In the late 1960’s, DuPont developed a fiber, known as Kevlar®, to replace the steel belting in radial tires, and in 1972 the National Institute of Justice (NIJ) began testing the use of this material for protection against high velocity projectiles. After a large-scale field test of Kevlar® body armor vests in 1975, a new industry was born that began to develop technologically enhanced materials; such as Spectra, Gold Shield, TWARON, and Dyneema. These new materials were used in the creation of body armor vests, helmets, shields, and lightweight vehicle armor plating. Over time the materials and the production techniques have continued to improve, and today there are a variety of fabrics, armor types, and companies marketing body armor (Seaskate Inc., 1998); (National Institute of Justice. U.S. Department of Justice, Office of Justice Programs, 2008).

Modern armor, in general, is composed of bullet-resistant panels that are built into a vest like carrier. The panel material and placement vary by armor manufacturer, and the specific carrier attributes vary by design, but fall into two main categories; concealable or external. Concealable armor carriers are designed to be lightweight with a minimal profile so they can be comfortably worn underneath clothing and for long durations. Typically, concealable armor is used by law enforcement officers during normal duty tasks to protect against handgun threats. For this study a concealable armor vest was used for the *concealable* armor condition. In contrast to the concealable body armor carriers, the external carriers are designed to be worn on top of clothing and tend to be much more rugged. Many designs have pockets and attachment points for combat or duty related equipment. Police departments in Europe and a few in the United States have started to use external carriers in conjunction with the lighter weight armor panels, common in the concealable carriers. However, externally worn armor often has thicker armor panels that are augmented with metal or ceramic plates to protect against higher velocity handgun and rifle threats, and is mostly used by military personnel or special weapons and tactics (SWAT) teams. This study used an external body armor vest, with thicker panels and ceramic plates for the *tactical* armor condition.

Founded as the National Institute of Law Enforcement and Criminal Justice in 1968, the NIJ was established to oversee and advance law enforcement and corrections technology. As part of that role, the NIJ establishes body armor performance standards that ensure certain levels of ballistic protection and quality for certified armor designs. The most current body armor standards document, *Ballistic Resistance of Body Armor NIJ Standard-0101.06*, was released in 2008 and contains all of the specific information needed to test and classify the minimal ballistics protection capability of personal body armor. Tested armor can be placed into one of five classification types based on the penetration protection provided from a projectile of certain mass and velocity: IIA, II, IIIA, III, and IV. Level IIA is the lowest rating and protects against, "9 mm Full Metal Jacketed Round Nose (FMJ RN) bullets with a specified mass of 8.0 g (124 gr) and a velocity of 373 m/s ± 9.1 m/s (1225 ft/s ± 30 ft/s) and with .40 S&W Full Metal Jacketed (FMJ) bullets with a specified mass of 11.7 g (180 gr) and a velocity of 352 m/s ± 9.1 m/s (1155 ft/s ± 30 ft/s)." Level IV is the highest rating and minimally protects against, ".30 caliber AP bullets (U.S. Military designation M2 AP) with a specified mass of 10.8 g (166 gr) and a velocity of 878 m/s ± 9.1 m/s (2880 ft/s ± 30 ft/s)." (National Institute of Justice. U.S. Department of Justice, Office of Justice Programs, 2008)

Following the same trend as armor of the past, modern armor is evolving to compensate for the increasing level of threats. The first generations of modern concealable armor were adequate to protect against the typical handgun threats of the time such as .45 and .38 caliber pistols. But with increasing popularity of the higher velocity .357 caliber rounds and the introduction of full-metal-jacket and armor piercing rounds, armor designs have shifted toward more robust augmented armor (Seaskate Inc., 1998). Even concealable designs of the past decade have begun including additional small panels of rigid armor to protect vital areas such as the heart and lungs. This progression towards more resilient armor is where the intrinsic problem facing body armor developers exists. Body armor must be sturdy enough protect against threats, but to be effective it must be wearable. Officers that choose not to wear armor are at a 14 times higher risk of death (U.S. Federal Bureau of Investigation (FBI), 1995) and the bulker and heavier the armor becomes the less appealing the armor is to wearers. When armor is left in the locker or in the vehicle trunk it cannot save lives. The future of armor panel design is to develop materials that are stronger, lighter, and more flexible so they can cover as much of the body as possible while not overheating or limiting the motion of the wearer.

Explanation of Shooting Stances

Shooting stance is a whole body posture that is designed to provide a stable, balanced, and tactically sound base to control a firearm's recoil and thus effectively and accurately fire a weapon. Since this posture is highly dependent on upper body positioning, it can be greatly affected by the use of body armor, and a reduction in mobility or the addition of unbalanced weight can be detrimental to a proper shooting stance. All shooting stances are rooted in the two main principles of balance and stability. In order to maintain balance, the knees are kept slightly bent and the shooter's weight is shifted slightly forward onto the balls of the feet. The weapon is raised level with the eye to reduce curving the back and neck when looking down the sights. For stability, isometric push and pull principles are used to control weapon recoil. The body's bone structure is used to redirect and dissipate force, and large muscle groups are targeted to avoid fatigue. There are many variations of shooting stance, each with pros and cons, but they all have the same goal of providing a comfortable, natural, and effective platform to fire weapons.

Officially named and trained shooting stances were developed within the competitive shooting sports, when marksmen began to understand and take advantage of how the body's posture could improve their accuracy. In the late 1950's when most people still shot pistols from the hip or one handed, Jack Weaver took principles of a basic fighting stance and began to shoot with a two handed stance that maintained control of the weapon. His success in the "Leatherslap" shooting competitions in Big Bear, California led to the Weaver stance being the principle handgun method trained by the U.S. Federal Bureau of Investigations (FBI) beginning in 1982 (Weaver, 2009). In 1976 the International Practical Shooting Confederation (IPSC) was founded to add structure to marksmanship competitions. Since that time members of the IPSC have worked hard to use systematic methods to analyze and develop shooting postures in order to improve the sport (International Practical Shooting Confederation, 2009).

Shooting stances are constantly being tested and modified in an effort to develop a general stance that can be quickly trained and used by law enforcement and military personnel. The two main stances trained today are the Weaver and the Isosceles stance. Historically the Weaver Stance was used in police training as the main firing platform, and it is still widely used today, though recently the Isosceles has been gaining popularity. One of the main reasons this stance is being adopted in the law enforcement community today, is because the shooter is presenting a more protected profile. It is assumed the officer will be wearing a protective vest, and with the Isosceles stance the armored chest is directly facing the target (Johnson, 2008). For this research, these two stances were used to classify the firing stances used by participants and both are described in detail below.

The Weaver stance is a modification of the classic police interview stance that places the officer standing at an angle to the target with their dominant side toward the rear, protecting the holstered weapon and providing a foot placement for quick reaction. For this shooting stance the hips and torso are at a 45 degree angle to the target. The strong arm, with wrist and elbow locked, pushes the weapon out toward the target. The weak arm provides support by pointing the elbow downward, and using an isometric pull backward to stabilize the weapon recoil. The back and neck are kept straight, and the body's weight is shifted slightly forward onto the balls of the feet. This stance presents a smaller profile to the target since the shooter is standing at an angle, but because of current body armor design there are large unprotected areas around the arm and down the side of the body. The purpose of the Weaver stance is to direct the backward recoil force along the strong arm and down into the wide leg stance. The weak support arm helps to control the upward component of the recoil force, so that the weapon stays on target. The strength of this stance is dependent on locking out the strong arm's joints to optimally transfer the impact force (Johnson, 2008). An example of the Weaver stance can be seen in Figure 1 below.

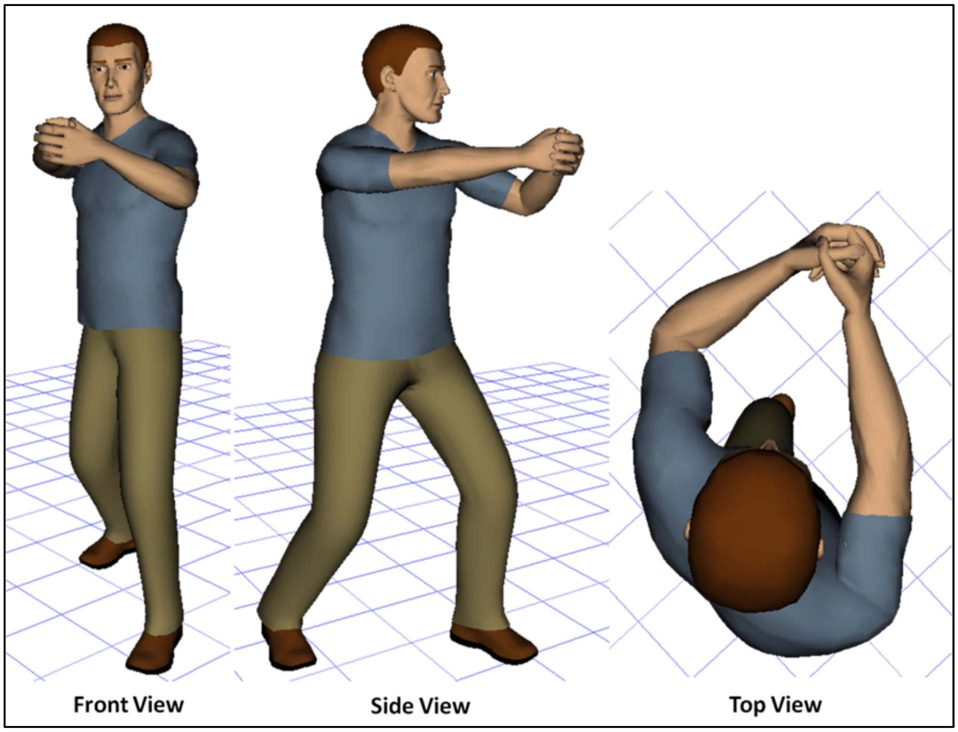

Figure 1 Weaver Stance

The Isosceles stance gets its name from the triangle that is formed with the arms and the torso. The shooter stands directly facing the target and holds the weapon out in front of them while locking the wrist and elbow joints of both arms. Like the Weaver stance the strong arm pushes outward, and the weak arm pulls back toward the body for isometric stability. The feet are shoulder width apart and pointing forward. The back and neck are held straight, and the body's weight is shifted slightly forward onto the balls of the feet, while keeping the knees slightly bent. This stance transfers the weapon's recoil force equally down both sides of the body, but care must be taken to keep the correct amount of pressure on the weak arm to prevent pulling the weapon laterally (Johnson, 2008). An example of this stance can be seen in Figure 2 below.

