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The Classic Suit of Armor

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by

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Abstract

This IQP team researched the history of armor collecting, the armor manufacturing process, the biomechanics of wearing armor, and the physical properties of armor's protection. This knowledge was applied to the study of HAM 429, a non-homogeneous armor harness of full plate armor from the Higgins Armory Museum's collection. This harness had never before been studied in depth. The culmination of this study was a video highlighting all the noteworthy aspects of each component of the harness.

Acknowledgments

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Introduction

The Higgins Armory Museum is the only museum in the Western Hemisphere which focuses solely on armor. It houses over one hundred complete harnesses, as well as thousands of single pieces that trace the evolution of armor from the ancient period to its apex in medieval Europe and its decline with the emergence of more sophisticated firearms. This project built upon the efforts of previous "The Classic Suit of Armor" IQP teams as well as pursued research into other areas of plate armor. Particular focus was centered on the history of armor collecting, the manufacturing process, the biomechanics of wearing armor, the physical properties of armor's protective ability, the fashion of armor, and their respective historical contexts. To put our acquired knowledge into practice, the team examined a highly non-homogeneous full plate harness from the Higgins collection and produced a video of our investigation. As part of some new steps forward for this particular IQP and the Higgins Armory, the team also investigated some future possibilities for the existing armor database, including the use of a wiki to house everything a database would.

Body armor of some form has been in use since time immemorial. Before the advent of metalworking, body armor may have consisted of thick furs. In the first millennium BCE, a type of body armor consisting of interwoven rings of metal came into use and was known as mail. The era of plate armor began around 1350 CE as armor technology evolved with advances in metalworking and the pressure of improved weapons. Medieval armor reached its high point around the late 1400s to early 1500s: the "knight in shining armor" that we envision today was most likely from this period. However, the modernization of armies led to the bulky and restrictive harnesses being gradually discarded from the late 1500s onward. As armor lost ground to more effective weaponry, the usefulness of armor dropped significantly and plate armor eventually became obsolete by the early 18th century. In the modern day, armor is largely a collector's item.

Armor collecting actually began in the late Middle Ages. The collected pieces were largely armor passed down through the families and descendants of the original wearer. Many of those armors were later acquired by royal houses for political reasons and as status symbols; some eventually found their way into private collections. Often, the harnesses were refashioned from mismatched parts to form composite harnesses and were sold to new owners. Armor purveyors sold these composites to increase revenue because full harnesses fetched higher commissions. As a result, one of the difficulties faced by curators is the determination of which components are original. Today museums own the vast majority of the world's remaining European armor. Armor collection was researched by the team to provide a basis for the investigation of the composite harness.

An understanding of the manufacturing process of plate is essential to interpreting its protective capability as well as its being a fashion symbol. Plate armor was manufactured by highly skilled craftsmen and artisans in trade organizations called guilds. The guilds provided both training and economic protection similar to modern workers' unions and became the focus for armor output. Manufacturing methods of armor progressed in order to meet new demands and take advantage of new materials and technologies. These demands were driven by both new military realities and the clients' desire for impressive armor. This project studied the evolution of armor manufacture in depth and focused on advancements in the knowledge of metallurgy, metal shaping, and movement with respect to human anatomy. It can be stated that with the technology of the time, the production of high-quality plate armor was an impressive accomplishment. This project documented the trip a typical harness took from the ore mine to the owner and ultimately to the museum.

The team also investigated certain functional aspects of the wearing of armor and began models derived from the research. The team investigated human anatomy and susceptibility to injury to establish the basis for the need to wear armor. Physiological processes that are affected by the wearing of armor, such as respiration and heat exchange were also researched. Basic human abilities such as exerting forces from various body positions and the range of motion of the body were examined alongside some concepts from the field of biomechanics to provide insight into what was physically required for armor to be worn. The team investigated some properties of modern body armor such as the materials it was made of, its overall weight, and how it was supported on the body to provide a better context for the analysis of historical armor. Models were also derived from some of the structural features of historical medieval armor. The emphasis of the team's research was placed on the concept of effective armor being an entity that had to protect the wearer, but not greatly hinder his freedom of movement and mobility in battle. Though the technologies employed in body armor may have changed dramatically over the centuries, the human body has not and thus the consideration of it has remained important.

The team investigated the form and function of medieval armor during this research project to further understand their concurrent evolution. Plate armor developed from previous armor styles in response to the battle tactics and offensive weapons of the day. Several main types of medieval weapons were modeled, including point impact and arcing weapons, to better understand why armor was constructed as it was. The functional aspects of armor were dictated by both advances in manufacturing methods, better materials, and the simultaneous evolution of weaponry and military tactics. From a historical analysis standpoint, an armor's form (shape) can be difficult to interpret as either directly functionally related or influenced by the civilian fashion of the times. Plate armor later became a decorative status symbol for the wealthy and influential. In addition customers became more obsessed with high-quality armor as a status symbol and battlefield effectiveness was supplanted by intricacy, detail, and uniqueness.

The Higgins Armory Museum collection contains many harnesses that have never been thoroughly studied. The core of this IQP project was examining HAM Harness 429 in detail. HAM Harness 429 was sold to the Higgins Armory Museum by Joseph Duveen in 1928. From an initial inspection, HAM 429 was determined to be of the 'Pisan' style. The 'Pisan' style was comprised of second-quality harnesses that were usually made in Milan in the late 16th century. The style was characterized by its distinctive etching that consisted of badly drawn foliage, grotesques, and trophies spread in a confused mass along borders and bands that spanned nearly all of the harness components. In a type-written transcript of the museum's purchase of the harness, it was purported that the harness was homogeneous, from the period of 1580-90, and contained all original components. However, the team determined that the harness was highly composite and could portray a fairly convincing image of a full cavalry harness, but failed any closer inspection by those knowledgeable in the field of armor. The size, decoration, and apparent age of components such as the gauntlets, vambraces, cuisses, and greaves did not match between the left and right sides. The team also discovered numerous indications that the harness had been reworked in the modern period, including repairs, cracks, and gouges in the metal, badly turned and sharp edges, and components that didn't fully join together. The handling of historical artifacts was a unique opportunity and many details were discovered that could only have been discovered by close inspection.

History of Armor and Armor Collecting (Ryan Meador)

The Knight and Chivalry

In the early middle ages, the terms "knight" and "nobility" had nothing to do with each other, and in fact were nearly opposites. "Knight" was a term used to describe a servant, whereas "nobility" was the class of people of high social status who were known for being wealthy and militarily skillful. The meaning of these words converged to our present concept of the knight as a nobleman at different times throughout Europe, but the change was complete everywhere by AD 1300. The development of chivalry helped propel the knight into a new class of society.[1]

> "The figure of the knight at once dominates the medieval world and distinguishes it from the classical era. The knight inherited both the lands and status of the magnate of the Roman world in his luxurious villa and the political power of the infantry soldier of the Praetorian Guard. His roots were barbarian; his ideals, born of the three turbulent centuries between the end of the western Empire and the accession of Charlemagne, were in sharp contrast to the Roman order. Above all, two characteristics stand out: in war, he fought on horseback where the Roman legions had fought on foot; in peace, he held his land because he was a skilled fighter."[2]

Knights were primarily mounted warriors throughout the Middle Ages, so having a horse was critical. Horses were very expensive to own and maintain, requiring a warrior to be financially well-off to equip himself as a cavalryman.

Cavalry units were much more valuable than foot soldiers because they would tend to arrive a the battlefield in better condition (less tired) than foot soldiers who had to walk. Also, as they are invested in being a cavalryman, they tend to be much better trained. The quality and condition of the

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1 "Knight". http://en.wikipedia.org/wiki/Knight
2 Barber, Richard. (1995) The Knight and Chivalry. The Boydell Press: Great Britain. 4.

cavalry troops were usually just as important to the outcome of a battle than the brute force of the cavalry charge.[3] The knight's most powerful weapon was the lance. Lances first came into use around AD 1000. By the late 1100's, lances were held at rest. The lance rest was a small metal bracket attached to the breastplate of the armor, permitting the force of the impact of the lance to be transferred less through the knight and more through his armor. Absorbing that force necessitated a number of changes to the war equipment of the era, including large shields and high-backed saddles. It is interesting to note that it is around this time that horses are commonly shod for the first time, greatly increasing the mobility of cavalry units; the horse shoe had been known for some hundreds of years, but wasn't in common use.[4]

As armor moved from mail covering only part of the body to full plate armor, the costs of armoring oneself also rose dramatically. The wealth needed to become a knight automatically made knighthood a high status mark in society.[5] Those who could not afford to become knights often became squires, support troops and servants for knights.

It was the advent of chivalry that made the knight class regarded as truly noble.[6] Chivalry was a moral or ethical code that supposedly bound the behavior of all knights. It can be loosely broken into three categories: duty to the King, religious devotion, and duty to women. The duty to the King was to show loyalty, bravery in battle, and a willingness to sacrifice oneself. Duty to women was to treat them as superior beings; every idealized knight was supposed to "have" a lady with whom he flirted, a concept usually called "courtly love". This relationship was usually entirely non-physical.[7]

The way knights acted towards women was a new invention at this point in European history.

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3 Barber. 4.
4 Barber. 7
5 "The Classic Suit of Armor" (2006) . 40
6 Barber. 67.
7 "Chivalry" http://en.wikipedia.org/wiki/Chivalry

The worship of the Virgin Mary was no different than that of any other saint until chivalry emerged in the early 12th century and all women were though of as higher beings by the religiously-devout knights.[8] This helped spawn the large number of medieval romance stories that commonly come to mind today when thinking of the deeds of knights (the "damsel in distress" in particular). Period fiction elevated the concept of the knight to larger-than-life.

The tournament was a fusion of military and chivalrous ideals. It is widely regarded as the central ritual of chivalry. "[The tournament] first appears when chivalry is in its infancy, and only vanishes when chivalry itself is no longer an active inspiration."[9]

Knights served as expert warriors and commanders when a king raised an army. Standing armies replaced the need for the knight with a full-time trained commander.[10] At the same time, armor also fell into disuse by the improvements in the design of firearms. These combined factors led to the death of the knight class and their chivalrous ideals.

Early Armor Collecting

Maintaining collections of armor for historical purposes is a natural outgrowth of keeping family heirlooms. For this reason, armor collecting began while armor was still in use by the families who were using it. Even after a given family member stopped using their armor (they became too old or died), the armor was kept as an heirloom. Very few armor collections still exist in the world today that has such a tradition as their beginning. Castle Churburg is nearly unique in that it contains an almost unbroken sequence of harnesses of each successive generation of its lords from the 14th to the

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8 Barber. 73.
9 Barber. 155.
10 Nicholson, Helen. (2004) Medieval Warfare. New York: Palgrave Macmillian. p53-59

middle of the 17th century, which is when armor fell into disuse.[11] Most other collections that have their roots in family armories from the times when armor was still in use have largely been destroyed by being over-cleaned or restored, or also mixed with other armor to create piecemeal suits. Because of the care taken with the Churburg collection, the linings and straps have mostly survived. A contributing factor this has likely been that the collection has remained in one place throughout its history.

The Churburg collection, being one of the best preserved and homogeneous collections of armor in the world, has helped medieval historians greatly. Some writers have tried to show that the royal armor preserved in most collections was only for kings and princes and the lesser nobility used the significantly lower quality armor as the rank-and-file troops. Churburg is virtual proof that this is not the case, as it is an out-of-the-way castle with a lesser noble ruling family, yet still has amazing armor. Early writers also ignored local differences in the style of the armor being produced at any one time, and tried to pass the differences off as chronological. Because of this misconception, they often illustrated contemporary accounts with armor from other regions, a practice that has continued until the 1930s (and perhaps later). Churburg refutes this as well by showing armor from a single location through the ages and demonstrates how local fashion influenced the designs.[12]

One of the reasons Churburg's armory has survived is the unusual requirements written into the ruling family's deed of partitioning. The Ulrich family estates were partitioned in 1422, with the requirement that “all family relics of any description preserved at Churburg should be left there”.[13]

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11 Trapp. vi
12 xi
13 xxxiv

Models Derived From Human Anatomy, Physiology, and Body Armor (David Sansoucy)

Human Anatomy

The human body naturally has its own means of protection in the form of the skeleton and to a limited extent, the skin. In everyday living, the skeleton and skin are usually enough to protect the body from serious harm. However, when one's intent is to fatally wound the enemy, as in warfare, then the natural means of protection loses its significance. The human body is replete with vulnerabilities that have been exploited by fighting men since time immemorial. Through these vulnerabilities, severely disabling or lethal wounds can be inflicted on the victim. In the highly visceral, face-to-face combat of the medieval period, full-plate armor was used to greatly improve upon the body's own natural protection.

Some of the most serious bodily injuries are those inflicted upon the body's internal organs. The body is made up of three main cavities that house those organs: the cranial, thoracic, and abdominal cavities.[14] The cranial cavity is the space in the skull that contains the brain. Nearby, the spinal cord is located within a canal formed by the vertebrae.[15] The thoracic cavity lies within the thorax (chest) and it contains the heart and lungs. The thoracic cavity also contains the esophagus, trachea, and several large blood vessels. The abdominal cavity is in the lower portion of the trunk and contains the digestive organs (liver, stomach, pancreas, small and large intestines), kidneys, and several large blood vessels.[16]

The bones of the human body can be grouped into the axial skeleton and the appendicular

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14 Erven, 38
15 Spence, 89
16 Erven, 39

skeleton.[17] The bones of the axial skeleton form the skull, thorax, and vertebral column. The internal organs of the cranial and thoracic cavities are protected by the skull and ribcage respectively. The vertebral column protects the spine and does provide some protection for the organs of the abdominal cavity, from the posterior side at least. The appendicular skeleton consists of the bones of the upper and lower limbs, as well as the means by which those limbs join the axial skeleton: the pectoral and pelvic girdles respectively.[18]

On the medieval battlefield, there was a plethora of ways in which combatants could be struck down. Weapons were designed for bludgeoning, piercing, and slashing, to name a few main types. An understanding of wounds is necessary for appreciating the types of damage that weapons caused to the body. By definition, a wound is "any injury which causes a break in the skin or other body membranes or in the underlying tissues." The two main dangers associated with a wound are serious bleeding and infection.[19] Internal wounds may be caused by any sudden forceful blow to the body's cavities. Any injury to the chest may shortly result in death if the heart or lungs are damaged. The heart's electromechanical system may be disrupted by severe blows to the chest cavity and life threatening arrhythmias (abnormal rhythms) such as atrial or ventricular fibrillation may result.[20] In the abdominal cavity, the liver is easily damaged by external blows and if the liver is lacerated, the hemorrhaging may be fatal. In general, the organs most likely to be damaged by external blows are the lungs and the intestines.[21] The brain may be severely damaged by sharp blows to the head. Upon impact, the brain strikes the skull which causes the release of cerebrospinal fluid. Since the skull is rigid, it won't expand with the increase in pressure, and the brain's blood vessels are compressed resulting in a

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17 Spence, 102
18 Spence, 125
19 Erven, 134
20 Erven, 148
21 Erven, 141

drastically reduced oxygen supply to the brain.[22]

Fatal Injuries

While an individual may be killed outright by severe trauma to the brain or heart, death of higher organisms usually is due to a lack of oxygen to the body's organs, tissues, and cells.[23] The lack of oxygen (hypoxia) may be due to an obstructed airway, respiratory arrest, or severe bleeding to name a few. Oxygen is the most crucial of survival necessities because survival time is severely limited when the body is deprived of adequate amounts of oxygen, even for a short amount of time. The human body is unable to store oxygen in any appreciable quantity, and therefore death will occur after a few minutes' deprivation.[24] An individual who has stopped breathing, but is still alive is in a state of asphyxia due to a deficiency of oxygen and an excess of carbon dioxide in the blood. If breathing isn't restored, death will occur in a matter of six minutes or less.[25] Anoxia refers to the total lack of oxygen and it occurs when the body's extremely limited reserves of oxygen, in the blood and lungs, are depleted. The first tissues of the body to suffer from decreased oxygen in the blood are the higher centers of the brain and irreversible brain damage usually occurs if the brain's supply is diminished for four to five minutes.[26]

Blood is the bodily fluid that carries oxygen to the body's cells and removes wastes such as carbon dioxide. Any damage or disruption in the flow or containment of blood in the circulatory system can cause oxygen deprivation in the cells. In the circulatory system, blood is carried away from the heart by large vessels known as arteries and brought back to the heart by other large vessels called veins. Smaller vessels known as capillaries connect the arteries and veins. The escape of blood

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22 Erven, 155
23 Erven, 95
24 Erven, 91
25 Erven, 95
26 Erven, 96

(hemorrhage) occurs whenever there is a break in the wall of one or more blood vessels.[27] The average adult contains about five to six quarts of blood, which accounts for one-twelfth to one-fifteenth of the body weight respectively. One pint of blood can usually be lost without any harmful effects. In adults, the loss of two pints of blood is usually serious, and the loss of three pints may be fatal.[28]

Bleeding from an artery is more serious than bleeding from a vein. The arteries are under high pressure from the heart's contraction and blood profusely spurts out from them when hemorrhage has occurred. A hemorrhage in an artery of average size will not clot because the blood is under too much pressure, which means that the blood flow through the hemorrhage is too great for a clot to form.[29] Venous bleeding is usually less serious than arterial bleeding, unless it is a really large vein that has been cut. Venous blood is under a lot less pressure than arterial blood, which makes clotting easier, but can allow for the formation of a potential deadly air embolism. If an air bubble in a vein reaches the heart, it can dramatically interfere with the heart's electromechanical pumping action. In the case of a severed jugular vein (a primary vein that drains the head) in the neck, there is an extreme risk of air embolism because of its proximity to the heart.[30]

At certain locations in the body, fatal hemorrhages may occur in a very short time. The cutting of the primary blood vessels in the neck, arms, or thighs may result in fatal hemorrhage in one to three minutes.[31] The right and left common carotid arteries are the primary blood vessels which pass from the thorax, through the neck, and to the head.[32] The right and left subclavian arteries supply the right and left arms respectively, and become the brachial arteries further down each arm. The main artery that supplies each arm is vulnerable in its axillary section, which is in the armpit. The two primary

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27 Erven, 127
28 Erven, 128
29 Erven, 127
30 Erven, 128
31 Erven, 128
32 Spence, 306

arteries that branch from the lower trunk to supply each leg are the right and left femoral arteries. The rupture of the main trunk blood vessels of the chest and abdomen may result in fatal hemorrhage in less than half a minute.[33] The main artery in the body is the aorta, and its thoracic and abdominal sections are the thoracic and abdominal aorta respectively.[34] The thoracic aorta is fairly well-protected by the ribcage, whereas the abdominal aorta and the nearby superior and inferior mesenteric arteries, which supply the abdominal organs, are fairly well-exposed to slashing wounds on the anterior side of the body. All of the above mentioned major arteries have their large venous homologues: the internal jugular veins, the right and left subclavian veins, the right and left femoral veins, the common iliac, and inferior vena cava.[35] Injury to those veins may also prove fatal because of their large diameters.

In the body, muscles are richly supplied with blood. In general, each muscle has its own independent blood supply, but almost all muscles have many supply arteries.[36] Some of those arteries are larger than others, depending on the muscle's oxygen requirements. Muscles will bleed freely when cut and from both sides of the cut. The amount of bleeding from either side of the cut doesn't necessarily have to be the same. The large and powerful muscles of the lower limbs require a large blood supply and will bleed a lot when cut. Some of those muscles include: the gluteus maximus, illiacus, rectus femoris, semitendinosus, and gastrocnemius.[37]

Disabling Injuries

Disabling injuries are worth noting because they might have led to the individual discontinuing the battle or even his later death. Any of the above-mentioned injuries likely to be fatal may also have been disabling if they were of lesser degree. However, injuries to the bones, specifically those of the

33 Erven, 128
34 Spence, 311
35 Spence, 316
36 Marshall, 380
37 Spence, 222

limbs, muscles, tendons, ligaments, and spinal cord are some of the common ways to become disabled. The arms and legs are the two major lever systems of the body and they are linked together by the spine.[38] Bruising, laceration, and other types of damage directly to the muscles of the limbs can lead to impaired muscular contraction and reduced mobility. Muscle functionality may be disrupted by damage to the cords of dense connective tissue that attach muscles to bones (tendons).[39] An injury to the thick calcaneal (Achilles) tendon can result in hampered control of the foot. Ligaments are structures made of dense connective tissue that bind bones together at joints. The arms may be disabled by injuries to the ligaments of the shoulder and elbow joints. The legs may be disabled by injuries to the ligaments of the hip and knee joints. The knee joint is vulnerable to horizontal blows, especially a lateral blow to the extended knee.[40]

Many kinds of injuries can occur in the limbs, but some of the more serious disabling injuries are limb avulsions and the various types of fractures. An avulsion is when a body part is forcibly torn away by trauma.[41] If occurring in a limb, an avulsion obviously results in the limb no longer functioning properly. In terms of fractures, open (compound) fractures, which involve adjacent wounds in the soft tissues or skin, are more serious than closed fractures which only involve the bone. In battle, a non-serious fracture may be made worse if the individual continuously receives blows because the broken bone(s) may produce sharp ends that can cut blood vessels or severe nerves.[42]

Any serious fracture in a limb's bone(s) is likely to result in the inability to use that limb. In the forearm, any fracture of the radius or ulna is likely to result in the inability to use the forearm.[43] In the upper arm, fracture of the humerus is likely to produce a wobbly motion about the point of fracture and

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38 Erven, 233
39 Marieb, 121
40 Marieb, 235
41 Erven, 143
42 Erven, 236
43 Erven, 240

seriously impair upper limb control. Loss of control of the upper limbs is serious because one would no longer be able to wield his weapon effectively. Fracture of the femur (thighbone) will produce a wobbly motion and complete loss of control below the fracture.[44] Serious damage to blood vessels and nerves in the upper leg often results from a fractured femur. One's mobility could be severely impaired depending on the type of fracture and the amount of surrounding tissue damage.

The bones of the aforementioned limbs do not need to be fractured for the limb to be disabled. Injury to the nerves that innervate the muscles of the limbs can result in the inability to move the limbs. Since the nerves of both the upper and lower limbs originate in the spinal cord, their functioning may be affected by damage to the spine. If the spine is fractured at any point, the spinal cord may be cut or severely damaged resulting in paralysis or even death. If the spinal cord is damaged in the lumbar region of the back (the region between the thorax and pelvis), then the person wouldn't be able to move his lower limbs. If the person can't move his upper limbs, the spinal cord is probably damaged in the neck.[45] Loss of function in the upper limbs may also result from local damage to the median, ulnar, or radial nerves in the arms.[46] Loss of function in the lower limbs may also result from local damage to the femoral, obturator, or sciatic nerves in the legs.

Human Physiology and Physical Abilities

The usage of full plate armor in Medieval Europe can be better understood in terms of basic human parameters as described by modern sciences such as biomechanics. Given that humans haven't evolved much in five hundred or so years, the vast majority of today's human body parameters remain

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44 Erven, 241
45 Erven, 246
46 Marieb, 487

relevant for persons who lived in medieval times. Body parameters such as height, weight, build, and mass distribution as well as the senses of vision and hearing are important. Physiological processes such as respiration and heat exchange and basic human abilities in terms of locomotion, lifting loads, and flexibility are equally important in the investigation of wearing full plate armor. An understanding of the aforementioned parameters of the "average" human is important because many of those parameters are affected by the wearing of full plate armor.

As its name suggests, biomechanics is a combination of engineering mechanics, biology, and physiology. In the field of biomechanics, the principles of mechanics are utilized to investigate various aspects of the human body and to design appropriate systems and devices.[47] Although there are many present applications of biomechanics, the discipline can also be used to better understand the use of full plate armor in the medieval period. The harness components apply various loadings, torques, stresses and wearing the armor affects the center of gravity of each body region as well as the overall center of gravity of the body. The analysis of those aforementioned conditions is relevant to biomechanics and the discipline provides powerful tools and methods with which to investigate the wearing of armor.

Human Body Parameters

Height and weight are body parameters with a high degree of variability between persons. For these measurements, use of the mean and standard deviation is usually insufficient, whereas the use of percentiles is more appropriate. However, percentile data was hard to obtain, and therefore averages will be used. One's level of physical fitness usually doesn't affect one's height, and the average height for young men (16~30 years old) from a select number of studies is around 175 cm or around 5 feet 9

47 Ozkaya, 5

inches.[48] The author arrived at said value by taking the average of the averages of several studies that were all conducted in the US. The aforementioned studies dated from 1951 to 1998 and no specific mention was made of their respective sample sizes. One's weight does vary more so with one's fitness level than does height, but it can be assumed that from large enough studies, the effects of one's fitness level on one's weight have been "ironed-out". Based on the same above-mentioned studies, the average weight for young men is around 158 lb.[49] It is well-known that in medieval times, people were a few inches shorter on average, but not to the extent as sometimes imagined. Skeletal surveys of medieval English graves found an average height for men of around 5 feet 7 inches (170.2cm). A survey in Denmark yielded the same results as the English survey.[50] No mention was made of the sample sizes in each of the aforementioned studies.

An important parameter of the human body is its mass distribution. In terms of tissues, on average the body's muscles comprise about 50% of the total body weight.[51] The average weights of the various body parts in terms of percent of the total weight for men are as follows: 1.3% for the hands, 3.8% for the forearms, 6.6% for the upper arms, 2.9% for the feet, 9.0% for the lower legs, 21.0% for the thighs, and 55.4% for the trunk (including the head and neck).[52] A related concept of mass distribution is the center of mass, which is the same as the center of gravity in most cases. The center of mass is the point in the body where the entire mass of the object is assumed to be concentrated and the center of gravity is the point where the total weight of all the body's particles acts as a concentrated load. An object can be balanced on a pointed edge directly below its center of gravity and can be cut

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48 McArdle, 788
49 McArdle, 788
50 Singman, 57
51 Spence, 177
52 Luttgens, 402

vertically to produce two halves of equal weight.[53] In humans, the limbs, head, and trunk each have their own respective centers of mass, but what is usually more important is the center of mass of the entire human body. The position of the center of mass can vary depending on the orientation of the body and its limbs, but in the case of a subject standing up with arms down at the sides, the center of mass is typically located in the pelvis in front of the second sacral vertebra.[54] As a result of the body's near left-right symmetry, the center of mass is located in the mid-sagittal plane that divides the body into left and right halves.

Human Senses

Two human senses are likely to be affected by the wearing of armor, specifically the helm: vision and hearing. The wearer's visual field is most likely to be affected by the helmet. Both eyes look about in the same direction and the visual field for each eye is about 170°. There is a considerable amount of overlap in the visual fields of each eye and in the horizontal plane; the total visual field is about 180°.[55] Another aspect of vision that may be relevant is that of line of sight. For a seated individual, the line of sight has often been reported as about 15° below horizontal and is depicted in Figure 1.[56] Though not explicitly mentioned by the source, the line of sight portrayed in the figure is likely to be that of when the eyes are at rest. The knight was seated on a horse and the design of the helmet's view slit may have affected the knight's line of sight.

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53 Ozkaya, 73
54 Ozkaya, 77
55 Marieb, 458
56 Freivalds, 497

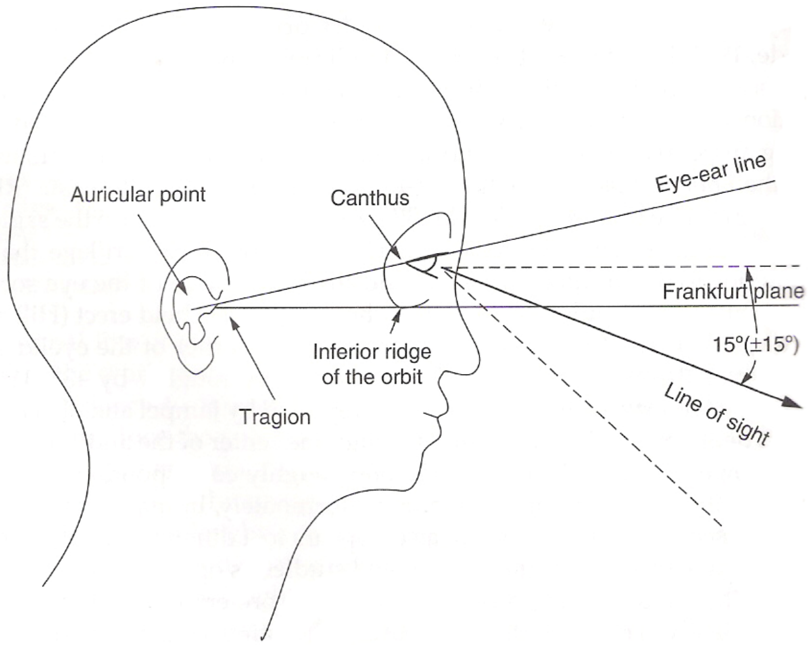

Figure 1: Line of sight

In terms of hearing, the conduction of sound to the inner ear via the bones of the middle ear was necessarily hampered by the wearing of the helmet and its liner(s). Since most helmets covered the outer ear, many of the sound waves entering the external auditory canal are weakened and thus wouldn't displace the eardrum as much as without a helmet on.[57] A quieter sound would result and this could have been problematic on the battlefield. The localization of the sound source may also be affected by the weakened sound waves and reverberation caused by the properties of the helmet's materials.

Physiological Processes

Two important physiological processes may be affected by the wearing of armor: respiration and heat exchange. The analysis must be simplified by making certain assumptions regarding the "average" knight in the Middle Ages. It will be assumed that due to his training, the knight was on

57 Marieb, 465

average more physically-fit than the average medieval man. The values for respiration assume that fighting a battle constitutes heavy, vigorous exercise. During vigorous exercise, breathing rate readily increases to 45-50 breaths/min for healthy young adults, and may be as high as 60-70 breaths/min for elite endurance athletes.[58] The tidal volume (the volume inspired or expired per breath) increases to around 3.0 L/breath and overall pulmonary ventilation is around 150 L/min. For a man in excellent cardiovascular health, the maximum oxygen consumption (expressed in ml of O_2 per kg of body mass per minute, ml/(kg*min)) can range from 45 to greater than 53 ml/(kg*min).[59] The above data clearly demonstrates that adequate ventilation is essential to the ability to fight on the battlefield.

Certain components of a harness affected the physiological process of respiration. The type of helmet and torso armor (breastplate and backplate) used are among the components which could directly affect respiration. An open helm would provide greater air flow and thus less restriction to respiration than a typical close helm would. Some close helms had hinged pieces which could open to allow for easier respiration, but this would have been at the expense of protection. Jousting helms were designed with providing maximal protection and frequently presented the greatest restriction to normal respiration. The pressure of the breastplate and backplate on the wearer's thorax would affect one's normal respiration. The thick layer of garments worn underneath the armor also would have added to the restriction. Such scenario is easy to imagine when considering how the ease of breathing is affected by the wearing of a heavy winter coat or other garment of considerable weight that lies close to the body and resists expansion due to its construction.