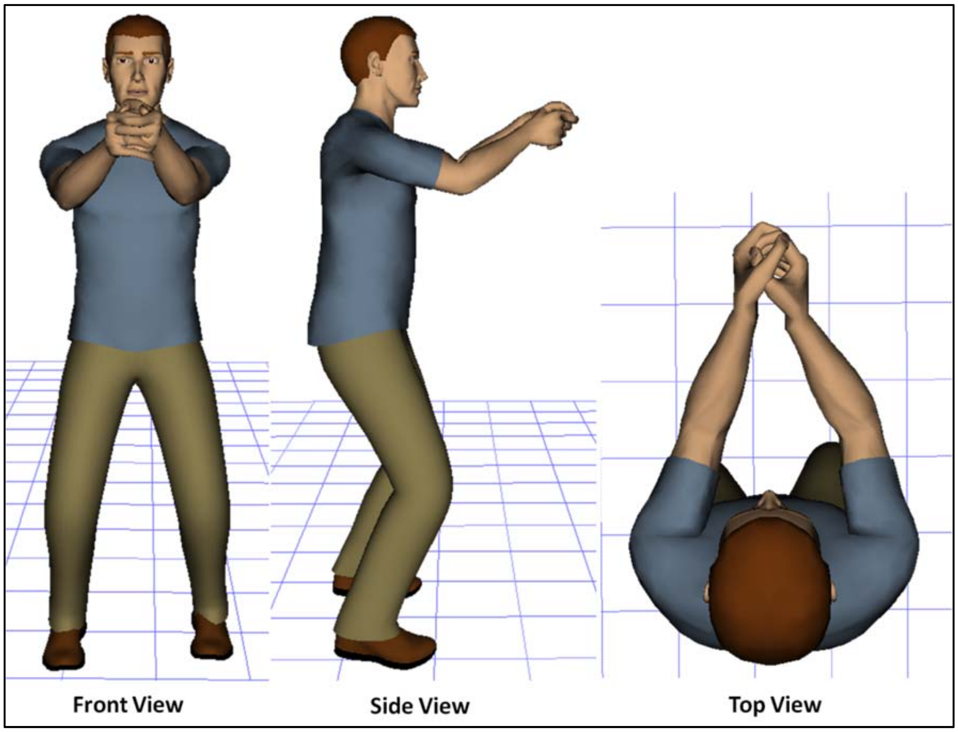

Figure 2 Isosceles Stance

Motion Capture Background Information

The motion capture system (MoCap) used in this study was a passive optioelectric camera system, which used software and a set of networked cameras to track retro-reflective beads that were attached to segments of the human body. The cameras used in these types of systems are arranged around the testing space so that their field of view overlaps to create a capture volume, where the reflective beads, also called markers, can be tracked. Light Emitting Diode (LED) arrays on the front of the cameras emit a specific wavelength range of near infrared light that the cameras record to produce images of the markers. The computer software then uses multiple camera views to triangulate the position of the markers in the capture volume and display these images, in near real-time, within a 3-D visual representation of the capture volume on the computer monitor. In order to perform these calculations the camera positions must be calibrated in reference to the capture volume and the markers must be visible to multiple cameras at all times. The 3-D positional marker data is then recorded for additional analysis.

The general theory of human motion analysis associated with the use of motion capture systems is that if a trackable marker is rigidly fixed to a position on the human body, then that marker's movement can be associated with the movement of the human body and reverse-kinematics can be used to calculate the body's motion. For most applications, and the method used in this study, the human body is modeled as a series of linked rigid segments, where the segments relate to skeletal elements, and the links relate to body joints. The MoCap markers are attached to the body so that vectors and planes can be established from the marker positions to represent body segment locations and movement analysis calculations can be done (Aggarwal & Cai, 1999).

This theory comes with several assumptions that are important to understand when interpreting human motion data. The first of these assumptions is that the markers only move in conjunction with rigid elements of the target body segment. If markers are placed on clothing or over bulky soft tissue regions the marker will move independently of the skeletal structure and introduce noise into the motion data. To avoid this extra noise, ideal placement of markers is on bare skin and on top of boney landmarks where there is limited musculature between the bone and skin surface. In some more invasive studies where precision is of high importance, the motion capture markers are attached to small rods that are screwed into the bone of subjects to reduce this noise as much as possible (Aggarwal & Cai, 1999).

Another common assumption with the use of motion capture data is that vertex points between linked segments represent the respective joint center of the target segment. This is an important simplifying assumption that makes motion capture data easy to use, but is highly debated within the biomechanics research community because of the implications it has on research results. A joint center is understood to be the actual point at which two bony structures rotate about each other. In the human body, joint centers are not static positions like a hinge, but move as the joint flexes or extends because of sliding and rolling motions within the joint. Since motion capture markers can only be placed on the body surface, there is a dynamic distance offset from that point to the true rotation point of the skeleton. Some research has been done using medical imaging tools to try and determine how best to pin-point a joint's center of rotation and relate that to motion capture marker locations, but currently there have been no breakthroughs to improve dynamic data collection techniques (Schwartz & Rozumalski, 2005), (Kirkwood, Culham, & Costigan, 1999). Many researchers who use motion capture data to perform biomechanical analysis take the same approach that was employed in this study. It is explicitly stated that the angles used for analysis are included angles between motion capture markers and not true joint angles. It is thought that precautionary measures, such as the careful use of bony landmarks and skin surface marker mounting should result in a highly correlated relationship between the included angles of motion capture markers and the true joint center, thus results from motion capture analysis can be implied for human motion (Poppe, 2007).

Objectives and Hypotheses

The main objective of this study was to examine the efficacy of a method which determines an effect of body armor design on shooting posture. The ultimate and future goal of this analysis method would be to quantify the effect armor designs have on the range-of-motion of law enforcement officers performing their duties. This method could then be used by armor design companies to help develop a vest that provides greater protective coverage without negatively restricting the wearer. Specific hypotheses to be tested included:

1. Armor configurations would affect the shooting stance by decreasing joint angles. The tactical armor will have more of an effect on joint angles than the concealable armor.
2. Tasks and trial will not have a significant impact on shooting posture.
3. Experience group will not have a significant impact on shooting posture.

CHAPTER II

DATA COLLECTION METHODOLOGY

The data used for this thesis work was taken from existing data that was collected as part of the Investigation of the Effects of Increased Coverage Area for Soft Body Armor (PBA) study at the Mississippi State University Center for Advanced Vehicular Systems (CAVS). This study was a joint effort between the Human Performance Laboratory at CAVS and the Human Systems Engineering Laboratory in the Mississippi State University Industrial and Systems Engineering Department. The PBA study was funded by the United States National Institute of Justice as an experimental effort to objectively evaluate the effect of soft body armor's increased coverage on wearers. The data used in the current paper was taken from the pilot work done for phase I, which was focused on developing a protocol to evaluate the ergonomic impact of body armor on police task performance.

The ergonomic evaluation in phase I of the PBA study consisted of a battery of tests and data collection methods that include motion capture, electromyography (EMG), thermography, task completion timing, anthropometric measures, range of motion (ROM) measures, body temperature, heart rate monitoring, pressure mapping, and questionnaires. The data used in this current thesis work was taken from the demographic questionnaires and motion capture data. Only the methods used for the collection of this data is explained further here.

Participants

Participants for this study were eight Starkville Police Department (SPD) officers. All participants were male ranging in age from 21 to 40 years. In order to participate in this study all candidates had to be free from injury that would pathologically reduce their range of motion; be departmentally qualified to use a handgun; be familiar with the use of externally worn body armor including ballistic plates; and be familiar with police tactical maneuvers.

Equipment

The hardware used in this study to collect motion data was a Motion Analysis optioelectric motion capture system. The system was set up with 14 *Eagle Digital* cameras and was running the EVaRT 5.5 software. The system was calibrated using a four-marker L-bracket calibration square, and a three-marker 500 millimeter calibration wand. The motion capture markers used on participants were 1 centimeter diameter spheres covered in reflective tape and attached to a small circular leather base.

Demographics and medical history information was collected using a questionnaire (APPENDIX A). Questions were asked verbally during a physiological rest period, prior to the active task phase of testing, and recorded on the questionnaire sheet.

The body armor used during the *concealable* armor condition was an NIJ threat level III-A classified, concealable vest produced by American Body Armor. The general model used during testing was the *Xtreme*, with no extra ballistic inserts. The exact armor model used varied between participants, since they provided their own fitted armor for this condition. An example of this armor can be seen in Figure 3.

Figure 3 Concealable Armor Condition Vest

The body armor used during the *tactical* armor condition was a Protective Products International, *Spitfire*, model GP-1000-IIIA with shoulder protectors. This vest without plates provided NIJ threat level III-A coverage, but the 8x10 front and rear metal inserts, model SN-III, would increase coverage to threat level IV. A general size large model was used during testing if the participant could not provide their own (see Figure 4 below).

Figure 4 Tactical Armor Condition Vest

The Airsoft weapon used for simulation in the laboratory was Crossman, Air Mag C11 model number SAMC11CB. This weapon used CO_2 propellant canisters to semiautomatically fire plastic pellets at designated targets. An example of this weapon can be seen in Figure 5 (Crossman, 2010).

Figure 5 Airsoft Weapon

The vehicle used for egress tasks was a police cruiser model Ford *Crown Victoria*. This vehicle was equipped with a caged divider between the front and rear seats and console modifications. The outside of the vehicle was covered with a black cloth and masking tape to prevent reflections that might show up as ghost motion capture markers.

Paper posters printed with near life-size images of armed suspects were used as targets for all shooting tasks. These posters were mounted on a cardboard backing and attached to a wooden frame to hold them at a relative standing height. This target set up was similar to the target configuration used by the local police department for weapon's qualification on their shooting range. Used targets were swapped for clean targets at the end of each participant's testing session.

Variables

Independent variables for this study were the body armor type, task, trial number, and experience group. The main focus of this paper was on the body armor conditions, but since this was an exploratory study the other factors are included to examine their effects and interactions on shooting posture.

Three body armor conditions were studied: tactical, concealable, and none (baseline or no-armor). These three conditions were chosen because they were the armor types familiar to the participants of this study and by observation they appear to differ enough to perturb the biomechanical shooting system in a measureable way. The no-armor condition was selected as the baseline to compare to the two armored conditions. The concealable armor was a representative concealable type vest that was expected to have a minimal effect on the shooter. The tactical armor condition was chosen as a stark contrast to the concealable armor and the baseline condition, and was expected to have a considerable impact on the shooters' biomechanics.

Four different tasks conditions used for data collection included weapon fire, egress-fire, egress-move-fire, and tactical walk. There were three trials completed for each task. Both the tasks and trials are described further in the *Task Descriptions* section.

Participants were placed into an experience group ('expert' or 'novice') depending on the number of years employed as a law enforcement officer. Work experience of tested subjects ranged between 0.5 and 15 years with a gap between 5 and 9 years. This gap was used to classify participants into experience groups, with a novice being defined as an officer with 5 or less years of experience (n=5) and an expert participants being greater than 5 years of experience (n=3).

Dependent variables for this study were included angles at the neck, shoulders, elbows, and wrists, extracted from motion capture data. These body angles were selected because they represent the locations of upper body motion required to assume a handgun shooting stance. Due to the limited resources available for this study and the exploratory scope, these angles were simple included angles at the joint, and were not broken down into component parts (e.g. flexion/extension, lateral bending, etc.) or separated by body planes. Discrete x, y, and z coordinates of the motion capture markers, used to calculate included angles, were taken as a single-frame subset of the continuous motion capture sequence collected during each task trial. These single frame data points were selected at the assumed time of weapon fire by examining the marker velocity profiles and choosing a point after the firing stance was assumed and the planar velocity of all critical markers was close to zero. Processing of the coordinate data into included angles is explained in more detail in the *Postural Analysis Method* section.

Motion Capture Methodology

The marker set used in this study was adapted from the standard marker set described in the Motion Analysis Cortex software manual. The marker set consists of 44 markers in the no-armor condition for the body, and 48 markers in the two armored conditions, which included the body markers and four additional markers to outline the bottom edge of the body armor. APPENDIX B provides a list of all the markers and their landmark location. Marker placement was determined by palpation to establish an associated bony landmark. Marker locations covered by body armor or the weapon belt were estimated by first finding the boney landmark structure under the obstruction and then translating that location to the outer layer. Some marker locations had to be slightly adjusted to reduce marker occlusion or accidental removal by impact with the equipment. This marker set was chosen to minimally outline the semi-rigid segments of the body with at least two markers, and reduce the number of markers needed since there was an elevated risk of them falling off due to perspiration and very active tasks.

The motion capture software used for this study was the Motion Analysis EVaRT 5.5 release. The data collection template utilized 14 Eagle Digital cameras set in a single ring configuration around the collection volume. The software was set to capture data at 60 frames per second. The cameras were set at 75 percent brightness and a threshold of 500.

The motion capture system was calibrated before each data collection session using both a static square calibration, and a dynamic wand calibration as outlined in the Motion Analysis EVaRT 5.0 user manual. Once each participant was prepped for motion capture data collection including marker placement, a static T-pose data set was collected. The T-pose data set consists of 60 frames of data collected with the participant standing erect with their arms held out parallel with the floor. The T-pose data was used to update the marker template linkage distances for that participant's anthropometry, and serves to improve the motion capture software's ability to distinguish markers and reduce post-processing time. After the participant's template has been updated, motion capture data was collected on a task by task basis with an operator starting and stopping the motion capture collection process between each task to update the task file name.

Task Descriptions

The tasks described here were only a subset of tasks used in the parent study. This subset of tasks focuses on weapon use, since the objective of this thesis was to analyze shooting posture. The task battery in the parent study was grouped into blocks by the type of task performed to optimize the transition between tasks and reduce overall time required to complete testing. In order to reduce potential order effects in the data, block order exposure was randomized, as well as the task order within the block. Participants were notified that all tasks would be timed, and their overall goal was to complete the tasks to the best of their ability and as fast as possible. Because the Airsoft weapon used in this study had the potential to malfunction and disrupt the test, participants were instructed to ignore any weapon malfunctions and simulate firing to complete the task. Once the trial was complete, the weapon malfunction could be corrected.

The tactical walk task was designed to establish a normal pattern of forward and backward weapon focused gait inside the data capture volume. Participants begin the task with their weapon holstered and standing in a relaxed position. When given the initiating command, the participant would draw their weapon and aim at a target in front of them. Keeping their weapon on target, they would complete three iterations of walking forward and backward in a straight path through the data collection space. Verbal cues were used to instruct participants when to change their walking motion. After completing the walking iterations, the participant would stop and holster their weapon, ending the task. The beginning motion, either forward or backward, was randomly counterbalanced to eliminate potential order effects within the data.

The egress-fire task was designed to capture a target engagement where the participant would have to rapidly egress the vehicle, take cover behind their vehicle door, and fire on a target. Participants begin the task inside the vehicle with their hands on top of the steering wheel. When given the initiating command, the participant would rapidly egress the vehicle, draw their weapon, fire on a target, holster their weapon, and place their hands on top of the vehicle door to end the task trial. This trial rotation was completed for each of three targets located in front of the participant. Target firing order was randomized to eliminate any potential order effects within the data, and verbal cues were used to identify which target to fire upon.

The egress-move-fire task was designed to be a dynamic task which incorporates several elements of complex motion, and captures the move-cover-fire technique of target engagement. This task began with the participant in the vehicle with their hand on top of the steering wheel. When given the initiating command, the participant rapidly egressed the vehicle and ran to a barrier to take cover. Once behind the barrier, a verbal cue indicated which of three targets to fire upon. Participants would draw their weapon, aim at the instructed target, fire one round, and take cover behind the barrier. A test conductor gave the participant a verbal movement command, and participants moved forward to the next barrier and repeated the target engagement process. After engaging the second target, the test conductor gave another verbal movement command, and participants moved backward to the first barrier to repeat the target engagement. After engaging the third target, the participant ran back to the vehicle door, holstered their weapon, and placed their hands on top of the vehicle door to end the trial. This whole process was repeated for a total of three iterations. Target order was randomized to reduce potential order, though barrier cover locations and movement path could not be randomized due to space restrictions in the test area.

The weapon fire task was designed to capture the basic motions required to draw and fire a weapon. This task began with the participant standing in a relaxed posture. Once given a verbal command, participants drew their weapon, fired one round at a specific target in front of them, and holstered their weapon to end the trial. This process was repeated for a total of three iterations.

Postural Analysis Method

The posture analysis method used for this study consisted of statistically examining included angles created by vectors between motion capture markers placed on a participant's body. The vertexes of these angles were defined by markers that were close to body segment rotation points. The end points of the angles were defined by markers placed at boney landmarks that outlined the body segment. The angles used in this study were not true joint angles since the dynamic joint center of rotation was not being calculated. However, the use of included angles in this study was a reasonable simplification since the values being compared are differences between angles not the discrete angle, and because of the close proximity of the markers to the body's joints and skeletal structure. For additional confidence that the correct angles were being tested, the final joint angle results were used as input for a digital human modeling program to visualize how the angles contributed to an overall posture.

The included angle at the neck captured the lateral bending of the neck and was defined by the rear head marker, and a line drawn between the seventh cervical vertebra (C7) and the Acromion marker on the dominant target eye side. The dominant target eye specification was used insure the acute included angle being calculated at the neck was consistently on the same side between tasks since the head was usually slightly canted down to align the targeting eye with the line of site of the weapon. The shoulder angle captured the adduction of the shoulder and was defined by the C7 marker, the Acromion marker at the vertex, and elbow marker. The elbow angle captured the flexion of the elbow and was defined by the Acromion maker, the elbow marker at the vertex, and mid-point between the two wrist markers. The wrist angle captured the extension of the wrist and was defined by the elbow marker, the mid-point of the wrist markers at the vertex, and the mid-point between the hand markers. All the angles except the neck were taken on the right and left side of the body. The included angles used in this study are summarized in Table 1below, the markers used are shown in Figure 6, and examples of the angles overlaid with the body can be seen in CHAPTER VFigure 13-Figure 16.

Table 1 Summary of Included Angles

Included Angle	**Marker Point 1**	**Apex Marker**	**Marker Point 2**
Neck	Rear Head	C7	Dominant side Acromion
Right Shoulder	C7	Right Acromion	Right Elbow
Left Shoulder	C7	Left Acromion	Left Elbow
Right Elbow	Right Acromion	Right Elbow	Right mid-point wrist
Left Elbow	Left Acromion	Left Elbow	Left mid-point wrist
Right Wrist	Right Elbow	Right mid-point wrist	Right mid-point hand
Left Wrist	Left Elbow	Left mid-point wrist	Left mid-point hand

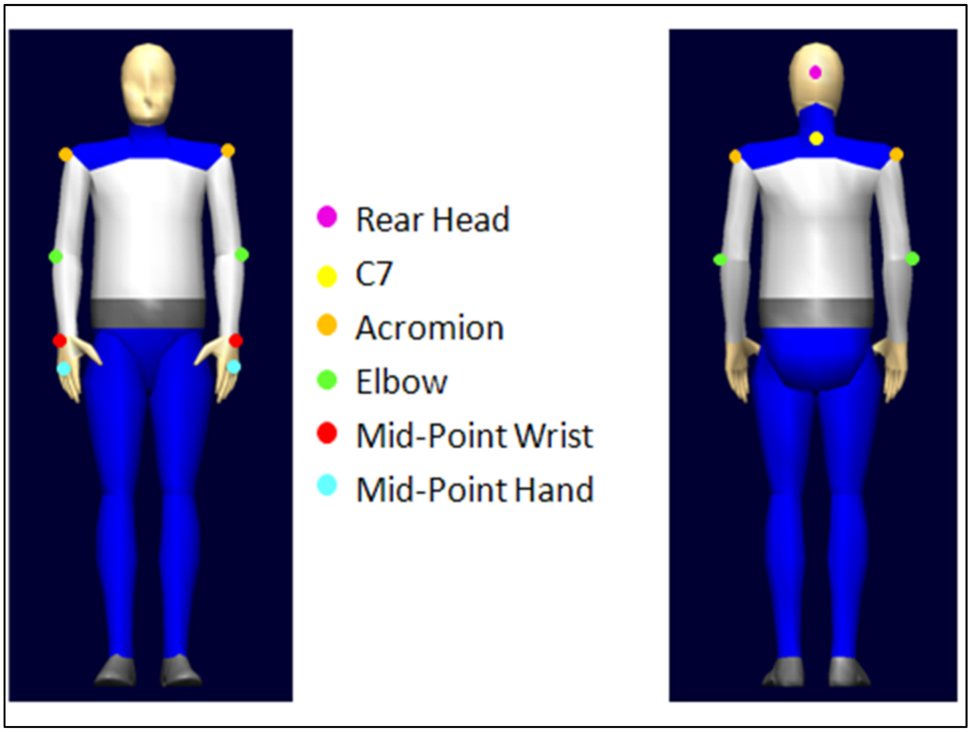

Figure 6 Included Angle Marker Locations

CHAPTER III

DATA ANALYSIS METHODOLOGY

Extraction of Included Angles

The included angles used for this study were all calculated from motion capture marker data collected during task trials. At the timeframe selected for each data collection point, each of the motion capture markers had a set of x, y, and z coordinates. These coordinates were used to create vectors between marker points representing body segments. Two vectors with a common vertex point, corresponding to a body joint, were created for each included angle. The angle between these vectors, θ, was calculated using Equation (1) below, where *P* and *Q* are magnitudes of the vectors representing two connected body segments.