The process of heat exchange between an individual and his environment is important in the maintenance of homeostasis. The basal metabolic rate (BMR) reflects the body's heat production and is usually expressed in units of energy per body surface area, or energy per body mass per time. For a

58 McArdle, 261
59 McArdle, 163

30 year old man at rest, the standard basal metabolic rate is around 154 kJ/(m^2*h).[60] During exercise, the metabolism of elite athletes can rise from about 1.2 kcal/min at rest to around 20.0 kcal/min. Such strenuous exercise means that the athlete's core temperature can increase by 1°C (1.8°F) every five to seven minutes.[61] From the literature, when on horseback at a full gallop, the likely energy expenditure of a 158 lb man is around 9.7 kcal/min. When fighting on the ground, the likely energy expenditure of a 158 lb man is likely an average of the values for kendo, judo, and wrestling, and is around 13.3 kcal/min.[62] The aforementioned values can be representative of a medieval knight in combat, but are unsubstantiated. The extra burden of armor, even on a fully-trained individual would be significant because the added weight would be put into motion resulting in the generation of more heat. In an example of weight carried on the ankles, a weight equal to 1.4% of the body mass would increase the energy required for walking by about 8% or nearly 6 times greater than if the same weight was carried on the torso.[63] Even seemingly insignificant increases in the amount of load supported and moved by an individual can result in increases in the amount of energy expenditure, which further increases the amount of heat produced.

Thermoregulation of the body is important to prevent overheating. Heat can leave the body by the mechanisms of conduction, radiation, and convection, but most importantly the evaporation of water. Under the right conditions, evaporative cooling releases about 18 kcal/min and each liter of water that vaporizes extracts 580 kcal from the body.[64] Clothing affects heat transfer from the body and a study found that out of all athletic uniforms and equipment, football gear presented the most significant obstacle to heat dissipation. The wrappings, padding, and helmet essentially sealed off

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60 McArdle, 190
61 McArdle, 624
62 McArdle, 1104-15
63 McArdle, 205
64 McArdle, 624-27

about 50% of the body's surface area and limited the evaporative cooling of those parts.[65] The football gear study is significant because parallels can be drawn with medieval full plate armor. Since full plate armor covered nearly the entire body, the avenues for heat dissipation by evaporation must have been severely limited.

Physical Abilities

An investigation of some basic human abilities is important to establish some baseline operating data. When encumbered by armor, those abilities may be affected. Locomotion (gait), lifting loads, rotational motion, and range of motion (flexibility) are just some of the fundamental abilities that will be covered. The analysis must be simplified by making certain assumptions regarding the "average" knight in the Middle Ages. It will be assumed that due to his training, the knight was on average more physically-fit than the average medieval man.

Human gait is the most prevalent of all human movements. It is a complex movement that is usually taken for granted, involving the action of numerous muscles across many joints.[66] The purpose of gait is to move the body safely and efficiently across the ground surface. There are five major functions that must be performed during the gait cycle and they are independent of how quickly the individual is moving (walking or running). The functions are: the maintenance of support for the upper body during stance, maintenance of upright posture and balance of the total body, control of the foot's path for gentle landings, generation of mechanical energy to maintain forward speed or to increase it, and absorption of mechanical energy for shock dampening, stability, and/or decreasing the body's forward speed.[67] As "natural" as gait may seem, it is an inherently unstable series of movements. To

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65 McArdle, 632
66 Winter, 1
67 Winter, 2

begin moving forward, one must voluntarily start a fall forward to move the center of gravity ahead of the body's base of support.[68] The reverse is true when the gait is terminated. The body's mass distribution further makes the maintenance of balance a challenge. Two-thirds of the body's mass is located in the head, arms, and trunk and is located two-thirds of one's height above the ground.[69] The wearing of full plate armor may have affected an individual's mass distribution and thus the ability to maintain balance when moving about.

The ability to exert forces on the surrounding environment is a fundamental ability of the human body. It may be surprising at first that the actual forces that most skeletal muscles exert are not the same as the externally applied force by whatever objects are being acted upon. Upon closer inspection the reason why is apparent in certain situations of static equilibrium because of the anatomy of how muscles, joints, and bones are related. The aforementioned anatomy can be modeled as various types of lever systems and most skeletal muscles in the body are third class lever systems in which the effort is applied between the load and the fulcrum.[70] Such lever systems operate with great speed, but are always at a mechanical disadvantage: meaning that the force exerted by the effort (muscle) must be greater than the load moved or supported. An example is the static equilibrium of an arm with the forearm at 90° to the upper arm and supporting a weight held in the hand. To simplify the analysis, the biceps brachii is considered the primary muscle supporting the forearm. The fulcrum is the elbow joint, the load is the weight, and the effort is the biceps force. The biceps inserts very close to the elbow joint, and its lever arm is much shorter than that of the applied weight. With the weight of the forearm and angle of pull of the biceps taken into account, the biceps brachii must exert a force of over

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68 Winter, 75
69 Winter, 76
70 Marieb, 284

eight times the external force to maintain equilibrium.[71]

Although muscular strength is highly variable across individuals, an idea of the reported maximum strengths that could be exerted is important in better understanding how knights were able to function in armor. In an extensive study of workers in the steel, aluminum, rubber, and electrical components industries, maximal voluntary isometric strength data was collected for ten basic postures according to Figure 2. Table 1 displays the strength data for those ten postures.[72] Since a knight was well-trained, it is likely that the average knight's strength would fall between the 50th and 75th percentiles of Table 1.

Test	Sample Size	Coeff. Of Variation	Males				
			Population Percentile				
			10	**25**	**50**	**75**	**90**
Arm Lift	1052	0.07	23	31	39	48	56
Torso Lift	1052	0.09	26	34	45	60	77
Leg Lift	638	----	49	69	91	114	134
High Far Lift	309	0.09	16	19	23	28	34
Floor Lift	309	0.08	59	74	91	108	123
High Near Lift	309	0.08	35	44	55	66	76
Push Down	309	0.08	34	39	44	51	58
Pull In	309	0.07	24	27	32	37	43
Pull Down	309	0.05	49	55	62	69	75
Push Out	309	0.08	23	27	31	37	42

Table 1: Maximal voluntary isometric strength (kg)

A different study regarding various grip strengths was performed. No mention of the sample sizes were made by the author, but it was determined that some males could exert almost 90 lb using a power grip.[73] A power grip is when a clamp is formed by partly flexed fingers and the palm, with the thumb applying opposite pressure. The power grip was chosen because it was probably the most commonly used grip with medieval weapons. The power grip is especially suited for tightly gripping

71 Freivalds, 11
72 Easterby, 147
73 Freivalds, 420

weapons with cylindrical handles or shafts.

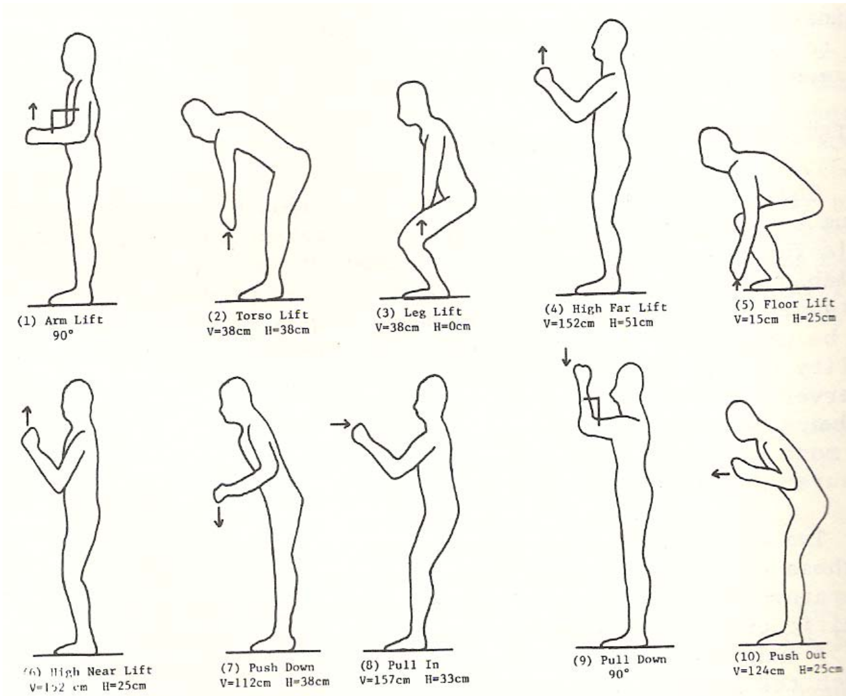

Figure 2: 10 strength test postures

Another important concept of muscular exertion is that the muscle's force-generating capability varies with the joint angle throughout the range of motion (ROM). This is due to the line of action of the muscle force relative to the long axis of the bone upon which the force is exerted.[74] For example, when the forearm is flexed to 90°, the biceps brachii muscle exerts only a rotational effect upon the forearm about the elbow. However, at other angles of flexion or extension of the lower arm, the muscle's effect isn't entirely rotational and thus the force that can be generated to actually move or support the external load is less. In terms of quantitative data, when the knee is extended through its full ROM, about 78% of the maximum force can be generated at the start of extension (when the angle between the lower and upper legs is about 50°), 100% when the angle is about 120°, and about 50%

74 Ozkaya, 89

when the angle is 180°.[75] In terms of elbow flexion, when the lower arm is fully extended (the angle between the upper arm and lower arm is about 180°) about 67% of the maximal force can be generated, 100% when the angle is about 130°, and a little less than 50% when the angle is fully flexed at around 50°. The above analysis is important because the wearing of armor may affect the ROM of various joints and thus the maximum muscular forces that can be exerted.

An understanding of the body's fundamental movements is necessary for the evaluation of the range of motion of its various parts. Although many motions are combinations of the fundamental movements, examining the fundamental movements is still worthwhile. Flexion is a bending movement that decreases the angle of a joint and brings two bones closer together.[76] Extension is the opposite of flexion at the same joint and hyperextension is an increase in the angle beyond 180°. The up and down movements of the foot at the ankle and relative to the lower leg are dorsiflexion and plantar flexion respectively.[77] Abduction is the movement of a limb away from the midline of the body and adduction is the opposite of abduction. Rotation is the turning of the bone around its own axis. Rotation directed toward or away from the midline of the body is termed medial and lateral rotation respectively.[78] The forearm has special movements known as supination and pronation. Supination is the rotation of the forearm laterally such that the palm faces up and pronation is the opposite.[79]

Although range of motion is highly variable like muscular strength, certain averages have been arrived at that can serve as a basis of analysis. Averages from four studies are presented, but no indication of the sample size in each is presented. The data is presented in Figure 3.[80]

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75 McArdle, 523
76 Marieb, 228
77 Marieb, 228
78 Marieb, 229
79 Marieb, 229
80 Luttgens, 21

JOINT	SOURCES 1	2	3	4	AVERAGES
Elbow					
Flexion	150	135	150	150	146
Hyperextension	0	0	0	0	0
Forearm					
Pronation	80	75	50	80	71
Supination	80	85	90	80	84
Wrist					
Extension	60	65	90	70	71
Flexion	70	70		80	73
Radial flexion	20	20	30	30	33
Ulnar flexion	30	4	15	20	19
Shoulder					
Flexion	150	170	130	180	158
Hyperextension	40	30	80	60	53
Abduction	150	170	180	180	170
Horizontal flexion				135	135
Horizontal extension	40	30	80	60	53
Shoulder					
Rotation (arm in abduction)					
Inward				70	70
Outward				90	90
Hip					
Flexion	100	110	120	120	113
Hyperextension	30	30	20	30	28
Abduction	40	50	55	45	48
Rotation (in extension)					
Inward	40	35	20	45	35
Outward	50	50	45	45	48
Knee					
Flexion	120	135	145	135	134
Ankle					
Plantar flexion	40	50	50	50	48
Dorsiflexion	20	15	15	20	18
Spine (thoracic and lumbar)					
Flexion	90			80 (4″)	85 (4″)
Hyperextension	30			20–30	30
Lateral flexion	20			35	28
Rotation	30			45	38

Sources:
1. Committee on Medical Rating of Physical Impairment, AMA.
2. Committee of California Medical Association and Industrial Accident Commission of State of California.
3. William A. Clarke, Mayo Clinic.
4. Committee on Joint Motion, American Academy of Orthopaedic Surgeons.

Figure 3: Average ranges of joint motion (angle in °)

Rotating the limbs and body about various axes to swing or throw objects has been an essential human ability since prehistoric times. The effectiveness of rocks, clubs, and other tools to hunt prey and fight other people is a result of rotational motion generated by the body. Many of the weapons of the medieval period employed rotational motion as a means of inflicting wounds on the enemy. The turning effect of a force is known as the torque or moment of force.[81] The torque about an axis of rotation is the product of the force magnitude and its moment arm. The moment arm is the perpendicular distance from the line of action of the force to the axis of rotation.[82] Since torque is a product of both the force magnitude and the moment arm, an increase in either will result in a larger torque. In the body, torques are the result of muscular, ligament, and friction forces acting to alter the rotation of a joint.[83] The mechanical power of muscles in watts (J/s) is related to torque and is the product of the torque and the angular velocity of the joint (radian/s).[84] From the above mentioned formulas, it can be expected that a more massive weapon, on a longer shaft, swung at a faster angular velocity will produce the greatest impact energy. However, the relationship between the weapon's mass, the length of it or the shaft its on, as well as the angular velocity of the joint involves certain trade-offs because of the limitations of the human body. The analysis of torques is important to a study of wearing full plate armor because parameters such as the angular velocity of the joint that could be generated by the knight may have been affected by the armor.

Modern Body Armor

Humans have been wearing some form of body armor for many millennia. Throughout the ages, the purpose of providing extra protection hasn't changed, but the available technologies have. For hundreds of years and even still today, there was an ongoing dynamic of producing better weapons to defeat armor and the simultaneous development of better armor to protect against more effective weapons. The modern body armor that exists today is employed by a variety of organizations,

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81 Luttgens, 351
82 Luttgens, 351
83 Winter, 37
84 Winter, 44

particularly armies and police forces around the world. As with most products, there are many manufacturers of modern body armor and much competition to win large contracts and bids. The competition can be thought of as a good thing for the end users of the armor, since it is likely to produce better quality armors.

The Beginnings of Modern Body Armor

Many of the concepts involved in some modern body armors were actually around hundreds of years before the present. In the 18th and 19th centuries, steel strips were sewn into fabrics which were then sewn into layers to make a modern type of breastplate.[85] This primitive form of "flak jacket" wasn't used by infantry because it was too heavy and cumbersome, but was used by aircrews of balloons and dirigibles. Body armor development made leaps and bounds in the 20th century. In WWII, a much improved type of flak jacket was used by US bomber crews. It consisted of ballistic nylon and steel plates sewn into cloth that hung over the over the chest and abdomen like a catcher's body shield.[86] The suits were heavy and bulky, but they did stop flak. Regular infantry didn't use the suits because they were too heavy and restricted mobility. Truly recognizable modern body armor (light enough to be used by regular infantry) didn't make its appearance until the Korean War when American troops used the M12 vest.[87] It contained thick aluminum plates, layers of nylon, and weighed 12 pounds and 3 ounces. By that time, all-nylon or doron vests were coming into use.[88] Body armor development progressed throughout the rest of the century and is an ongoing process.

Though the modern forms of armor components such as the protective vest didn't appear until the Korean War, protection for the head in the form of a helmet made its reappearance in the early 20th

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85 Military.com, (2004)
86 GlobalSecurity.org, (2006)
87 GlobalSecurity.org, (2006)
88 GlobalSecurity.org, (2006)

century. During World War I, the French appear to have been the first to accept the helmet as a standard piece of armor for the regular infantryman.[89] The effectiveness of a helmet made out of various metal alloys was demonstrated by the widespread usage of that form of body armor by many nations as part of their standard military equipment during the war.[90] The helmets were able to resist projectiles of medium to low velocity and possibly deflect one of higher velocity. Some of these early forms of helmets had visors for eye protection that were faintly reminiscent of the ones found on some medieval helms. However, English medical statistics of the period demonstrated that the chances of a soldier becoming totally blind were very low: about 1 in a 1000.[91] Due to the statistics and the detrimental effect of some visors on the soldier's visual perception, visors were not incorporated into the most commonly used infantry helmet designs of WWI and later conflicts. As with protective vests, helmets evolved considerably in the 20th century to provide better protection against more advanced projectiles.