$$\theta = \cos^{-1}\left(\frac{P_x Q_x + P_y Q_y + P_z Q_z}{PQ}\right) \tag{1}$$

Hypothesis and Statistical Testing

A repeated measures analysis of variance (ANOVA) model with a 95% level of significance ($\alpha = 0.05$) was used for this study. The model for these tests included each of the main effect factors (armor condition, task, trial, and experience group), as well all the two-way, three-way, and four-way interactions. The main hypothesis of this thesis addressed the question of whether there was a statistically significant difference between the different sets of independent variables or their interactions, with a primary focus on the armor condition factor. The other factors were included to help gain additional insight into what might influence the posture of the test participants. This is explained further in the discussion section of CHAPTER V.

The data was prepared for statistical testing by first removing outliers using a combination of Cook's Distance, DFITS, and Studentized residual comparisons. Minitab 14 statistical software was used to calculate the indicator values for all three tests. To be flagged as an outlier the data point had to meet the criteria seen in Equations 2, 3, and 4 below. If at least two of the three outlier tests flagged the value, it was determined to be an erroneous data point and was removed. There were a total of 2016 data points for the study, and 437 were classified as outliers (22% data loss). An average of 62 data points were lost for each of the seven angles examined. After the outliers were removed, a Johnson transformation was used within the Minitab 14 software to make all the data sets normal.

$$Cook's\ Distance: D_i > \frac{4}{n} \tag{2}$$

$$DFITS: D > 2\sqrt{\frac{(n - DoF\ Error)}{n}} \tag{3}$$

$$Residual: -2 > r_i > 2 \tag{4}$$

Separate ANOVA tests were run for each included angle segment resulting in seven total ANOVA hypothesis tests. Following traditional statistics methodology, the null hypothesis (H_0) for each of these seven tests was that there was no difference between the treatment effects. The alternative hypothesis (H_1) for each test was that at least one of the treatments had a significant effect. The general model for the armor condition hypothesis can be seen in Equation 5 below, where μ is the overall mean, τ_i is the treatment effect, and ϵ_{ij} is the random error (Montgomery & Runger, 2007). A post hoc pair-wise Tukey comparison test, with 95% level of significance ($\alpha = 0.05$), was done for each test where the main statistical test indicated that there was a significant difference between factor means.

$$\begin{gathered} Y_{ij} = \mu + \tau_i + \epsilon_{ij} \begin{cases} i = armor = baseline, light, heavy \\ j = participant = 1, 2, 3, \dots, 8 \end{cases} \\ H_0: \tau_{baseline} = \tau_{light} = \tau_{heavy} = 0 \\ H_1: \tau_i \neq 0 \text{ for at lease one } i \end{gathered} \tag{5}$$

CHAPTER IV

RESULTS

Descriptive Statistics

Descriptive statistics for joint angles based on each of the four study factors (armor condition, task, trial, and group) are shown in Table 2 on the next page. Figure 7 below demonstrates the shooting posture in the mean no-armor condition applied to a digital human model for visualization.

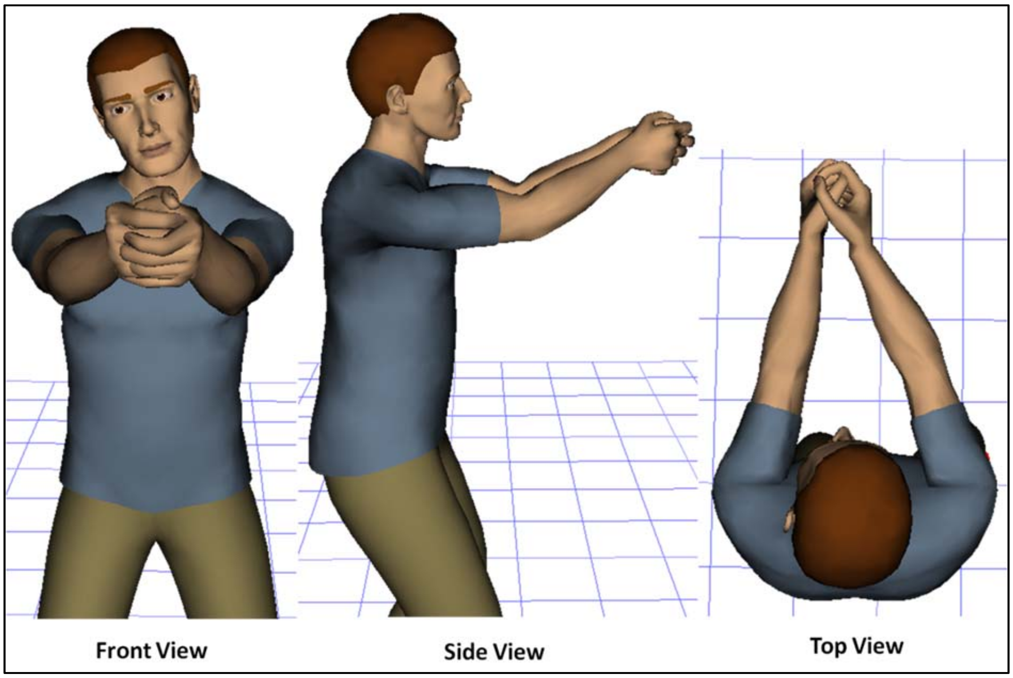

Figure 7 No-Armor Shooting Stance

Table 2 Descriptive Statistics, Values are mean (standard deviation)

		Mean Joint Angle (degrees)						
		Neck	R. Shoulder	L. Shoulder	R. Elbow	L. Elbow	R. Wrist	L. Wrist
Armor Condition	No	75.92 (11.78)	124.14 (11.21)	130.64 (12.20)	133.10 (13.27)	122.91 (16.66)	161.94 (4.80)	149.11 (16.95)
	Concealable	77.65 (14.54)	124.00 (8.21)	126.28 (9.94)	131.94 (14.77)	124.32 (16.87)	159.72 (8.12)	143.79 (16.79)
	Tactical	71.57 (15.49)	131.15 (7.95)	129.31 (12.52)	117.51 (12.24)	133.87 (15.87)	153.37 (11.66)	143.81 (19.06)
Task	Egress Fire	75.30 (11.54)	123.38 (8.89)	125.68 (12.85)	133.20 (12.12)	127.05 (15.82)	158.42 (11.16)	144.79 (19.53)
	Move Fire	78.68 (16.50)	127.81 (12.06)	132.02 (14.18)	123.62 (18.29)	114.69 (18.77)	158.17 (10.56)	143.46 (19.51)
	Tac Walk	70.62 (14.69)	129.18 (7.92)	130.89 (9.88)	116.99 (15.13)	109.08 (16.27)	155.54 (4.86)	146.33 (17.39)
	Wep Fire	73.62 (13.17)	126.21 (8.26)	127.58 (7.51)	131.56 (9.19)	124.98 (11.34)	159.44 (8.10)	148.00 (14.20)
Trial	1	75.22 (14.51)	126.20 (9.59)	128.55 (10.44)	126.94 (14.21)	120.33 (16.69)	156.93 (9.88)	147.65 (16.89)
	2	75.07 (13.54)	126.37 (9.77)	128.88 (12.37)	128.12 (14.34)	121.35 (16.87)	158.68 (10.25)	145.58 (18.02)
	3	75.04 (14.70)	126.78 (10.07)	128.99 (12.45)	126.83 (16.95)	118.88 (17.65)	159.10 (8.02)	143.57 (18.41)
Group	Novice	68.94 (13.87)	125.90 (11.91)	130.65 (11.87)	125.34 (16.64)	116.34 (18.72)	157.21 (11.02)	142.61 (17.14)
	Expert	84.03 (9.15)	127.22 (5.64)	125.97 (11.11)	130.09 (12.44)	126.11 (12.08)	159.76 (6.19)	150.69 (17.91)

“No” refers to the no-armor condition. “Move Fire” refers to the egress-move-fire task. “Tac Walk” refers to the tactical walk task. “Wep Fire” refers to the weapon fire task.

Inferential Statistics

Table 3 displays the ANOVA results for neck angle. The main effects of armor and task were significant, along with the armor*task, armor*group, task*group, and armor*task*group interactions. Pair-wise Tukey comparisons revealed that tactical armor angle (71.57° ±15.49°) was significantly smaller than the concealable armor angle (75.92° ±11.78°) ($p\text{-value} < 0.001$). For the task variable, the neck angle of the shooting posture during the egress-move-fire task (78.68° ±16.50°) was significantly larger than the neck angle from both the tactical walk (70.62°±14.69°) and the weapon fire tasks (73.62°±13.17°) ($p\text{-value} < 0.001$ for both). The neck angle for the novice group (68.94°±13.87°) was found to be significantly smaller than the neck angle for the expert group (84.03°±9.15°) ($p\text{-value} < 0.001$). The interactions plot (Figure 8) revealed several findings about the interactions between the armor, task, and group factors. For the armor*task interaction the tactical armor had a larger impact in the tactical walk task and in the egress-move-fire task. In the no-armor condition the egress-move-fire tasks seem to have less of an impact than the other tasks. The concealable armor appears to have a high variability across all the tasks. The armor*group interaction seems to indicate that the tactical armor had a more substantial impact only on the novice experience group. The task*group interaction indicated the egress-fire task had less of impact between the two experience groups, but the novices showed marked differences during the tactical walk. The three-way interaction between armor, task, and group seemed to show that the group effect was seen throughout all armor conditions and tasks, but the greatest impacts were on the novice group wearing the tactical armor, while performing the tactical walk.