Classification of Modern Body Armor

Modern body armor can be classified into two main categories: soft body armor and hard body armor.[92] However, numerous armor systems are modular and can up- or downgrade protection depending on the expected threat level. Soft body armor consists of layers of bullet-resistant webbing that are weak individually, but are strong collectively. The web of fibers absorbs and disperses the energy of a bullet over a wide area.[93] Hard body armor consists of plates of metal, rigid reinforced plastic, or ceramic. These plates are of such thickness that they do not deform much upon being struck

89 Dean, 64
90 Dean, 68
91 Dean, 73
92 Harris
93 GlobalSecurity.org, (2006)

by a bullet.[94] The modern "bulletproof" vests worn today by various organizations evolved from research sponsored by the US National Institutes of Justice (NIJ) in the late 1960s and early 1970s. The research investigated the development of body armor using the newly developed synthetic polymer Kevlar.[95]

In the US, the NIJ has established seven body armor categories: six standard and one special category. The six categories are: I, II-A, II, III-A, III, and IV. Figure 4 is a table of the six main categories and their associated performance requirements. The performance requirements were generated with the active participation of body armor manufacturers.[96] Type I provides the lowest level of protection and type IV the highest. Types I through III-A are soft armors and are designed to resist only various types of pistol ammunition. Type III-A is the highest level of protection obtained in current concealable armors.[97] Types III and IV utilize plate inserts to add greater ballistic protection against rifle ammunition.[98] Body armor generally increases in weight from Type I to Type IV. Based on the results of laboratory testing, any new body armor designs are classified into one of the seven categories.[99]

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94 GlobalSecurity.org, (2006)
95 GlobalSecurity.org, (2006)
96 NIJ, (2001)
97 GlobalSecurity.org, (2006)
98 Harris
99 Harris

Test Summary (NIJ Standard–0101.04)

Armor Type	Test Variables				Performance Requirements						
	Test Round	Test Bullet	Bullet Weight	Reference Velocity (± 30 ft/s)	Hits Per Armor Part at 0° Angle of Incidence	BFS Depth Maximum	Hits Per Armor Part at 30° Angle of Incidence	Shots Per Panel	Shots Per Sample	Shots Per Threat	Total Shots Req'd
I	1	.22 caliber LR LRN	2.6 g 40 gr.	329 m/s (1080 ft/s)	4	44 mm (1.73 in)	2	6	12	24	48
	2	.380 ACP FMJ RN	6.2 g 95 gr.	322 m/s (1055 ft/s)	4	44 mm (1.73 in)	2	6	12	24	
IIA	1	9 mm FMJ RN	8.0 g 124 gr.	341 m/s (1120 ft/s)	4	44 mm (1.73 in)	2	6	12	24	48
	2	.40 S&W FMJ	11.7 g 180 gr.	322 m/s (1055 ft/s)	4	44 mm (1.73 in)	2	6	12	24	
II	1	9 mm FMJ RN	8.0 g 124 gr.	367 m/s (1205 ft/s)	4	44 mm (1.73 in)	2	6	12	24	48
	2	.357 Mag JSP	10.2 g 158 gr.	436 m/s (1430 ft/s)	4	44 mm (1.73 in)	2	6	12	24	
IIIA	1	9 mm FMJ RN	8.2 g 124 gr.	436 m/s (1430 ft/s)	4	44 mm (1.73 in)	2	6	12	24	48
	2	.44 Mag SJHP	15.6 g 240 gr.	436 m/s (1430 ft/s)	4	44 mm (1.73 in)	2	6	12	24	
III	1	7.62 mm NATO FMJ	9.6 g 148 gr.	847 m/s (2780 ft/s)	6	44 mm (1.73 in)	0	6	12	12	12
IV	1	.30 caliber M2 AP	10.8 g 166 gr.	878 m/s (2880 ft/s)	1	44 mm (1.73 in)	0	1	2	2	2

*These items must be specified by the user.

Panel = Front or back component of typical armor sample.
Sample = Full armor garment, including all component panels (F&B).
Threat = Test ammunition round by caliber.

Notes: Armor parts covering the torso front and torso back, with or without side coverage, shall each be impacted with the indicated number of fair hits. Armor parts covering the groin and coccyx shall each be impacted with three fair hits at 0° angle of incidence. The deformation due to the first fair hit shall be measured to determine compliance. No fair hit bullet or one impacting at a velocity lower than the minimum required bullet velocity shall penetrate the armor.

Abbreviations:
AP—Armor Piercing
FMJ—Full Metal Jacket
JSP—Jacketed Soft Point
LRHV—Long Rifle High Velocity
RN—Round Nose
SJHP—Semi-Jacketed Hollow Point
SWC—Semi-Wadcutter

Figure 4: NIJ body armor classification

Modern Body Armor Manufacturers

There are numerous companies that manufacture modern body armor for various organizations. Ceradyne has been a leader in the manufacture of advanced ceramics for ballistics applications since

1969.[100] Ceradyne is an established leader in the manufacture of ceramic body armor upgrades and is a key supplier of the US Military. For the most threatening situations, Ceradyne has a line of personnel protection plates that can sustain multiple hits and maintain their durability.[101] Point Blank Body Armor Inc. is recognized as a leading manufacturer of concealable, tactical, corrections, government, and military body armor.[102] Since 1973, Point Blank has been the leading innovator of products and designs that maximize ballistic protection. Second Chance Body Armor Inc. is one of the leading manufacturers of concealable body armor for law enforcement.[103] The founder of the company invented the concept of soft and concealable body armor in 1971. Second Chance manufactures "bullet proof" vests using high performance materials such as Kevlar and Zylon. The company designs the materials to be resistant to an adversary's knife or bullet.[104]

Modern Armor Systems

A host of multi-million dollar contracts have been given out to manufacturers to produce one of the most modern body armor systems for the US military: the Interceptor Multi-Threat Body Armor System (depicted in Figure 5). The Interceptor System consists of an Outer Tactical Vest (OTV) and Small Arms Protective Insert (SAPI) plates.[105] The OTV, weighing 8.4 lb, was a significant improvement over the Personnel Armor Systems for Ground Troops (PASGT) Vest utilized since the 1980s.[106] The OTV is capable of stopping 9 mm rounds (level III-A protection) whereas the PASGT Vest only protected against fragments. The Interceptor System utilizes two ceramic SAPI plates, weighing 4 lb each, which are capable of stopping 7.62 mm rounds and correspond to level III

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100 Ceradyne.com, (2006)
101 Ceradyne.com, (2006)
102 Pointblankarmor.com
103 Marconi, (2001)
104 Marconi, (2001)
105 GlobalSecurity.org, (2006)
106 Military.com, (2004)

protection.[107] Overall, the Interceptor System weighs about 35% less than the PASGT Vest and its Interim Small Arms Protective Overvest upgrade: 16.4 lb versus 25.1 lb. Production of the Interceptor System began in 1998 when Point Blank Body Armor Inc. received a multi-million dollar contract to produce OTVs.[108] Since then, the company's contract has been renewed and expanded to include production of upgraded protection for the deltoid and axillary regions (depicted in Figure 6). Several companies, including Ceradyne Inc., were also awarded large contracts to produce the SAPI plates for the Interceptor System.[109]

Currently, the PASGT Helmet (depicted in Figure 7), weighing 3.1-4.2 lb and made of Kevlar, is the standard infantry helmet.[110] The helmet, along with a lighter upgraded version made of more-advanced Kevlar, was used along with the PASGT Vest and is used with the Interceptor System. However, it is being replaced with the Advanced Combat Helmet, which is lighter, offers better ballistic protection, and allows for greater sensory awareness than the older helmet. Federal Prison Industries Inc., also known as UNICOR, produces both the PASGT and Advanced Combat Helmets.[111]

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107 GlobalSecurity.org, (2006)
108 GlobalSecurity.org, (2006)
109 GlobalSecurity.org, (2006)
110 GlobalSecurity.org, (2006)
111 GlobalSecurity.org, (2006)

Figure 5: Interceptor body armor

Figure 6: Interceptor upgrades

Figure 7:

PASGT helmet

Table 2 is a summary of the key aspects of some of the aforementioned US Military body armor components. All of the data was obtained from the GlobalSecurity.org website. One uncertainty in the presented data was the level of protection mentioned for the Advanced Combat Helmet. The source didn't specifically point out what type of 9 mm rounds the helmet was designed to protect against. From Figure 4, it can be seen that 9 mm rounds span 3 categories: from II-A to III-A. Nonetheless, it is an improvement over the PASGT Helmet, even if it only resists 9 mm rounds in the level II-A category.

Table 2: US body armor summary

Models Derived From Modern Body Armor

Many types of modern body armor exist. At the very least, a helmet and bullet-resistant vest could be considered as armor protection for today's soldiers. Many armor systems consist of add-on pieces that can provide more protection for higher threat level situations. Components such as axillary, throat, and groin protection can be added to some armor systems to increase the amount of protected area. Regardless of the complexity of the armor, there are many fundamental attributes concerning each piece and its application to the body. Some of those attributes include the amount of ballistic protection offered, its weight, comfort in wearing, and durability. The analysis of those aforementioned fundamental attributes has a substantial history, but the documented investigation of those parameters for modern body armor began during World War I.

The effectiveness of a metal helmet for the infantryman was proven during the WWI era. It didn't take long for people to realize that similar types of armor worn on the chest, abdomen, or limbs could be of practical value. During the war, most of the involved nations developed protective armors for the torso and limbs of the average infantryman, but largely on an experimental basis.[112] Practical objections for torso and limb armor such as the added weight of the pieces, the discomfort in wearing, and the lack of adequate protection restricted its use by the regular infantry. However, sentinels, patrol members, and stationary machine gun crews successfully used body armor which was too encumbering for the infantryman to use.[113]

According to Bashford Dean, there are nine important factors concerning body armor that can be used to judge its relative value: ballistic value, weight, comfort in wearing, security in support, ease of recognition (and non-visibility to the enemy), noiselessness, cleanliness, durability, and adaptation.[114] The factors arranged in order of their importance assigned by Dean are displayed in Table 3. While Dean's figures may be dated, there is still some relevance to modern body armor systems. Materials and technologies evolved over the course of the 20th century, but the fundamentals of what constitutes effective body armor had been well-established for a long time.

Parameter	Assigned Importance (%)
Ballistic Value	45
Weight	15
Comfort in Wearing	10
Security in Support	10
Ease of Recognition (and non-visibility to enemy)	10
Noiselessness	3
Cleanliness	3
Durability	2
Adaptation	2

Table 3: Body armor parameters in order of importance

112 GlobalSecurity.org, (2006)
113 GlobalSecurity.org, (2006)
114 Dean, 295

Ballistic Resistance

From Table 3, it can clearly be seen that the ballistic resistance of the body armor is the most important aspect of its relative value. However, the ballistic resistance as measured by absolute tests cannot be used as the sole factor in determining the effectiveness of the armor.[115] The safety of the user also depends on conditions that may be entirely accidental, such as the angle of impact of the projectile onto the armor. In the studies of World War One casualties, it has been noted that seemingly light defenses, which would have failed absolute ballistic tests, were able to protect the wearer from high velocity machine gun bullets.[116] The French helmet of WWI was rated to resist the normal (perpendicular) impact of a pistol ball traveling at about 400 feet per second (ft/s), but had been known to deflect bullets of three times that velocity and reduce the velocity of bullets to such an extent that when the metal was penetrated, the wearer's skull was not fractured. As summarized by Bashford Dean:

> "In a word, it is unfair to state that a helmet or breastplate is valueless because it failed at the normal impact from service rifle ammunition at 100 yards; for it may still save its wearer from similar shots at longer range or from shots at close range which do not impinge directly. Whoever, therefore, deals with the problem of modern armor will go far astray if he does not consider on generous lines the index of probability."[117]

Although the survival of the body armor wearer may depend on incidental circumstances, an established minimum level of ballistic resistance is important for body armor systems. According to Dean, all armor of the WWI era should have resisted the impact of a jacketed automatic revolver bullet weighing 230 grains with a velocity of 650 ft/s. In the testing of the defenses of the era, special cartridges with standard bullets were produced to give velocities such as 450, 600, 750, and 1000

115 Dean, 294
116 Dean, 294
117 Dean, 295

ft/s.[118] Those cartridges were used by various countries and provided some of the most obvious definitive tests of armor's effectiveness. In the present-day, the Kevlar of the Interceptor System's OTV is capable of stopping a jacketed, high-velocity 9 mm handgun bullet with a mass of 124 grains and an impact velocity of 1400 ft/s or less.[119] The SAPI plates of the Interceptor System are rated to stop 7.62 mm jacketed rifle bullets with an impact velocity of 2750 ft/s or less.

An important aspect of the ballistic resistance of armor is its shape. The concept of utilizing curved surfaces to deflect blows and projectiles has been around for much of human history. While not as important for soft body armors, the shape of hard armor surfaces has been an important design feature from before the medieval period, through the experiments of the WWI era, and to the present-day. In Figure 8, a comparison of the curvatures of some breastplates is presented. In the figure, the breastplate on the left was made by a well-known Augsburg armorer. The middle one is an American experimental heavy breastplate for sentinels in WWI and the other one is from German heavy body armor of the same era.[120] In the figure, the areas of similar curvature are indicated by similar shading and the angles represent the angle from normal of the shaded section. A breastplate with a flat surface offers less protection than a well-arched one because the chance of a projectile striking the curved plate at an angle (and being deflected) is greater than for the flat plate.[121] Likewise, armor plate is weakest when struck on a concave surface. The principle is true for every kind of armor including helmets. From the helmets of the WWI era, to modern-day helmets such as the PASGT Helmet, their shapes have been curved not only to anatomically conform to the skull, but also to present a greater chance of a projectile being deflected. Modern hard armor plates, such as the one in Figure 9, may also exhibit a

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118 Dean, 296
119 GlobalSecurity.org, (2006)
120 Dean, 303
121 Dean, 300

curved design.[122]