Table 3 Neck Angle ANOVA Results

Source	df	F-Value	P-Value
Armor	**2**	**7.840**	**0.001**
Task	**3**	**8.020**	**< 0.001**
Trial	2	0.260	0.772
Group	**1**	**170.930**	**< 0.001**
Armor*Task	**6**	**2.300**	**0.038**
Armor*Trial	4	0.710	0.585
Armor*Group	**2**	**4.140**	**0.018**
Task*Trial	6	0.900	0.500
Task*Group	**3**	**6.040**	**0.001**
Trial*Group	2	2.330	0.101
Armor*Task*Trial	12	1.000	0.451
Armor*Task*Group	**6**	**2.230**	**0.043**
Armor*Trial*Group	4	1.200	0.314
Task*Trial*Group	6	1.650	0.138
Armor*Task*Trial*Group	12	1.020	0.436
Error	149		
Total	220		

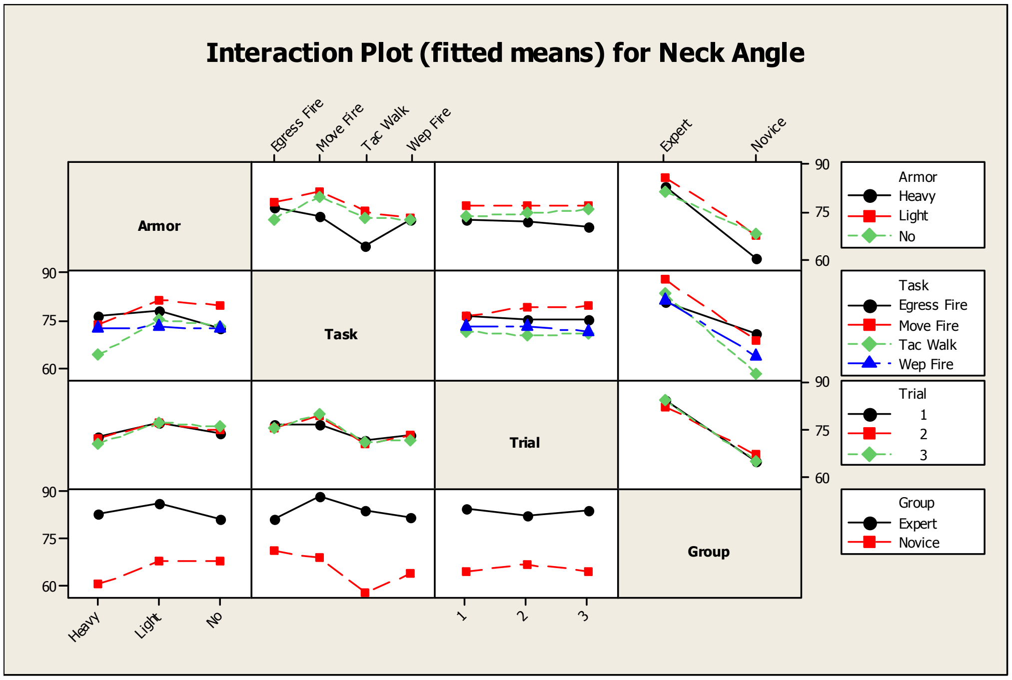

Figure 8 Neck Angle Interaction Plot

Table 4 below shows the ANOVA test results for the right shoulder included angle. The four-way interaction term between armor, task, trial, and group had to be removed from the general linear model for this variable due to missing data points. The armor main effect and the armor*group interaction were found to be significant. Pair-wise Tukey comparisons revealed that the right shoulder angle when wearing tactical armor (131.15°±7.95°) was found to be significantly larger (more adducted) than the angle when wearing both the concealable (124.00°±8.21°) and the no armor condition (124.14°±11.21°) (p-value < 0.001 for both). The interactions plot (Figure 9) and significant armor*group finding indicates that the tactical armor significantly increased shoulder adduction primarily in the novice experience group. The task*group interaction, while not significant at the 0.05 level was close (p-value=0.061), and showed that the tactical walk task lead to a larger shoulder angle in the novice group over the expert experience group, but that the egress-fire and egress-move-fire tasks showed smaller shoulder angles for the novices. The weapon fire task did not show any effect from the group factor.

Table 4 R. Shoulder Angle ANOVA Results

Source	df	F-Value	P-Value
Armor	**2**	**11.370**	**< 0.001**
Task	3	1.410	0.243
Trial	2	0.090	0.918
Group	1	0.000	0.961
Armor*Task	6	0.980	0.439
Armor*Trial	4	0.270	0.899
Armor*Group	**2**	**4.450**	**0.013**
Task*Trial	6	0.180	0.981
Task*Group	3	2.510	0.061
Trial*Group	2	0.130	0.878
Armor*Task*Trial	12	0.530	0.889
Armor*Task*Group	6	0.770	0.593
Armor*Trial*Group	4	0.280	0.889
Task*Trial*Group	6	0.220	0.969
Error	148		
Total	207		

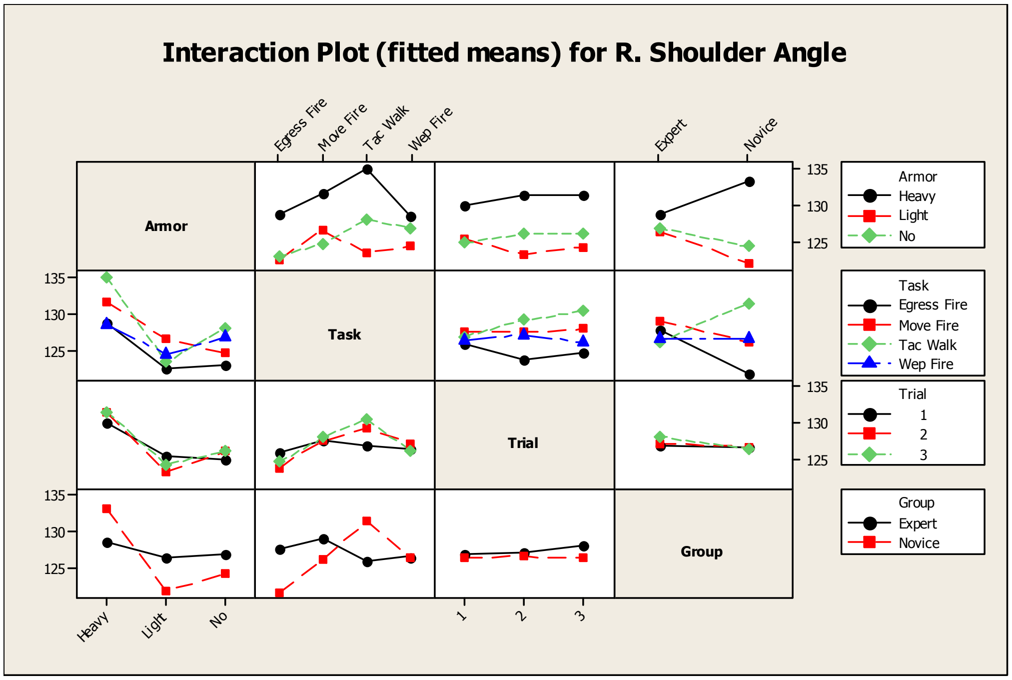

Figure 9 Right Shoulder Angle Interactions plot

Table 5 shows the ANOVA test results for the left shoulder included angle. The four-way interaction term between armor, task, trial, and group had to be removed from the general linear model for this variable due to missing data points. The group main effect and the task*group interaction were found to be significant. Pair-wise Tukey comparisons revealed that the left shoulder angle of the expert group (125.97°±11.11°) was significantly smaller (more abducted) than that of the novice group angle (130.65°±11.87°) (p-value < 0.001). The interactions plot (Figure 10) and task*group interaction results indicate a similar finding to the right shoulder results in that the novice group showed a substantially larger angle than the expert for only the tactical walk task.

Table 5 L. Shoulder Angle ANOVA Results

Source	df	F-Value	P-Value
Armor	2	2.650	0.074
Task	3	2.590	0.055
Trial	2	0.640	0.531
Group	**1**	**12.610**	**0.001**
Armor*Task	6	1.310	0.255
Armor*Trial	4	0.550	0.700
Armor*Group	2	1.870	0.157
Task*Trial	6	0.480	0.820
Task*Group	**3**	**3.330**	**0.021**
Trial*Group	2	1.830	0.164
Armor*Task*Trial	12	0.590	0.848
Armor*Task*Group	6	0.920	0.485
Armor*Trial*Group	4	0.190	0.942
Task*Trial*Group	6	1.260	0.281
Error	150		
Total	209		

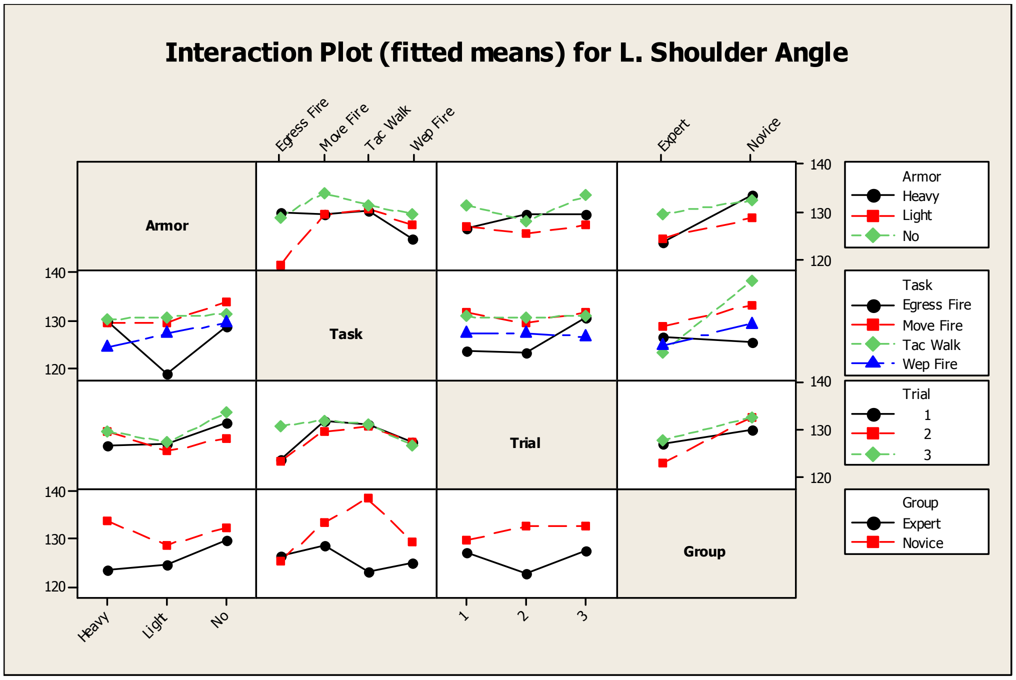

Figure 10 Left Shoulder Angle Interaction Plot

Table 6 displays the ANOVA results for right elbow included angle. The four-way interaction term between armor, task, trial, and group was removed from the general linear model for this variable due to missing data points. The main effects of armor, task, and group were significant. Post hoc pair-wise Tukey comparisons revealed that the right elbow angle in the tactical armor condition (117.51°±12.24°) was significantly smaller (more flexed) than the right elbow angle in both the concealable armor (131.94°±14.77°) and no armor (133.10°±13.27°) (p-value < 0.001 for both). For the task variable, the right elbow angle in the egress-fire task (133.20°±12.12°) was significantly larger than the right elbow angle in both the tactical walk (116.99°±15.13°) and the egress-move-fire tasks (123.62°±18.29°) (p-value < 0.001 for both). The right elbow angle in tactical walk (116.99°±15.13°) was found to be significantly smaller than the angle during the weapon fire task (131.56°±9.19°) (p-value < 0.001). In addition, the novice group's angle

(125.34°±16.64°) was found to be significantly smaller than the expert group's right elbow angle (130.09°±12.44°) (p-value < 0.001).

Table 6 R. Elbow Angle ANOVA Results

Source	df	F-Value	P-Value
Armor	**2**	**28.200**	**< 0.001**
Task	**3**	**12.760**	**< 0.001**
Trial	2	1.000	0.370
Group	**1**	**10.260**	**0.002**
Armor*Task	6	0.330	0.923
Armor*Trial	4	0.410	0.805
Armor*Group	2	1.100	0.337
Task*Trial	6	0.640	0.695
Task*Group	3	2.410	0.069
Trial*Group	2	1.180	0.310
Armor*Task*Trial	12	0.460	0.933
Armor*Task*Group	6	0.560	0.758
Armor*Trial*Group	4	1.630	0.171
Task*Trial*Group	6	0.400	0.878
Error	145		
Total	204		

Table 7 below displays the ANOVA results for left elbow included angle. The four-way interaction term between armor, task, trial, and group had to be removed from the general linear model for this variable due to missing data points. The main effects of armor, task, and group were found to be significant along with the task*group interaction. Pair-wise Tukey comparisons revealed that the left elbow angle in the tactical armor condition (133.87°±15.87°) was significantly larger (more extended) than the left elbow angle in both the concealable (124.32°±16.87°) and no armor (122.91°±16.66°) conditions (p-value < 0.001 for both). For the task variable, the left elbow angle during the egress-fire task (127.05°±15.82°) was significantly larger than the left elbow angle during the tactical walk (109.08°±16.27°) (p-value < 0.001) as well as the egress-move-fire task (114.69°±18.77°) (p-value < 0.001). Like the right elbow, the tactical walk angle (109.08°±16.27°) was found to be significantly smaller than the weapon fire task (124.98°±11.34°) (p-value < 0.001). In addition, the novice group angle (116.34°±18.72°) was found to be significantly smaller than the expert group angle (126.11°±12.08°) (p-value < 0.001), but the task*group interaction and interaction plot (Figure 11) indicates that this was only for the novice group during the tactical walk task.

Table 7 L. Elbow Angle ANOVA Results

Source	df	F-Value	P-Value
Armor	**2**	**13.060**	**< 0.001**
Task	**3**	**14.410**	**< 0.001**
Trial	2	0.890	0.412
Group	**1**	**22.600**	**< 0.001**
Armor*Task	6	0.250	0.958
Armor*Trial	4	0.400	0.810
Armor*Group	2	0.630	0.536
Task*Trial	6	0.530	0.787
Task*Group	**3**	**4.220**	**0.007**
Trial*Group	2	0.360	0.701
Armor*Task*Trial	12	0.740	0.714
Armor*Task*Group	6	1.630	0.142
Armor*Trial*Group	4	0.620	0.648
Task*Trial*Group	6	0.540	0.777
Error	151		
Total	210		

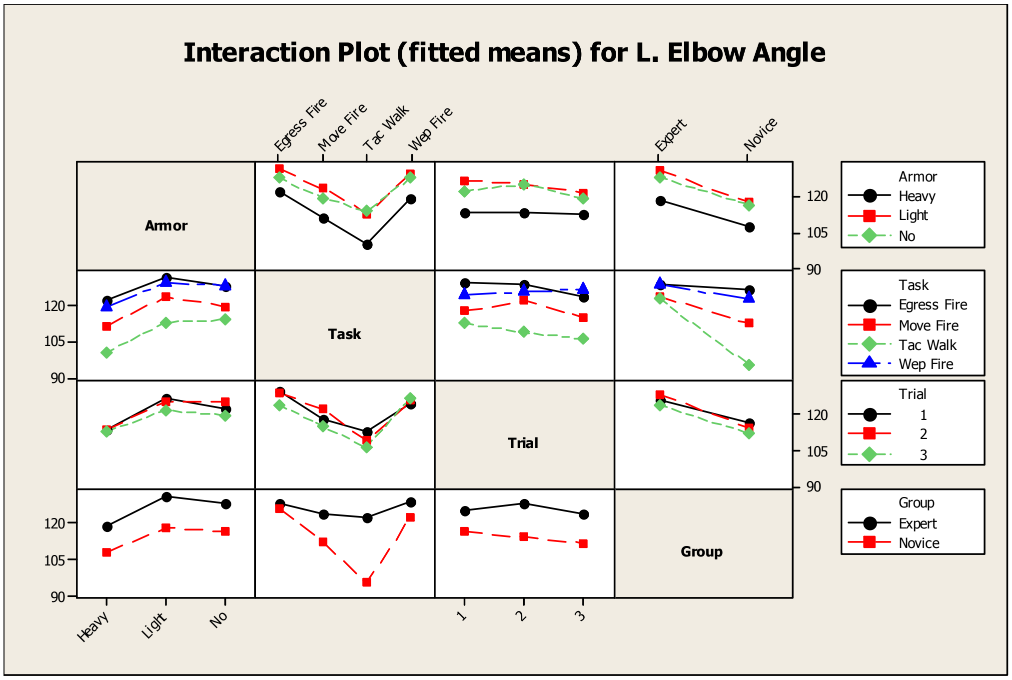

Figure 11 Left Elbow Angle Interactions Plot

Table 8 shows the ANOVA test results for the right wrist angle. The four-way interaction term between armor, task, trial, and group along with the three-way interaction term between armor, task, and group had to be removed from the general linear model for this variable due to missing data points. The armor and task main effects were found to be significant. Pair-wise Tukey comparisons revealed that the right wrist angle when wearing tactical armor (153.37°±11.66°) was significantly smaller (more extended) than in both the concealable (159.72°±8.12°) and the no armor (161.94°±4.80°) conditions (p-value < 0.001 for both). For the task variable, the right wrist angle during the tactical walk (155.54°±4.86°) was found to be significantly smaller than the right wrist angle during the egress-fire (158.42°±11.16°), weapon fire (159.44°±8.10°) (p-value < 0.001), and the egress-move-fire tasks (158.17°±10.56°) (p-value = 0.03).

Table 8 R. Wrist Angle ANOVA Results

Source	df	F-Value	P-Value
Armor	**2**	**17.770**	**< 0.001**
Task	**3**	**4.750**	**0.003**
Trial	2	1.240	0.291
Group	1	2.140	0.146
Armor*Task	6	0.580	0.748
Armor*Trial	4	0.100	0.981
Armor*Group	2	0.590	0.556
Task*Trial	6	0.350	0.911
Task*Group	3	0.160	0.921
Trial*Group	2	0.310	0.736
Armor*Task*Trial	12	0.470	0.929
Armor*Trial*Group	4	0.510	0.730
Task*Trial*Group	6	0.300	0.935
Error	155		
Total	208		

Table 9 shows the ANOVA test results for the left wrist angle. The four-way interaction term between armor, task, trial, and group along with the three-way interaction term between armor, task, and group had to be removed from the general linear model for this variable due to missing data points. The group main effect and the task*group interaction were found to be significant. Pair-wise Tukey comparisons revealed that the novice group's left wrist angle (142.61°±17.14°) was significantly smaller (more extended) than the expert group's left wrist angle (150.69°±17.91°) (p-value < 0.001). The task*group interaction plot (Figure 12) shows that the novice group was more different from the expert group when performing the tactical walk and egress-fire tasks. This difference did not seem to be affected by armor condition.