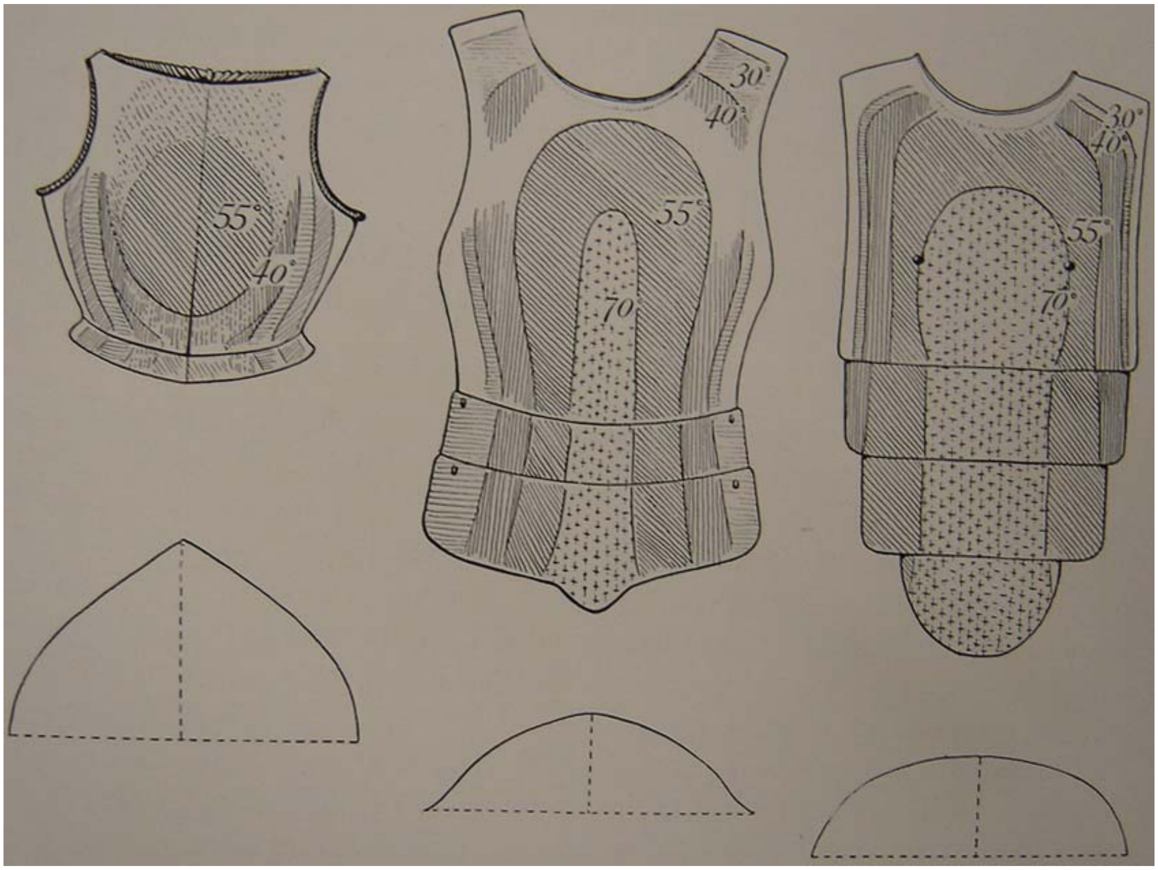

Figure 8: Breastplate curvature comparison

122 Military.com, (2004)

Figure 9: SAPI plate from

Interceptor System

Body Armor Weight

In Dean's list, weight is the second most important factor in an armor system's overall value. The weight of the armor has been, and continues to be, one of the most influential factors in the development of body armor. Generally, heavier armor offered greater protection than lighter armor, but at the expense of decreased mobility and increased physiological strain. During the WWI experiments with body armor, it was suggested that the average American soldier would refuse to wear a body defense that was heavier than 6-7 lb, assuming that he was expected to carry his armor for considerable distances.[123] It was theorized that if the armor was given to the infantryman immediately before action, then armor of 10-20 lb could be worn for short intervals. Today, servicemen of many nations routinely use body armor systems that are heavier than 10-20 lb. In the US Military, the Interceptor System weighs on average 16.4 lb and was designed to replace the upgraded PASGT system which weighed 25.1 lb.[124] When equipped with a PASGT Helmet, the total weight of the body armor of a typical US soldier might be around 20 lb. In India, two types of armor vests weighing 9 and 11 kg (19.8 and 24.3 lb) are commonly used by military and paramilitary personnel in many Indian

123 Dean, 304
124 GlobalSecurity.org, (2006)

cities with hot and humid climates.[125]

An enduring quest in the development of armor is the reduction of its weight while maintaining or improving upon its protective capability. Recently, the US Marine Corps began fielding the Lightweight Helmet (LWH). The LWH is about 0.5 lb lighter than its comparably-sized PASGT Helmet and its newer materials provide a 6% improvement in fragmentation protection and the ability to stop a direct hit from a 9 mm bullet.[126] The current weight of the Interceptor System is still too heavy. The Natick Soldier Systems Center is exploring new materials and composites of materials to reduce the weight by one-third to one-half while providing increased protection. The plan to upgrade the Interceptor also includes the replacement of 20 layers of Kevlar with the newer M-5 fiber that weighs about one-third less. The body armor system being developed for the Objective Force Warrior program will use improved boron-carbide ceramic plates that will weigh 10-30% less than the Interceptor's SAPIs and will provide equal or greater protection.[127]

Wearability

The design of armor to produce as little discomfort as possible in its normal usage is the third most important aspect of an armor's value. Several factors affect the level of discomfort produced, including the weight, how the weight is supported, hindrance to free mobility, and the consideration of physiological processes such as heat exchange. In a study which assessed the physiological effects of wearing heavy body armor on Indian male soldiers, it has been cited that the maximum carried load while maintaining efficiency and safety should be from 33-40% of the body weight.[128] The 11 kg body armor used in the testing was on average about 20% of the subjects' body weight and was within the

125 Majumdar, 156
126 GlobalSecurity.org, (2006)
127 GlobalSecurity.org, (2006)
128 Majumdar, 159

suggested load-carrying limits. However, when a treadmill test was performed on the subjects, their heart rate increased to around 145 beats/min: 15 beats/min more at the 10^{th} minute of treadmill exercise than when no armor was worn. At the same time mark, the measured oxygen uptake (VO_2) was 6.0 ml/(kg*min) higher than when armor was not worn. The results indicated that heavy work was being done under high physiological strain and that wearing the body armor increased the physical effort required for the task from 'moderate' to 'heavy'.[129]

For armor to produce as little discomfort as possible, how and where its weight is supported are important design considerations. Certain points of the shoulder, neck, back, head, and hips are well adapted to supporting loads.[130] However, pressure upon regions such as the temple can produce serious fatigue and discomfort. The design of a helmet's lining is extremely important. For the helmets of the WWI era, it was suggested that a helmet lining cushioned at three points be used to ensure adequate ventilation over each temple and the back of the head.[131] Modern helmets such as the PASGT Helmet, the Advanced Combat Helmet, and the Lightweight Helmet have advanced linings, padding, and strapping to ensure a comfortable fit. The support for the bullet-resistant vest and the hard armor inserts that some armor systems utilize is important. The 'double pack' (front and backpack load carrying system) is the most convenient and comfortable method of load carrying.[132] The Interceptor System and the Indian body armor from the physiological study of armor usage both utilize a double pack arrangement.

The hindrance to free mobility can lead to discomfort in the wearing of armor. Generally, the more protective an armor system is, the more it restricts natural movement. The flexibility of the armor

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129 Majumdar, 159
130 Dean, 304
131 Dean, 304
132 Majumdar, 156

is generally assumed to be one of the major factors in the overall wearability of an armor system.[133] Hard armor inserts will resist bending and prevent the wearer from certain movements. The soft armor components of bullet-resistant vests will resist being bent to some extent. However, a quantitative flexibility study of several bullet-resistant vests revealed that although the flexibility of the actual panel (layers of bullet-resistant polymers) contributed to overall comfort, other factors unrelated to the panel flexibility such as compliant shoulder fastenings also influenced the comfort factor.[134] Vests with compliant shoulder fastenings preserved a good fit during the movement trials and the subjects reported less discomfort with them. The study indicated that flexibility in armor is desirable because it allows the armor to conform and move with the wearer, but the proper fitting of armor is the most important factor in the wearability and comfort of body armor.[135]

The consideration of heat exchange is important for a body armor system. In the Indian study involving the measurement of the physiological effects of wearing of body armor, it was observed that the subjects' mean skin temperature was higher during exercise with body armor on than the same exercise without it. At the 40th minute of stool-stepping light exercise, the subjects' mean skin temperatures were 0.17°C (no armor) and 0.65°C (armor) higher than their corresponding resting skin temperatures.[136] The greater temperature increase was attributed to the fact that the body armor reduced the body's evaporative cooling mechanism by covering some of the skin surfaces on the chest and back. The authors of the article suggested that a larger skin temperature increase was expected than what was actually obtained. They attributed the obtained data to the armor's ability to move with the subject: "The foam padding under the metallic plates provided greater spaces for air exchange with

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133 Horsfall, 283
134 Horsfall, 291
135 Horsfall, 291
136 Majumdar, 158

motion."[137] Adequate ventilation in a helmet is important to allow air flow to cool the head. In the US, an under-armor cooling system has been developed to maintain the wearer's body temperature at a safe level.[138] The system utilizes a shirt with embedded cooling channels and a heat exchanger that circulates cold water to provide cooling when necessary.

Dean's above-mentioned attribute 'security in support' refers to armor maintaining its proper position on the wearer's body during combat. It is important that armor be properly supported on the body to ensure the best possible protection. For example, a helmet shouldn't be worn if it rests improperly on the head. As far back as the helmets of WWI, it was proposed that a helmet's balance must be perfect and its center of gravity should be evaluated when the chin-strap was adjusted to the user.[139] The consideration of those details minimizes the chances that the helmet will gradually shift or displace during the rigors of combat. The proper fitting and wearing of the helmet are important factors in its maintenance of proper protective position. In the US Military, photo surveys from Operation Iraqi Freedom and Operation Enduring Freedom have revealed that about half of the soldiers are improperly wearing the PASGT Helmet or Advanced Combat Helmet.[140] When those helmets are worn incorrectly, the solder is at higher risk for fragmentation or concussion injuries. A properly fitted PASGT Helmet should have a minimum 0.5 inch clearance between the head and the helmet.[141] The majority of improperly fitted helmets were found to be too small, meaning that ventilation, comfort, and safety would be decreased. Also, a helmet that was too large could block the wearer's vision.

The proper support of the bullet-resistant vest, and especially any hard plate inserts, is important. Dean mentions that to be properly supported, an armor component does not have to be

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137 Majumdar, 160
138 GlobalSecurity.org, (2006)
139 Dean, 307
140 GlobalSecurity.org, (2006)
141 GlobalSecurity.org, (2006)

attached rigidly.[142] He recommended supports that are elastic or other flexible material because they can lessen the jolt of the armor during quick movements. The OTV of the Interceptor System contains pockets integrated into the front and rear of the vest to allow the insertion of a SAPI plate.[143] The SAPI plate maintains its position by being enclosed in the pocket and not by being rigidly attached to it. The body armor in the experiment involving Indian soldiers remained very close to the trunk as well as the body's center of gravity.[144] The foam padding under the metallic plates not only serve to provide cushioning and space for air exchange, but also to ensure the proper orientation and positioning of the body armor on the wearer's body.

Adaptability

In Table 3, the adaptability of an armor system is ranked at the very bottom by Dean. However, such an attribute of armor may be of greater importance in modern times when one armor system can be expanded and upgraded for missions of varying threat level. In the WWI era, adaptation may have referred to something such as a helmet strap that quickly and easily allows a soldier to don a gas mask.[145] For breastplates, one that is laminated to allow a user to keep a position close to the ground, but still be able to push forward would be of greater value than one that permits lesser mobility. Dean suggests that another instance a helmet could exhibit useful adaptability is if it doesn't block the ear region too completely so that a telephone receiver could be used.[146] Today, numerous body armor systems and individual components exhibit a wide range of adaptability for varying combat situations. Today, newly fielded helmets such as the US Military's Advanced Combat Helmet and Lightweight Helmet are fully capable of supporting communications packages, night vision devices, and nuclear,

142 Dean, 308
143 GlobalSecurity.org, (2006)
144 Majumdar, 156
145 Dean, 311
146 Dean, 312

biological, and chemical (NBC) defense equipment.[147] In terms of bullet-resistant vests, the Interceptor System is modular and highly adaptable. Recently, four levels of add-on armor have become available for the Interceptor that offer the same level of protection for other body parts as the OTV does for the thorax and abdomen. The new armor pieces can be configured for specific mission requirements by protecting the neck, shoulders, arms, groin, and legs as necessary, resulting in up to 75% of the body being covered with armor.[148]

Models Derived From Medieval Armor

Medieval harnesses were elaborately constructed to provide protection to the wearer, but also not greatly hinder his mobility or freedom of movement. Armor makers of the Middles Ages used a variety of methods to fasten sections of plate armor together as well as allow as much of the body's natural mobility as possible. Some of those ingenious fastenings included sliding rivets and adjustable latches. Physical features of the harness components varied depending on their location. The overall weight of the harness and the extent of its interference with natural human mobility were not as great as may be imagined. However, that is not to say that the wearing of full plate armor was entirely comfortable.

Body Coverage

The full-plate harness covered nearly the entire body. When fully armed, as can be seen from the drawing of a 16th century harness in Figure 10, areas such as the back of the thigh, buttocks, crotch, and the medial side of the arm at the elbow (indicated with red lines) were not covered by plate

147 GlobalSecurity.org, (2006)
148 GlobalSecurity.org, (2006)

metal.[149] The palm of the hand, sole of the foot, and armpit were not protected by plate as well. The arm, elbow, and shoulders would have secondary protection in the form of mail sleeves. The crotch, thighs, and buttocks would have an arrangement of mail protection. The covering of nearly the entire body, especially the arms, hands, legs, and feet suggests that the vulnerability at these body parts to a disabling injury was considered by the armor makers.

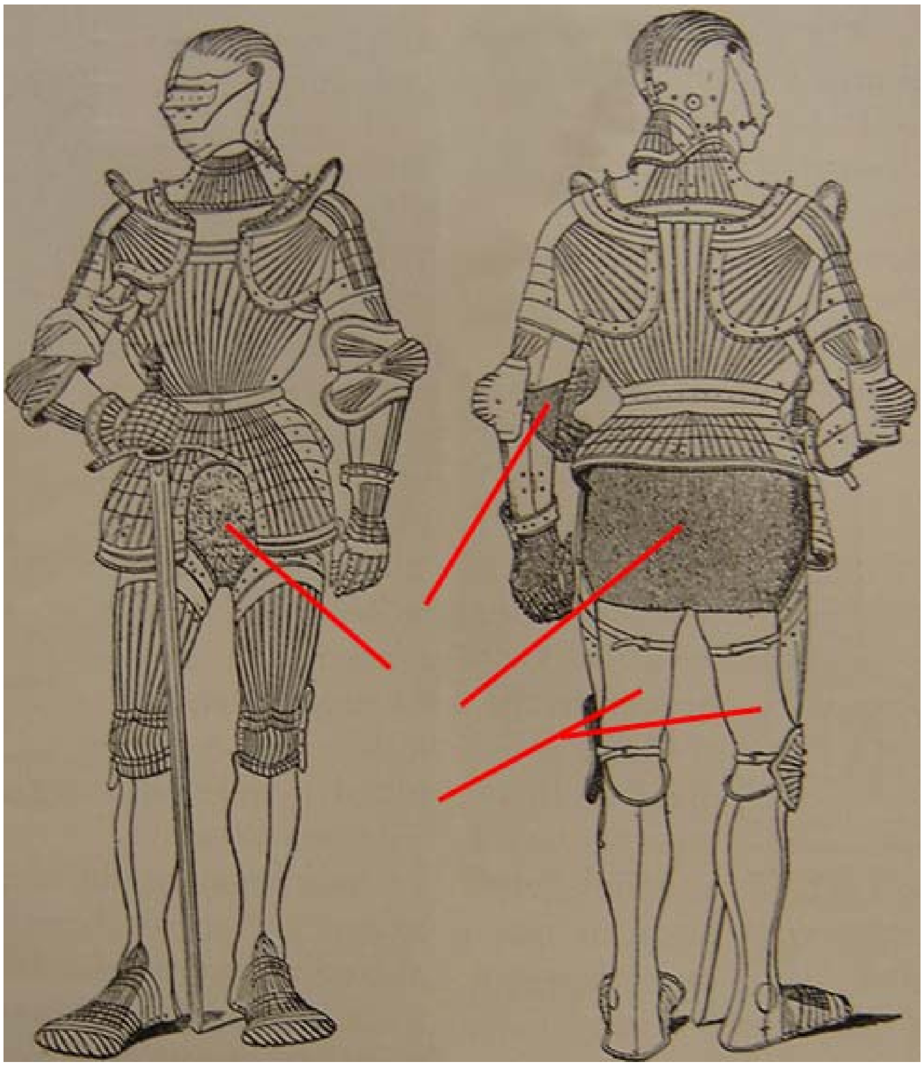

Figure 10: Sixteenth century suit of plate

149 Ffoulkes, 110

There are accounts of some harness components being discarded because it hampered the wearer: at the battle of Mont Auray (1364), Sir Hugh Calverly ordered his men to take off their cuisses to enhance mobility.[150] However, the great military reformer of the 16th century, Sir John Smith, said that Sir Philip Sidney's discarding of his cuisses resulted in his death from a bullet that could have been deflected by armor.[151] Smith strongly advised against the removal of the arm and leg defenses as had been advised by other authorities. He insisted that the limbs were just as important as the chest, abdomen, and back and required the appropriate protection.[152] Yet as firearm technology and employment improved, the discarding of some harness components became inevitable. Harness components covering the vital organs were increased in thickness resulting in increases in weight. To counter the added weight, components covering less vital parts of the body, such as the feet and lower legs were discarded. Harnesses that covered from the head to the knee (3/4 armor) and from the head to the hips (1/2 armor) became more common after 1550.