Table 9 L. Wrist Angle ANOVA Results

Source	df	F-Value	P-Value
Armor	2	1.840	0.162
Task	3	0.520	0.666
Trial	2	1.360	0.260
Group	**1**	**31.050**	**< 0.001**
Armor*Task	6	0.420	0.867
Armor*Trial	4	0.910	0.462
Armor*Group	2	0.270	0.761
Task*Trial	6	1.040	0.401
Task*Group	**3**	**5.960**	**0.001**
Trial*Group	2	0.320	0.724
Armor*Task*Trial	12	0.560	0.873
Armor*Trial*Group	4	0.450	0.770
Task*Trial*Group	6	0.400	0.878
Error	148		
Total	201		

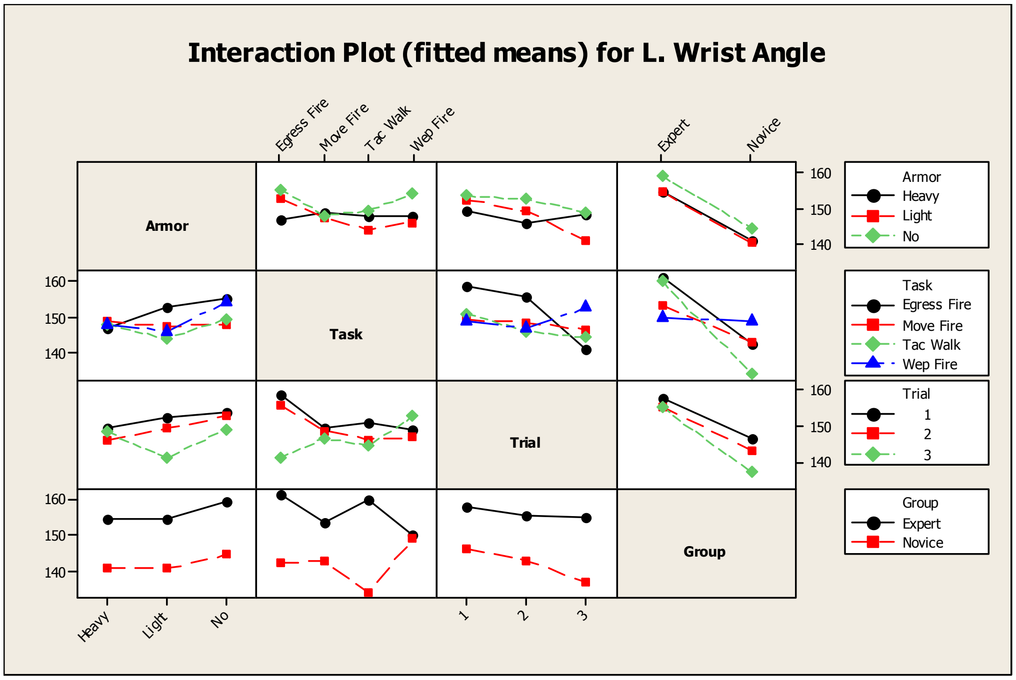

Figure 12 Left Wrist Angle Interaction Plot

Table 10 provides a summary of significant results at different alpha levels. The 0.05 alpha threshold was used for this study, but the 0.10 and 0.01 levels are shown as a comparison of the strength of the findings.

Table 10 Summary of Significant Results

	Included Angle						
Significant Factor	Neck	R. Shoulder	L. Shoulder	R. Elbow	L. Elbow	R. Wrist	L. Wrist
Armor	**	**	#	**	**	**	
Task	**		#	**	**	**	
Group	**		**	**	**		**
Armor*Task	*						
Armor*Group	*	*					
Task *Group	**	#	*	#	**		**
Armor*Task*Group	*						

= significant at 0.10 level

* = significant at 0.05 level

* *= significant at 0.01 level

CHAPTER V

DISCUSSION

Results Discussion

One objective of this research was to determine if the described posture analysis method was effective at distinguishing between different armor conditions for a shooting posture. Before quantifying differences in neck and upper extremity joint angles, as a function of armor condition, there needed to be some confidence that the included angles being analyzed described the shooting stance used by the participants. Using digital human modeling software as a visualization tool, the no-armor mean joint angles were used as input, and CHAPTER IVFigure 7 shows that by observation the posture assumed does look very similar to the Isosceles shooting stance seen in CHAPTER IFigure 2. The only obvious difference was the neck angle which tilts toward the dominant firing side for the tested shooting posture. This angle was produced by the effort to look down the handgun sights for a target, and is a common deviation for novice shooters. This was evidenced by the expert group's neck angle that was found to be 84 degrees, which was much closer to the ideal 90 degrees than the 69 degrees found for the novice group. Figure 13-Figure 16 below are additional images taken from the digital human modeling software that highlight how the included angles described in this study aligned with the body. These images also demonstrate how the angles contribute to the overall shooting posture.

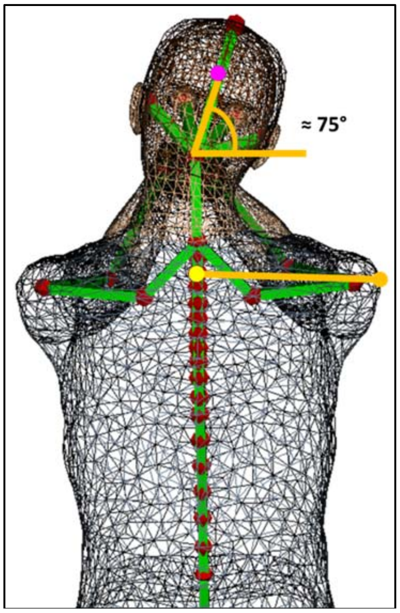

Figure 13 Example Neck Angle for Shooting Posture

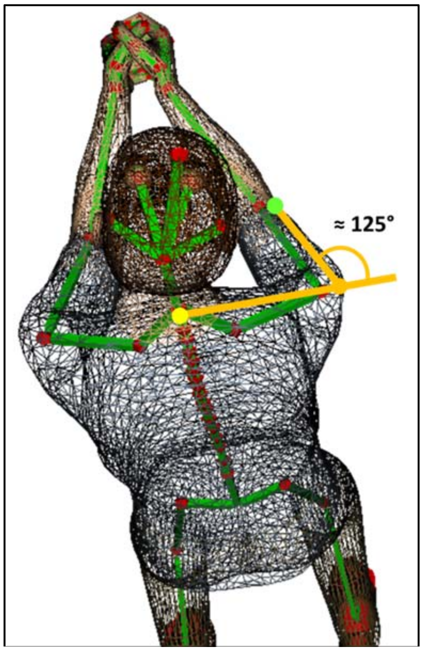

Figure 14 Example Right Shoulder Angle for Shooting Posture

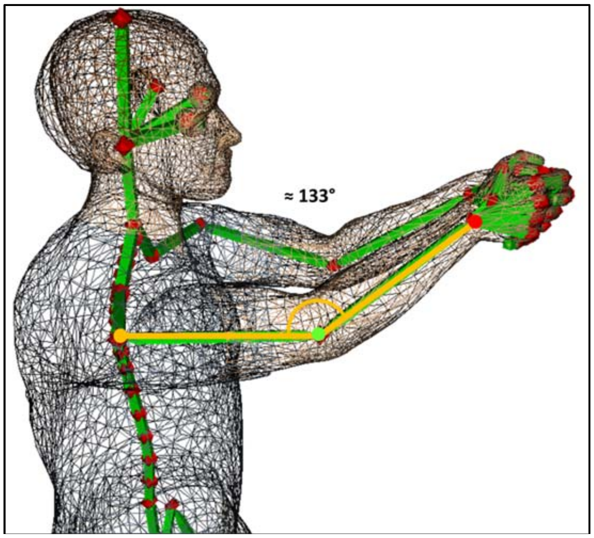

Figure 15 Example Right Elbow Angle for Shooting Posture

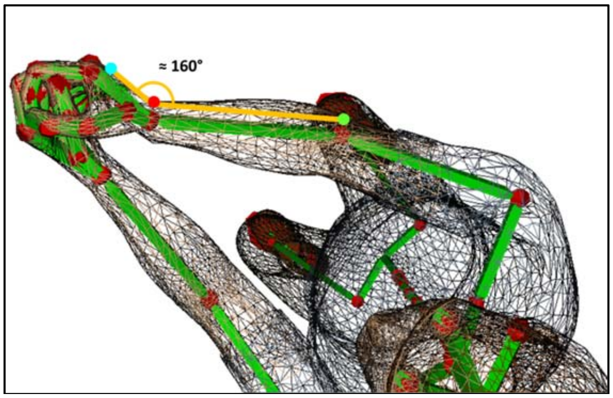

Figure 16 Example Right Wrist Angle for Shooting Posture

Five of the seven included angles examined in this study had significant results for the body armor factor. Only the left shoulder and left wrist did not have a significant shooting posture differences after the addition of body armor. The left shoulder armor factor had a p-value of 0.074, which is close to the 0.05 threshold value chosen for this study. If a less restrictive significance threshold had been used both shoulders would have had impacts from the armor factor. The left wrist was most likely not found to be significant because of how this joint is used for the shooting stance. The non-dominant hand and arm, was supposed to provide an isometric pull to stabilize the weapon during firing. This pulling force likely had a tendency to stabilize the left wrist for the participants tested here, and resulted in less variation over the range of conditions.

Post hoc analysis of the armor factor showed that the tactical armor condition caused shooting posture differences when compared to both the concealable or baseline condition for the right shoulder, right elbow, left elbow, and right wrist. The right shoulder effect was somewhat diminished since it had some interaction with the group factor. Examining the interaction closer revealed that the novice group had the most effect from the tactical armor. The neck angle tactical armor condition was significantly smaller than the concealable armor but not the no-armor condition. There were a significant number of interactions for the neck angle and examination of the interaction plot did not reveal any obvious anomalies, but it is certain that the neck angle has a complicated relationship between many factors.

Since the majority of the shooting posture angles examined here showed significant differences between more than one of the armor conditions, it can be inferred that the main objective of this paper was shown to be plausible for the externally worn tactical type armor, especially for the novice group. Because no significant results were found between the concealable and baseline armor conditions, the described posture analysis method may not have the necessary sensitivity to distinguish between body armor designs of similar type. However, this study does provide a proof of concept, and more robust future studies could provide more sensitive results.

An intriguing additional result of this study was found from testing of the experience group factor. The group factor, against prediction, was shown to have significant differences in the neck, left shoulder, right elbow, left elbow, and left wrist included angles. In addition, the interactions between the armor*group (neck, right shoulder), task*group (neck, left shoulder, right shoulder, left elbow, left wrist), and armor*group*task (neck) were significant. Initially it was hypothesized that this experience factor would not have a significant effect on shooting posture because all of the participants of this study were trained and departmentally qualified with their duty weapons. Previous research on manual handling tasks found that there was a significant difference between novice and expert test subjects; however the novices in these studies often have no previous training (Authier, Lortie, & Gagnon, 1996). Weapon firing technique is a highly practiced task in the law enforcement community, and while the novices in this study did have some previous training, the results seem to follow the results of other manual handling tasks, where experts had safer and more stable postures (Gagnon, 2003). Some evidence of this statement can be seen in the descriptive statistics for the experience group variable, shown in CHAPTER IVTable 2. Most of the shooting posture angles for the novice group had a higher standard deviation than the expert group, and were therefore less stable. Some additional evidence is found within the interaction plots. For the task and armor factors that interacted with the group factor, it was found that the results major contributor was within the novice group. While more focused testing would be needed for definitive proof, these results in conjunction with the higher angle variability within the novice group, seem to indicate that the expert group was better able to compensate for the addition of the body armor, and they seem to have had a more consistent shooting posture between the different shooting tasks. This finding is important for usability testing of new armor designs, since it is likely that the two experience groups would have different opinions about how restrictive armor may feel. It would be important to pay attention to this demographic and insure that all segments of the user population are considered.

There were no significant results found between trials for any condition. This indicates that all participants had a reasonably similar shooting posture between each of the three trials, but this was not the case for all the tasks. Significant differences were found between tasks for the neck, elbows, and right wrist. Post hoc analysis of the task main effect results showed that many of the significant differences were between the tactical walk and the egress-move-fire tasks. While it was initially assumed that the shooting posture would be very similar across all tasks used in this study, the significant differences seen with these highly mobile tasks was not surprising. Both the tactical walk and the egress-move-fire tasks involved excessive movement of the torso and lower body. These types of movement disrupt the lower body foundation of the shooting stance (Johnson, 2008), and as the results of this study show, it affects the upper body portion of the firing posture. The shoulders would be least affected by lower body and torso movement, since they provide the gross posturing of the weapon fire stance. However, the elbows, neck, and wrists provide the detailed movement for weapon sighting, and would have to compensate more to maintain proper target focus when the body was in an altered position. The egress-move-fire and the egress-fire tasks may have caused exceptional changes to the standard shooting posture of test participants because of the barriers, which could either be used for support or were an obstacle to the shooter.

Additionally there was some task*group interaction effects seen in the neck, left shoulder, left elbow, and left wrist. These interaction effects were almost exclusively limited to the novice experience group, while performing the tactical walk and egress-fire tasks. As discussed in the previous paragraph, one explanation for the differences seen in with the tactical walk task may be found within the details of the shooting stance. The officers of this study were trained on the Isosceles shooting stance, which has its foundation in a front facing semi-crouch. Attempting to walk in this stance and keep a weapon on target is difficult and requires more active compensation by the upper body. In contrast, the Weaver stance has its foundation in the police interrogation stance, which allows for a more stable upper body and a cross-over foot step to move forward (Weaver, 2009). The novice experience group had more difficulty moving forward while attempting to maintain their trained stance as evidenced by the task*group interactions and increased angle variability. The expert group's additional years of training seem to have helped them control their posture between tasks as well as armor conditions. Less of an effect may be seen in a group of police officers that were trained in the Weaver stance.

Significant findings involving the types of tasks used in this study highlight how variable the duties of law enforcement are. This study attempted to isolate a vital and common posture used by police officers in many different situations. It was expected this posture would be constant throughout the range of tasks, but it turned out that even the trained shooting stance has some variation, especially within the novice experience group. It is now evident that when testing ergonomics of body armor design, task selection is important and should include a wide range of tasks to ensure a full assessment of the armor effects on posture.

Suggested Future Work

Even though this study had several significant results, there were a few additional considerations that might increase the knowledge that can be gleaned from this line of research. The first improvement would be to the biomechanical model used to determine the joint angles. Because this was a proof of concept study with limited scope, simple included angles were used as the dependent variable. A more robust analysis should break the included angles into component parts, within different anatomical body planes. This would provide much more detail into the shooting posture differences induced by the body armor. Understanding these postural changes within specific body planes would help quantify the performance differences between armor designs, and provide better information to the designers for optimizing range-of-motion.

Anthropometric variations were another factor that was not examined in this study due to scope. Differences in the upper body segment dimensions may have a profound effect on the degree to which body armor affects a shooter’s posture. Anthropometry is intimately associated with the fit of body armor and with the ability of a shooter to assume a weapon firing stance while wearing armor. Certain design features may not have the same benefit across each of the body armor sizes, so future studies need to evaluate and distinguish between the effects on user population anthropometric groups.

Another useful metric that was not collected during this study was the accuracy of the participants’ shots while wearing body armor. Knowing that the shooters’ posture was altered by the wearing of body armor, one of the best ways to determine the performance impact of this change would be to record their accuracy while shooting at targets in different armor conditions. This study did not look closely at the degree of posture change, beyond the statistical significance of the mean variation of joint angles. How these angle changes impact the ability of law enforcement officers to accurately fire on targets is a more direct measure, and would be of paramount importance when choosing a body armor design. Future research in this area should certainly look to gain insight from how much posture change is acceptable before a shooting accuracy decrement is seen.

This information would be very helpful in determining how sensitive an analysis should be, and what posture areas are most important for the shooting task.

Conclusion

The shooting posture analysis method explored in this study was able to establish some significant results and prove the concept that posture analysis could be used for examining body armor designs. It was shown that by using upper body included angles it was possible to statistically distinguish between the posture of a shooter wearing external tactical body armor and the posture of a shooter wearing a lightweight concealable vest or no body armor. The shooting tasks used for this type of analysis were also found to be important and task selection should be planned carefully for future studies. This study indicated that weapon firing tasks that introduce obstacles or additional directions of movement may influence the ability of shooter to assume a stable shooting stance. It was also discovered during this study that a shooter's posture was affected by the number of years of law enforcement experience they have, as well as their ability to maintain that posture between shooting tasks, and their ability to compensate for the effects of worn body armor.

While not as sensitive as expected, this study did provide some useful information. With further development and considerations, such as participant anthropometry, the careful selection of tasks, and a more robust joint angle analysis, this research could be developed into a benchmarking method for armor designs. By quantifying the effect of body armor on law enforcement personnel performing simulated duty tasks, armor designers would be able to determine more optimized modifications to create a vest that provides increased protection as well as an acceptable range of motion.

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APPENDIX A

DEMOGRAPHIC QUESTIONAIRE

Baseline Measurements

Heart Rate	5min	6min	7min	8min	9min	10min
BPM	____	____	____	____	____	____
Baseline Ear Temp	____	____	____			
Ambient Room Temp	____	____	____			

Supplementary Information

Police officer/military experience

Police Military (branch/position: ___________________)

Number of years in service: __________

Body Armor Experience

Type of armor: ___________________

Years of experience: __________

Typical duration: __________

Handgun Training

Years of experience: __________

Firing Stance: ____________________

Dominant hand: __________

Additional Notes: ____

Form A

Section 1. Subject Data

Age _______________

Gender: Male Female

Section 2. Anthropometric and Vision Data

Anthropometrics

Weight _______________kg

Stature _______________cm

Waist Height _______________cm

Shoulder (Acromion) Height _______________cm

Upper Arm (Shoulder – Elbow) Length _______________cm

Lower Arm (Elbow –Fingertip) Length _______________cm

Upper Leg (Hip – Knee) Length _______________cm

Lower Leg (Knee – Heel) Length _______________cm

Vision

Color Blindness? No Yes (specify type: _______________)

Visual Acuity with corrective devices _______________

Eyeglasses or Contacts (circle) Contacts: Hard or Soft (circle) Colored: Yes or No (circle)

Brand of contact if known _______________

Dominant firing eye _______________

Form B Musculoskeletal Data

1. Have you had a significant injury? ______________________________
2. If yes, which body parts were affected by the injury? _______________
3. How would you describe your general fitness level?
   a) Poor b) Moderate c) Average d) Above average e) Excellent

Musculoskeletal Trouble

Have you had pain, ache, discomfort, injuries in	In the past 12 months			In the last 7 days		
	When did it occur	Rate (1-10) *1: lowest* *10: highest*	Duration it lasted	When did it occur	Rate (1-10) *1: lowest* *10: highest*	Duration it lasted
Neck						
Shoulders						
Elbows/Wrist/Hands						
Upper /Lower Back						
Knees/Legs						
Hips/Thighs						
Ankles/Feet						

APPENDIX B

MOTION CAPTURE MARKER NAMES AND ANATOMICAL LOCATION

Marker Name	**Location Description**
Front.Head	Anterior Skull along sagittal body plane, mid-way between brow and hairline
Top.Head	Top of Skull along sagittal body plane
Rear.Head	Posterior Skull along sagittal body plane, in-line with Front.Head
Offset.Head	Right Lateral side of Skull, creates plane with Front.Head and Rear.Head parallel with standing surface
C7	Protuberance at 7th Cervical Vertebrae
R.Clavicle	Right side, medial Clavicle
L.Clavicle	Left side, medial Clavicle
Sternum	Mid Sternum
R.Shoulder	Right, anterior, Acromial process
R.Bicep	Center of Biceps Brachii muscle
R.Elbow	Right side, lateral Humeral epicondyle
R.Wrist.Medial	Right side, Radial stylon
R.Wrist	Right side, Ulnar stylon
R.Hand	Right hand, distal 2nd Metacarpal
R.Hand.F4	Right hand, distal 4th Metacarpal
L.Shoulder	Left, anterior, Acromial process
L.Bicep	Center of Biceps Brachii muscle
L.Elbow	Left side, lateral Humeral epicondyle
L.Wrist.Medial	Left side, Radial stylon
L.Wrist	Left side, Ulnar stylon
L.Hand	Left hand, distal 2nd Metacarpal
L.Hand.F4	Left hand, distal 4th Metacarpal
T7	Spinous process of 7th Thoracic Vertebrae
R.Asis	Right side, anterior, superior, Iliac Spine
L.Asis	Left side, anterior, superior, Iliac Spine
V.Sacral	Superior articular process of Sacrum
R.Thigh	Mid-way down Rectus Femoris muscle on anterior right leg
R.Knee.Medial	Right leg, medial Femoral epicondyle
R.Knee	Right leg, lateral Femoral epicondyle
R.Shank	Right leg, mid-way down Tibia on lateral side
R.Shank.Rear	Right leg, mid-way down Tibia on posterior side
R.Ankle.Medial	Right leg, medial Malleolus
R.Ankle	Right leg, lateral Malleolus
R.Heel	Right posterior Calcaneus
R.Toe	Right distal 2nd Metatarsal
L.Thigh	Mid-way down Rectus Femoris muscle on anterior left leg
L.Knee.Medial	Left leg, medial Femoral epicondyle
L.Knee	Left leg, lateral Femoral epicondyle

L.Shank	Left leg, mid-way down Tibia on lateral side
L.Shank.Rear	Left leg, mid-way down Tibia on posterior side
L.Ankle.Medial	Left leg, medial Malleolus
L.Ankle	Left leg, lateral Malleolus
L.Heel	Left posterior Calcaneus
L.Toe	Left distal 2nd Metatarsal
M1	Right, anterior, inferior edge of body armor
M2	Left, anterior, inferior edge of body armor
M3	Right, posterior, inferior edge of body armor
M4	Left, posterior, inferior edge of body armor