The thickness of the metal in each harness component was not the same. The thicknesses varied because of knowledge of where attacks against the knight would be directed. However, some of the thickness differences may have been the result of consideration of the body's anatomy. The breastplate was generally thicker than the backplate to be proof against a shot fired at the knight's front side.[153] In specially made jousting helms, the top of the skull was more exposed to the lance and was made much thicker than the back of the helm. The left side of the jousting and war harness was usually made thicker than the right side because most people were right-handed and thus the attack of the lance or sword would be directed to the left side.[154] By the 16th century, the shield held by the left arm gave

150 Ffoulkes, 115
151 Ffoulkes, 115
152 Ffoulkes, 117
153 Ffoulkes, 52
154 Ffoulkes, 52

way to a left side of the harness that was thicker than the right side and could be reinforced by other harness pieces such as the Grandgarde and Passgarde.

Harness Weight

The overall weight of the harness and its effects on the trained knight is one of the most widely misunderstood aspects of the usage of armor. With the exception of certain jousting harnesses, armor before the 17th century was no heavier, and often considerably lighter, than the full equipment worn by modern army units up to the time of WWI.[155] In 1911, the British Under Secretary of War stated that the infantry soldier marched on average 30 miles a day while carrying 59 lb 11oz. of equipment and kit.[156] As comparison, the weights of several medieval complete harnesses are presented in Table 4. Table 5 displays the weights of several types of helmets from various locations of manufacture.[157] Blair adds that for modern (c1972) military equipment, much of the weight is suspended from the shoulders whereas the weight of a properly-fitted medieval harness was distributed over the entire body.[158] Literary and artistic evidence from the medieval period shows a fully-trained man was not inconvenienced to a great extent by his armor before the weight of the harness greatly increased in the 17th century.

Modern experiments made with genuine 15th-16th century armors have shown that even an untrained man wearing a properly-fitted harness can get on and off a horse, lie on the ground and rise again, bend, stoop, and move his arms and legs quite freely. The chief discomfort comes not so much from the weight of the armor as from its lack of ventilation, a fact referred to by Shakespeare in *Henry IV*, Pt. 2 (4, i, 104) where he describes Majesty as: "Like a rich

155 Blair, 191 (1972)
156 Ffoulkes, 118
157 Blair, 192 (1972)
158 Blair, 191 (1972)

armour worn in heat of day, that scalds with safety."[159]

Armor Type	Manufacture Location	Date	Weight
Field Armor	Italian	c1450	57 lb (4 st. 1 lb; lacks tassets and 1 gauntlet)
Field Armor	German	c1525	41 lb 13.5 oz (2 st. 13 lb 13.5 oz)
Field Armor	Italian	c1550-60	45 lb 13.5 oz (3 st. 3 lb 13.5 oz)
Field Armor	Greenwich	c1590	71 lb 14 oz (5 st. 1 lb 14 oz)
Cuirassier Armor	Augsburg	c1620-30	69 lb 5 oz (4 st. 13 lb 5 oz)
Armor for joust (Gestech)	Augsburg	c1500	90 lb 1.5 oz (6 st. 6 lb 1.5 oz)

Table 4: Medieval harness weights

Helm Type	Manufacture Location	Date	Weight
Bascinet and aventail	Italian	c1390	12 lb 9 oz
Barbut	Italian	c1440	5 lb 14 oz
Sallet	Innsbruck	c1485	7 lb 2 oz
Armet	Italian	c1450	7 lb 15 oz
Close-helmet	German	c1530	6 lb 14.5 oz
Embossed burgonet	Italian	c1550	5 lb 4.5 oz
Comb morion	Nuremberg	c1580	3 lb 15 oz
Zischagge	Augsburg	c1620-30	6 lb 5 oz
Stechhelm (Jousting Helm)	Augsburg	c1500	19 lb 11 oz

Table 5: Medieval helmet weights

Integration With the Body

The integration of the harness components with the wearer's body was a considerable feat. The means with which the harness components were connected to the body was almost as important as the actual physical properties of the metallic plates. Although the armor had its own linings of silk, cloth, leather or other fabric, the garments worn underneath that covered the head, legs, arms, and body were

159 Blair, 191 (1972)

crucial in preventing chafing from the armor.[160] The undergarments consisted of a thick arming doublet lined with silk, but with no shirt beneath. The arming doublet contained attachment points for the harness components. In Figure 11, the arming points for the arm and shoulder defenses are displayed. Arming points on the foot are displayed in Figure 12. Other under-armor components included trussing-bolsters worn around the waist to keep the weight of the cuirass from the shoulders.[161] Some plate components, such as the cuisses and knee cops (poleyns) were secured with leather straps and buckles which went around the back of the leg.

160 Ffoulkes, 105
161 Ffoulkes, 111

Figure 11: Arming points for arm defenses

Figure 12: Arming points on foot

To be effective, armor had to be able to move with the body and adjust as necessary. When no armor or restrictive clothing is worn, an individual possesses a high range of motion in many joints. However, when harness components are worn, limb and body movements such as flexion and rotation may be reduced from their natural values. Armor makers used many ingenious methods to preserve as much of the body's natural dexterity as possible. For example, at the elbow and knee joints, the harness component protecting each joint did not extend around the circumference of the limb. The medial side of the elbow joint and the posterior of the knee joint were not enclosed with armor plate to permit flexion of the lower arm and leg respectively.[162] For the upper arms, a sleeve bearing was utilized in the rerebrace pictured in Figure 13. The sleeve bearing allowed the arm to rotate about its

162 Ffoulkes, 110

long axis, although the system would cease to function properly if the cylinder was damaged.[163] For the gauntlets, complete mobility was a necessity and they were usually the most complex of movable pieces. Some gauntlets contained many riveted lames covering the hand, an articulated thumb piece, and finger pieces.[164] For the protection of the neck, a gorget was worn. On some harnesses, a flange around the neck of the gorget engaged with a channel around the base of the helm to permit head rotation without exposing the neck.[165] The gorget also contained overlapping lames which were riveted to leathers to permit greater flexibility.

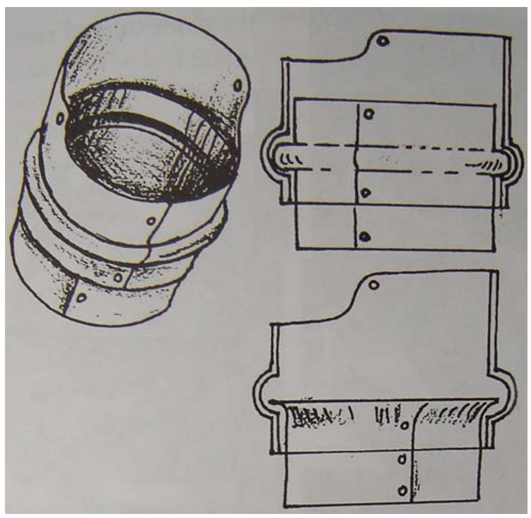

Figure 13: Rerebrace sleeve bearing

One of the most creative means of allowing the armor to move with the wearer while maintaining proper protection is the sliding rivet. An example of a sliding rivet is portrayed in Figure 14. The head of the rivet was burred over and fixed into the upper plate and the lower plate was slotted

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163 Valentine, 49
164 Valentine, 54
165 Edge, 179

for about ¾ in. The arrangement allows movement along the shank of the rivet and is less restrictive than a fixed rivet, but it will not let the two plates slide so far apart as to expose the wearer.[166] Sliding rivets were used in many harness component connections. In the late 1400s, they were used to join the upper and lower portions of the breastplate to allow a degree of flexion and extension of the torso.[167] They were used to connect the lames of the taces to make mounting a horse and sitting down easier for the knight. According to Ffoulkes, the most appropriate use of sliding rivets was in the brassards (vambrace, elbow cop, rerebrace unit) of the late 15th to 17th century. A balance was struck between the defensive and offensive needs of the wearer's arms. The wearer's right arm had to be able to hold a lance and strike with a sword; meaning that the arm defenses would need to allow for the arm to be bent for holding the lance and raised for striking with the sword. The lames of the rerebrace were joined with sliding rivets in such a manner that movement was allowed for the aforementioned actions, but after a blow had been delivered (arm is dropped) the lames closed over each other to protect the arm and allow no rearward movement.[168] Arrangements of sliding rivets were also found on cuisses and tassets: the inner edges of the lames were joined by leather straps and the outer edges by sliding rivets.

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166 Ffoulkes, 53
167 Ffoulkes, 53
168 Ffoulkes, 53

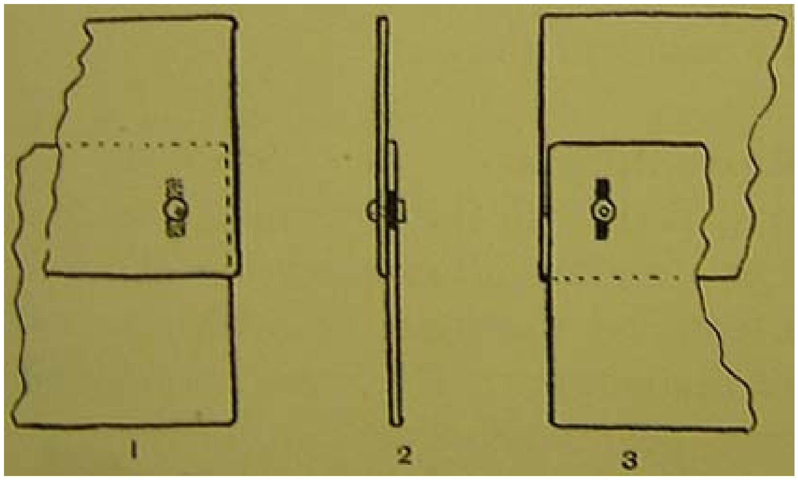


Figure 14: Sliding rivet - 1) Front; 2) Side; 3) Back

A full plate harness was very expensive. The extent to which harness components could be adjusted and adapted to fit changes in the body of the wearer must have been an important concern for the wearer as well as the armor maker. It was part of the armor maker's duties to be present during the process of a knight being armed to make small adjustments if necessary. The traveling knight took his armorer with him and this indicates that the armorer or similarly skilled craftsman was useful in the procedure of arming the knight.[169] In terms of harness components, pieces such as the cuisses that were secured using straps and buckles could be easily adjusted in a manner similar to adjusting a belt today. Other pieces that were tied with various laces could be easily re-tied to accommodate changes in the wearer's physique. Built-in adjustments also were part of components such as the cuirass. At the waist of a cuirass made for King Wladislas (c1510), there is a three-hole fastening that allows for the expansion of the waistline or the wearing of a thicker arming doublet.[170]

169 Ffoulkes, 104
170 Edge, 180

Consideration of Physiological Processes

The consideration of physiological processes was important to the design and construction of plate armor. Heat exchange, respiration, and processes such as vision could be affected by improperly-designed armor and were at the very least, altered with even the very best armor. Ffoulkes mentions that in long marches, there was no warmth in a plate harness, but in fact “an added cold which had to be counteracted by warm garments worn underneath.”[171] However, it seems as if discomfort due to excess heat was more likely. A full plate harness covered nearly the entire body and left very few avenues for the body’s evaporative cooling system to work. As already mentioned, Shakespeare refers to “armor that scalds with safety.” A passage from *The Art of Warre* (1619) by Edward Davies mentions that harquebusiers wearing a heavy mail shirt and a burgonet were more likely to rest than be ready to fight after marching 10-12 English miles regardless of if they were in the heat of summer or the deep of winter.[172]

In regards to respiration and vision, the various types of helms used would have affected those processes. The ventails and bevors on some field and tournament helmets, especially close helms had very limited openings for air flow. Some helmet designs incorporated hinged cheek pieces which could be opened to provide a better air flow when needed. Depending on the design of the visor, the wearer’s field of vision could be reduced a little or a considerable amount. Jousting helms usually reduced the visual field the greatest extent to protect against the splinters from lances. Some close helms could also reduce the wearer’s visual field depending on the construction of the visor. Concerning the fit of a harness, Rich Hals wrote to Edmond Verney in *Verney Memoirs, IV* (1667): “The armour fits well enough only the man did cut away to much just under the arme pit both of back and breast, but for the

171 Ffoulkes, 105
172 Ffoulkes, 116

head piece it is something heavy, yet I think it well enough if it did not come downe so low upon my forhead as to cover all my eyes and offend my nose when I put my head backwards to look upwards."[173]

173 Ffoulkes, 105

Armorers, Guilds, Clients, and Manufacturing Techniques (Eric Van Dyke)

When investigating features of a suit of armor one should consider the process undergone to create the artifact. It is therefore important to investigate the armorers and their craft guilds, methods, and clients. When arrows became an effective weapon to pierce even fine and double-linked mail, craftsmen began to fasten small plates to the most susceptible areas. In 1288 a historian mentions an early use of plate armor connected with mail (Pfaffenbichler 8). Most knights still wore mail until the end of the fourteenth century because plate armor was economically prohibitive even for piecewise components. “The period of plate armor goes from about 1340 up to about 1650, but after 1560 there were growing difficulties in most armour-producing centres” (Pfaffenbichler 9). Later with more firearms in use on the battlefield, plate armor became thicker and thicker until it proved too heavy to wear. This led to a steady decline in the use of plate armor until its eventual end in the late 1600s.

Armorers

Most of the surviving evidence of the activities and lives of armor craftsmen comes from the 14th through 17th centuries, considered to be the great period of plate armor, comes from German and Italian records and artifacts (Pfaffenbichler 6). Researchers today rely on primary resources like sketchbooks made by armorers, often called albums. These books depict concept art for armor design and images of their proudest suits. Armorers used these catalogs to show potential clients the examples of their fine quality work. Contemporary art also plays an important role in depicting armor production. Since virtually no practicing medieval armorer left a record of tools, materials, or exact processes, there are no known surviving manuscripts defining how these craftsmen worked. As a result, current researchers must rely on period artists’ depictions of armorers at work.

Armorer's Communities

Through much of history craftsmen have organized themselves for reasons of social and economic protection, to provide a training structure and a mode for quality control. In 1399 armorers assembled to form a new guild for plate armor, marking an important step in the move away from the use of chain mail (Pfaffenbichler 26).

The craft of armor making required certain political, social and economic conditions to thrive. In addition, natural resources like charcoal, iron, and manual labor combined with proximity to flowing water that allowed waterwheels to be used to power trip hammers and polishing wheels. Pfaffenbichler concisely described the interconnected production system of armor artisans.

> "The manufacture of armour required the skills of other craftsmen besides the armourer. After forging, the armour was still rough and blackened. It needed to go to the polisher or millman who polished the surface with swiftly rotating wheels in water-driven harness mills. Then it went to the finisher who was responsible for the strapping and linings, the padding and the leather gloves. In most high-quality armour the work of these craftsmen was enhanced by the decorative artists, the etchers and the gilders" (Pfaffenbichler 12).

Armorers could also subcontract portions of large orders to lesser masters. These were poorer and could not afford to buy materials and wait for client payment. Guild regulations allowed this but made sure the subcontractor was a master and a citizen. Thus the guild supported new armorers and bolstered the economy. Additionally, the Nuremberg guild tried to spread work evenly and limit competition between armorers. When one master wanted to buy tools or materials he had to notify the guild so they could also participate in the deal.

Italy and Germany

Italy and Germany were the two main centers of armor production, with Italy leading until about 1500 (Pfaffenbichler 13). Milanese armorers reached the height of their fame in 1450 and many moved abroad to continue armoring in "Greenwich, Innsbruck, Landshut, Tours, Paris, Bordeaux, Bruges, Lyons, and Arbois." The main armoring rival to Milan was Brescia. By the second half of 16th century there was a general falling off of Italian armor quality.

German armor manufacture was concentrated in Augsburg, Nuremberg, Landshut, and Innsbruck. These south German centers made mostly high-quality armor for noble clientele while Cologne also mass-produced low-quality munition armor for armies (Pfaffenbichler 14). In Germany, each master had to qualify to make an armor component to be able to manufacture it. This small shop specialization in southern Germany, combined with rich deposits of iron from nearby Amberg-Sulzbach made Nuremberg famous for munitions and medium-quality armor. Along with Cologne, Nuremberg was the main supplier of German armies against Turks in wars along the Hungarian border. Home to the famous Helmshmid family of armorers, Augsberg became Germany's high-quality manufacturing center to compete with rival Milan after 1450, peaking in about 1560 (Pfaffenbichler 15-17).

Several important armorers had privately-sponsored workshops in Germany to provide for specific patrons. Emperor Maximilian I chartered his own armor production center in Innsbruck 1504. Conrad Seusenhofer was a highly talented master who oversaw the production of Maximilian's magnificent armor. Judging by the high-profile client-craftsman partnerships of this time, Landshut was similar to Innsbruck in that it was the location of a major center for important armorers. Unfortunately the characteristics of their armor are unknown because almost no artifacts from Landshut armor workshops remain today.

Low Countries

Following Italy and Germany were the Low Countries (The Netherlands, Belgium, etc.) , which by the 15th century had become an important manufacturer of low- to mid-quality armor. The most important center in Flanders was Tournai where the Rondel family, originally from Milan, produced armor. When the Duke of Brabant contracted Brussels for specialty armors in the 15th century it grew to become a center for finer quality products. Later that century, this duke commissioned massive artillery cannons some thirty-five tons in weight (Contamine 142).

France

France filled only a minor role in armor manufacture and had no city as a permanent seat of armor production. France imported and employed Italian armorers who congregated in Milanese colonies after emigration from Italy. "South Germany also exported a large quantity of arms and armor into France … to the benefit of the French commercial centers such as Montpelier, Beaucaire, Marseilles and Lyons" (Pfaffenbichler 23).

Spain

The scenario in Spain was similar to that of France. Like France, the Iberian Peninsula was a large importer of Italian and German armor. Spanish noblemen commissioned craftsmen in Habsburg court of South Germany for their famous armor. Italian armorers also immigrated to Spain and by the 16th century the Pamplona region was considered a center for high quality armor.

England

England's only armoring center was London "where the makers of plate armor received their regulation as a separate company under the name of the Guild of Heaumers (helmet-makers) in 1347 BC." Out of this emerged the Armorers' Company, an organized body of armorers granted a royal charter in The Armorers' Company of London did not make armor comparable to superior Italy and Germany (Pfaffenbichler 23-24).

Advancement

Guild organization and advancement processes are found detailed in elaborate charters of mail makers documented as early as 1293. This charter said that an apprentice must serve for four to six years before becoming a journeyman. The English armorers' guild demanded a seven-year apprenticeship versus only four years in Augsburg. Four years (eight in Milan) of employment as a journeyman under a master were then required before one could become a master in his own right.

The apprentice system provided cheap labor for armoring workshops. Apprentices were forced to work hard and guild regulations restricted their social lives. Apprentices could be publicly punished in the guild hall for social violations including fighting or visiting taverns. Initially, workshop staffs were limited to two journeymen and one apprentice per master but the guild council could make exceptions to keep market share. In Nuremberg in 1385 each member of the armorers' guild had to be a citizen of the town in good standing. Narrow restrictions on number of people who could serve under a master were indicative of the size of the market. In 1507 Nuremberg allowed four journeymen to each master and by 1574 the quota was back down to three. Once a master, guild members were permitted to set up a workshop and were restricted to one shop and one forge (Pfaffenbichler 27). Masters were required to register a stamp with the guild as a trademark and testament to quality workmanship.

Quality Control

Perhaps one of the most important functions of guilds was the examination and approval of candidate member works by a panel of master craftsmen. To be accepted as a master in Nuremberg, a journeyman had to fabricate and present a trial piece of armor that had to be approved by five masters in the guild. Upon approval, each master would imprint his view mark upon the armor near the armorer's mark. A registered mark of the guild was a safeguard against faulty goods. In 1499 the craftsman had to present his work before final decoration and polishing. If it passed, the city mark was made deep into metal. Later, the guild ensured further quality control by requiring official inspection both before and after finishing (Pfaffenbichler 28-29). If the guild member made only one piece, he was allowed to only produce that piece. If he wanted to market another piece, he could be examined for another piece one year later and start making that also. Most Nuremberg armorers were not allowed to make full suits. By contrast, Augsburg armorers were required to present a complete suit of armor for inspection before an elected council because the guild was more focused on ensuring high quality suits for wealthy clientele.

Clients

Due to the high cost of armor, knights and nobles were the primary purchasers of custom made-to-order armor. Often a full suit of armor could cost an entire year's income or more, so excellence in design details and workmanship were the cornerstone of armorers' ideals. As mentioned, "the historical armorer would have showed the client various designs, drawn in a book for him to choose from. Most likely, he would have wanted his suit to be unique, to reflect his needs, tastes, and possibly his beliefs" (Valentine 1). Since master armorers were essentially tailors whose medium was steel plate rather than fabric, most armor was custom made to fit.

Armoring Guidelines

Charles Ffoulkes presents a discussion of the "rules of armoring." His first tenet calls for "suitability for purpose" emphasizing that design and creation follows a need for the product. For example, as helmets were found to shift upwards when struck from the lower edge, locking mechanisms were invented to keep the helmet attached to the gorget. Since scant records of armorers' practices exist it can be said that they largely experimented and innovated within their craft. Armorers conducted studies of glancing surfaces using experimental armor geometry and overlapping plates (lames). This internal research helped armorers design better protection from striking blows and improved anatomical articulation (Flint 2).

Second, Ffoulkes discusses the importance of convenient use of armor. Top quality armor allowed for maximum mobility. Clothing could be worn underneath with comfortable linings that did not require adjustment. Dressing in armor for combat usually required assistance so many knights kept a squire. The arming process progressed from bottom to top:

Table 6: Order of the Arming Process

Sollerets or sabatons	Feet
Jambs & knee-cops	Lower legs
Cuisses	Thighs
Skirt of mail	Waist
Gorget	Throat
Breast & back plates	Torso
Brassards & elbow-cops	Upper arms
Pauldrons	Shoulders
Gauntlets	Lower arms
Helmet	Head

Initially, armorers strove to design for function over fashion. Ffoulkes refers to this as "recognition of material". Later, armor was made to imitate period trends in clothing. Master embossing craftsmen ornately recreated puffed and slashed velvet and silk in steel. These and masks in the grotesque style and likenesses allowed armoring artists to show off their skill as in the intricately detailed Conrad Seusenhofer's "Engraved Suit" for Henry VIII.

One of the best ways to understand how components were assembled into a whole suit of armor is to study the physical characteristics of the components and their joints. Today, much remaining armor has been restored or created from composite portions. One must take care in inspecting artifacts for authentic indicators of manufacture.

Production Processes

Smelting

Many operations and considerable time were required to complete a suit of armor. Initially iron ore was mined or quarried. Second the iron metal was extracted from the ore by smelting processes in large blast furnaces. After refinement, wrought iron was formed during the blooming process. A bloom produced a spongy mass of metal formed in a furnace by additional smelting processes. Uncontrolled impurities and slag in the iron made it brittle. Discovered by accident, the best armorers had some knowledge of carburization, the process by which carbon diffuses into iron when held at high temperatures at length. Steel is simply carburized iron that has vastly preferable mechanical properties for manufacturing and use (Price 110). Steel ingots were beaten into plates either by the refinery and could be ordered in different sizes and thicknesses by the 16th century (Valentine 2).

Plate Cutting

After first measuring the client's anatomical dimensions with large tong-like calipers, wooden templates were probably used to mark stock metal though no such tools remain today (Valentine 2, Price 73). Large shears resembling scissors were then clamped in a vice and used to cut the plate to rough dimension (Valentine 2-3). Though contemporary artwork depicts almost no change in the design of these tools from the 14th to 17th centuries, open throat shears may have been developed later to accommodate thicker stock. The rough-cut plate was hot worked (raised) to approximate shape and cold worked to final dimensions using various hammers, tool posts, and anvils (Price 76-86).

Carburizing

Heat treatment was applied to further harden the material surface. The plate was then polished at a polishing mill, powered by waterwheel. Depending on client demands the armor may have been tested by impact or “proofed” as a guarantee of protection. Usually fasteners including rivets, buckles, and hinges were custom crafted by armorers or assistants. Welding and soldering were also used regularly to join components rigidly. The installation of fabric linings and leather connective material was usually outsourced to other specializing craftsmen (Valentine 28). Artists applied plating, decoration, and detailing in final stages of armor production.

Conclusion

In summary, ancient armorer’s communities compare in some aspects to modern labor unions. They offered a means of providing economic direction through municipal regulation. The advancement system from apprentice to master craftsman under the guild system ensured high quality products. As a result, demand for excellence in workmanship encouraged healthy competition between armoring regions.

The Physics of an Armor's Protection and a Weapon's Damage (Caroline Mallary)

Plate armor of the 14^{th} through 17^{th} Centuries was some of the most advanced technology of its time. It was in continuous evolution throughout its heyday, as the weapons and tactics of European battlefields evolved to counter it. The skill involved in making these suits is hard to overestimate. The knights who wore them paid handsomely for them, and expected quality in return. This section of the IQP will examine the physics of armor: what made it strong, what weapons did to it, and how it could be punctured or broken.

The shape of the suit and the treatment of its materials were primary in protecting its wearer from harm. Weapons that struck the suit released energy into it: If the weapon penetrated, it was because this energy was sufficient to break the molecular bonds of the metal. The strength of these bonds depended on the metallurgical skills of the armourer. Furthermore, in order to penetrate armor, a weapon had to release its energy efficiently. It was the job of the armourer to prevent weapons from doing that.

Energy, Momentum, and Shock Waves of an Arrow

In order to understand how armor could block weapons, it is necessary to understand how weapons could penetrate it.

Suppose we are talking about an arrow. The flight of an arrow is difficult to model mathematically, but once it makes impact, the arrow is physically simpler than a sword. This is because no one is driving the arrow forward after it hits. A properly swung sword is being driven forward by "follow-through", which allows it to make deep injuries. That complicates matters, as will be seen later on. The arrow relies only on its own momentum to keep it moving through the target. In physics, momentum is usually labeled *p*. Its mathematical definition is $p = mv$, where *m* is the arrow's mass and *v* is its velocity. Momentum, like velocity, has a particular direction. The simplest kind of arrow-strike hits at 90° to the armor, because all the arrow's momentum is directed straight into the armor plate.

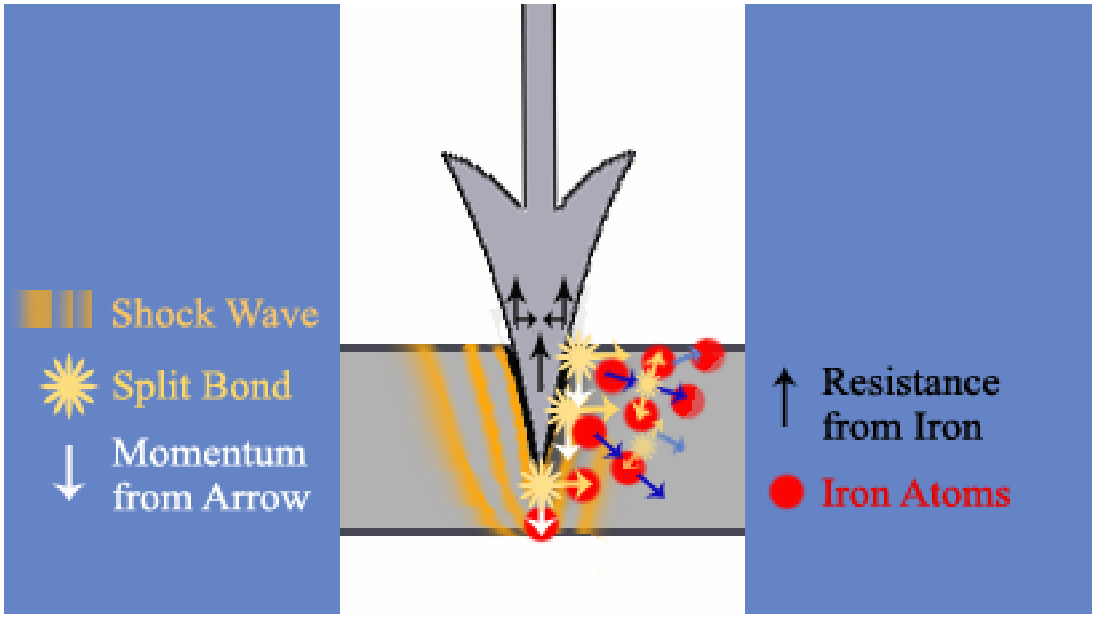
Having a lot of momentum in the right direction allows the arrow to release its energy into the plate efficiently. This is because energy itself isn't directional: Energy, scientifically speaking, is just a quality something has when it is moving or might move. When we are talking about the arrow, all the relevant energy is kinetic, meaning that it depends on the arrow's speed. This is opposed to potential energy, which the arrow has a lot of before it's shot, or when it's high in the air and about to fall. In physics, kinetic energy may be labeled KE, T, or just E. The mathematical definition is $KE = \frac{1}{2} mv^2$, with *m* meaning mass and *v* meaning velocity, just as before. Although velocity has particular direction associated with it, the rules of mathematics and physics dictate that squaring *v* gets rid of that direction. KE is not directional. When it dissipates into the armor, it stresses molecular bonds all around the impact site: Think of a meteorite's crater, shallow and much wider than the meteorite itself. It is the directional quantity momentum that allows the arrow to keep moving forward, and depositing its energy deeper into the plate.

An Arrow's Impact

In Figure 15, two different views of the arrow's impact are shown. In the left view, the arrow's effect on the iron plate is modeled as a shock wave. This shock wave takes kinetic energy away from the arrow: The friction in the iron slows the point down (lowering its energy and momentum), and creates the wave's vibrations. As the point descends, the iron atoms are forced to move away from it, as shown in the right view. In the process, they further destroy the structural integrity around the impact site. The net sideways momentum of all the atoms is zero.

Figure 15: Self-made. An arrow's

impact



The net forward momentum is not zero. The greatest pileup of atoms occurs beneath the arrow's tip, like a boat's bow shock. This is where high forward momentum is most helpful, as there is more momentum available to push these atoms forward: with lower momentum and higher energy, they recoil sooner, and do not make as cohesive of a wave-front. As will be seen later, these wave-fronts are an essential part of the impact.

Energy and Momentum in Archery

In the case of archery, a bowman was limited to a bow-weight he could draw. A bow of that weight could give its arrow a certain amount of kinetic energy. For that energy, the arrow would have greater momentum if it had greater mass [1]:

$$KE = \frac{1}{2}mv^2 = \frac{p^2}{2m} \Rightarrow p = \left(\sqrt{2KE}\right)\sqrt{m}$$

For a fixed energy, momentum is proportional to the square root of the mass. (Actually, because of the way a bow works, a more massive arrow gets somewhat less kinetic energy. That effect is negligible here.) Heavier arrows are better armor-piercers. This was likely understood by bowmen of the day: late medieval arrows were much heavier than modern arrows, even modern wooden ones. As a result, they moved slower for their bow-weight, but had more momentum. This would have been adaptive for armor-piercing. In fact, the US military uses depleted uranium in many of its armor-piercing rounds, because it is 1.7 times heavier than lead rounds of the same size.[174] (It is also harder, another good quality for either armor or armor-piercing, and burns, a popular feature in military projectiles throughout history.)

What exactly is meant by a "massive" arrow? The mass of a late medieval or Renaissance arrow is not something I have been able to find specifically. Part of the problem is that none survive in their original condition. It is known that ash, poplar, and aspen were often used for shafts. Some shafts have survived, such as those recovered from the *Mary Rose*, Henry VIII's flagship[175]. While they have been chemically altered by their centuries underwater, their size is hopefully similar to their original size. From this information, and data on *matweb.com*, the original mass of each arrow can be estimated:

	Dimensions	Volume	Density[176]	Mass

174 "A Bundle of Tudor War Arrows"
175 "A Bundle of Tudor War Arrows"
176 "A Bundle of Tudor War Arrows"

Shaft (Ash or Poplar)	30" length x 0.4" diameter	3.77 cubic in. = 61.78 cc	~0.4 g/cc (Range: 0.2 to 0.8 g/cc)	24.7g = 381.4 grains
Arrowhead (Steel)	Variable	Estimate: 5 cc	7.8 g/cc	39 g = 601.8 grains Reproduction bodkin-points found are 37 g = 570 grains (outpostknives on eBay)
Total				950-980 grains = 61.7-63.7 g = 0.0617-0.0637 kg, about twice the weight of a heavy modern arrow.

Table 7: Arrow properties

At twice the weight of a heavy modern arrow, a medieval arrow would carry 40% more momentum if shot from the same bow. In future discussions of arrows, I will take arrow mass to be 0.0625 kg = 1/16 kg. An arrow of this mass moving at 64 m/s has 4 kg.m/s of momentum.

Fracture Modes & Starting a Wave

What happens when the arrow's high forward momentum its transferred to the iron atoms? It depends largely on the arrow's shape. The reputed best point for armor-piercing[177], the bodkin point, had a sharp tip and steeply sloping sides, similar to a Concorde jet. When this point struck some iron atoms, they would experience intense downward compression, while the ones next to them would barely be compressed at all. The bodkin causes fracture more readily than a dull point of the same

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momentum and energy, because its momentum and energy are distributed among fewer atoms. Those few atoms beneath the tip would be pushed so far from the others that they wouldn't spring back into place. (See the two red atoms directly below the point in Figure 15)

There are multiple ways for a material to fracture, depending mostly on how it is made. These fracture modes should be considered.

In cheap armor, fracture would often be caused by flaws in the metal, such as the presence of slag. Slag refers to impurities that remain after the metal is extracted from the ore. Armors hammered new "blooms" of iron until much of the less-dense slag had risen to the surface of the metal, and could be removed. Cheaper armors generally had a higher slag content. Slag-filled metal can often be recognized by the presence of small pits in over-polished armor. These pits once contained slag particles that have been polished away. The image below in Figure 16 is of the gorget of HAM 429, the harness studied in our IQP. Many slag-pits, some greater than a millimeter across, can be seen. If struck, this metal would be most likely to fracture at the edge of large slag particles, where there are tiny voids between the impurities and the iron.

Figure 16: Slag pits in the gorget of HAM 429. Photo: Eric Van Dyke

A purer metal may fracture along the "grain boundaries". Metals tend to be made of many small (about 10^{-6} m) crystals, called grains. The exact size and shape of the grains depends on heat treatment, and they have many interesting metallurgical properties.

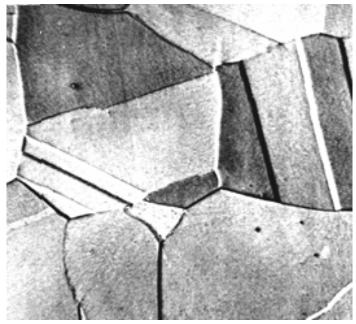


Figure 17: Austenite steel crystals. Room temperature austenite is retained by quenching. Photo: info.lu.farmingdale.edu

Sometimes fractures occur more easily within the crystals, because their lattices may allow cracks to grow in a straight line. This is called transgranular fracture, and the energy required varies with the crystals' orientation. In brittle materials, the rigid orientation of the crystals allows fractures to propagate readily from one to the next. In many metals, fracture-type is mixed.[178]

In addition to where the fractures occur; *how* they occur is important. The arrow can atomically separate metal in two different ways (Figure 18). It can cause cleavage, in which atomic bonds are snapped cleanly in two, and shear fracture, in which the surrounding atoms are pulled along by the arrow's point and eventually torn off. Many pure metals are ductile; that is, they are atomically sticky,

178 "The Medieval Crossbow"

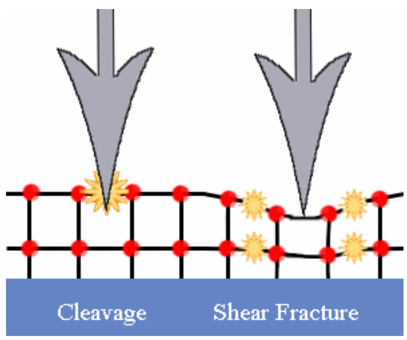
like chewing gum. This results in shearing.

In low-carbon steel, most fracture occurs by trans-granular cleavage. However, shearing is important too; all the more so in soft wrought-iron armor . Shearing makes high momentum especially necessary, since excess material is pulled along with the arrow. This is much of what is meant by "friction" between the point and the plate.

Figure 18: Self-made.

Cleavage and shear

fracture



Kinetic Energy Effects

Friction is not a smooth process, and the arrow's point is wider near its base, and must push even more material out of its way to penetrate. Because of this irregularity, multiple, omni-directional shock-wave fronts are generated (Figure 15). These are kinetic-energy effects, and the waves' total energy is never more than the arrow had to begin with. (The truth, of course, is that kinetic energy and momentum are very closely tied, but transverse shock waves have zero net momentum.) Shock waves can help the arrow through the armor by "jostling" its atoms: If the energy is released cohesively enough, as by a high-momentum arrow, it is possible that the forward-moving waves can rupture the plate before the arrow itself gets there. Alternately, a high-energy, blunt weapon like a bullet may release lots of high-frequency, transverse waves that shatter or rip all the armor around the impact site. The frequency, and destructive power of the shock waves, rise with the arrow's velocity, just as kinetic energy does.

Energy Required to Pierce: Estimations

When it comes down to it, what is the energy needed for an arrow to penetrate armor? Certainly momentum is important, but energy is often cleaner to work with. More fracture-data refers to energy, and energy is used to talk about atomic bonding. There are tests, called Charpy or Izod Impact tests, which measure the energy it takes to break a material. This energy is usually called "impact toughness". The tests consist of striking a standard sample of material under standard conditions. The results can be used to compare materials.

Unfortunately, they say nothing quantitative about the toughness of non-standard samples. A typical Izod value for mild steel bar might be as high 130 J (J is for Joules, the SI unit of energy), or under 10 J. The Izod test is done with a notch already cut into in the metal, to aid crack propagation. Furthermore, the results seem to be independent of bar diameter, although they usually fall with increasing hardness. This test is not similar to the arrow impact. Its results cannot be directly converted into energy needed by the arrow. Another approach to the problem to the problem must be found.

One such approach is to look at the threshold displacement energy (TDE) of steel. This is the energy needed to remove one atom from the steel's crystal lattice. TDE is dependent on the direction from which the crystal is struck, and intend primarily for use in calculating radiation damage. Nonetheless, it is worth a look. According to the ASTM, the average TDE of "steel" is 40 electron-volts, or 6.4×10^{-18} J. This is an extremely small number, but there are an extremely large number of atoms in a visible amount of steel. There are, in fact, 8.4×10^{22} atoms per cubic centimeter. It's not necessary to break every one of these out of the lattice. We might decide that a cylinder of atoms, the same width as the bodkin point and same length as the armor-thickness, might do. (This is a simplification to avoid dealing with fracture modes and other inefficiencies: it is assumed that the cylinder alone is affected, but that it is getting pulverized.)

If a bodkin point is 0.5 mm across at the tip, and the armor is 4.76 mm thick (3/16 of an inch) then the number of atoms in the volume of the cylinder is:

$$\pi\left[\frac{0.5mm}{2}\right]^2 \times 4.76mm \times 1000\,\frac{cm^3}{mm^3} \times 8.4 \times 10^{22}\,\frac{atoms}{cm^3} = 7.85 \times 10^{19}\,atoms$$

Each of these atoms requires 6.04×10^{-18} J to separate it from the lattice, so a total of 503 J are needed.

Both of these energies, Izod Impact and total TDE, are estimations. Some of the steels with the lowest Izod results are hard steels, and if we were to take these numbers at face-value, a toy arrow could crack them without a problem. On the other hand, no arrow has enough energy to penetrate armor according to the TDE model. (A longbow arrow may have between 50 and 150 J, according to my own estimates. Maces and bullets can mange over 500 J. With these weapons, shattering can be a more important means of defeating armor than piercing.)

Ultimately, the question of a weapon's ability to penetrate armor cannot be answered based on its energy and momentum alone. There are too many variables in the metal. Weapons can be compared to each other, based on physical models, and they can be compared to literature and artifacts. And although destructive tests cannot be performed on actual artifacts, experiments designed specifically to mimic impacts on armor can be done. Alan Williams, author of "The Knight and the Blast Furnace", did experiments like this. It is from his poster, "The Archaeometallurgy of Armour", that the following information is taken.

Alan Williams did his impact experiments using a Rosand Instrumented Falling Weight Tester.

The weights used were shaped variously like points, edges, and bullets. He tested riveted mail, wrought iron, and mild steel plate. The exact treatment of these metals was not stated for all data, although it may be available in "The Knight and the Blast Furnace". (A copy of the book could not be obtained during this project.) It was found, as suspected, that slag has a large effect on strength, with the work of fracture being reduced to almost nothing at 8% slag.

The energies of various weapons were also given, although not justified there. My own calculations of weapon energy are done in the "Weapon Mechanics" section.

Figure 19: Weapon energy

Weapons	Energy (J)
Axe, sword (since Bronze Age)	60-130
Longbow arrow (12^{th} cent)	80
Crossbow bolt (13^{th} cent)	100-200
Earliest handgun (14^{th} cent)	250
Developed handguns (mid-15^{th} cent)	500-1000
Arquebus (1475+)	1300
Musket (1525+)	2300

Williams' impact experiments yielded the following energies necessary for the of penetration of armor:

Riveted Chain Mail :	**Plate: 2mm thick, 0.5% carbon, air-cooled:**	**15^{th} century plate, unspecified:**	**Mild Steel plate (<2% carbon) vs. simulated arrowheads:**

200 J (edged weapon)			20 J (0.5 mm thick)
120 J (point weapon)	230 J (point, implied that strike is at "30°")		30 J (1.0 mm thick)
150 J (point vs. mail with hardened leather reinforce)	280 J (point strike at 30° plus padding)		38 J (1.2 mm thick)
220 J (point vs. mail + slaggy coat of plates)		900 J (bullet)	80 J (1.55 mm thick)

Table 8: Comparion of several armor types resistance to certain weapons

The work of fracture for the mild steel plate was found to rise approximately with the thickness (in mm) to the power of 1.6. That is, a thicker plate is exponentially more difficult to pierce. A 3/16" (4.76mm) mild steel plate would require about 400 J to penetrate with a projectile point, and a 3mm plate would require up to 200 J. This means, according to Williams' calculations, all but the thinnest sections of mild plate would likely be longbow-proof, and a crossbow could penetrate thin sections, but would be uncertain to penetrate a breastplate.

My chief comment on this data is that homogeneous mild steel is probably not a good approximation for the best armor, but that it may work for well-made wrought iron armor. This is because the unusual distribution of carbon in traditional steel armors may significantly improve both hardness and toughness. It is again possible that the topic is addressed in Williams' book, but a copy could not be obtained.

Another comment is that if the bullet-shaped weight used in the testing machine is made out of steel, the needed bullet energy may be underestimated: Bullets are usually soft lead, and should absorb some energy by deforming on impact. However, iron balls may have been used sometimes: They seem to have been used in mortar rounds a few centuries later.[179]

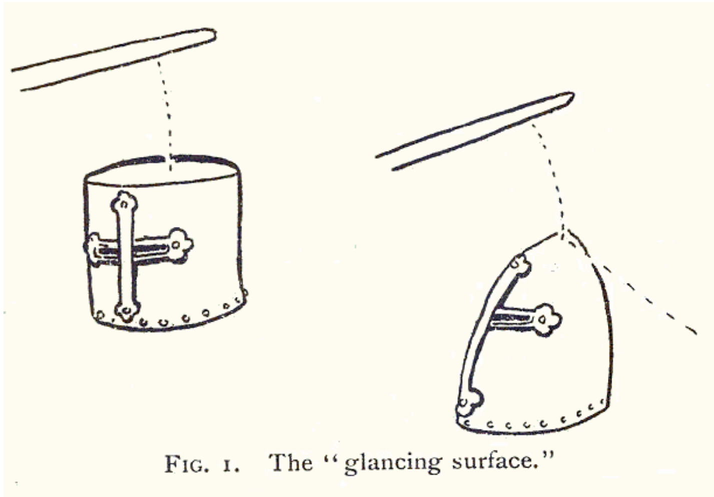
Some design and metallurgical tricks to reduce weapon efficiency are gone over in the next section.

Glancing Surfaces, Ricochet, and Wave-Reflection

One common means of foiling weapon-blows was to design "glancing surfaces"[180] on armor. The shape of a suit affected what angles it was most likely to be struck at, which affected weapon efficiency. The keeled breastplates of many suits from the late 1400s onward were designed with this in mind. Similarly, pointed or crested helms replaced flat-topped helms before full suits of plate were even used. This was because pointed helms could deflect blows that came downwards at the wearer's head. The glancing surface of a pointed helm is illustrated in Figure 20.

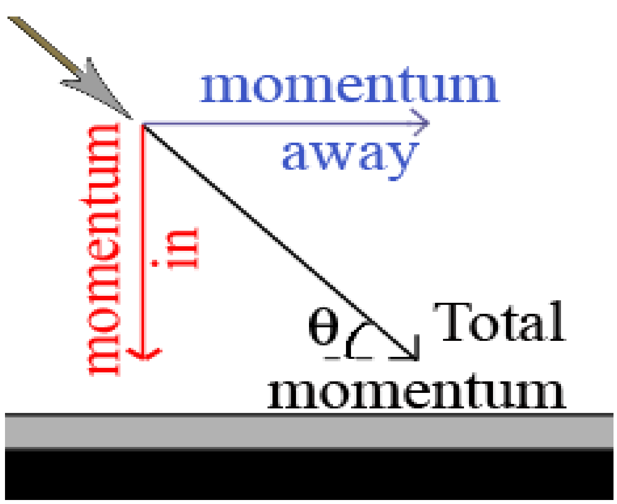
179 Jones, Colonel John T.
180 Ffoulkes

Figure 20: From Ffoulkes. The Armorer and his Craft, 1912



It is intuitive that having a weapon glance off you is better that having one hit you dead-on. Why it is better can be put in scientific terms. Glancing surfaces make it more likely that a weapon will strike the armor at an odd angle. The weapon's momentum is then not directed entirely into the armor. The first result of this is that the weapon's effective momentum is lower. You can regard any impact momentum as split into two components: the momentum going in, and the momentum going away.

Figure 21: Self-made. The momentum in, p(in) = p(total)*sinθ



Only the momentum going in is really effective for piercing. Its magnitude can be determined by the formula: $p_{in} = p_{total} \sin\theta$. In the case of Fig. 6, θ is about 45º. This means that the effective momentum of the arrow is only 71% of what it would have been, had the arrow struck directly. This alone would be enough to prevent piercing many cases. However, there are secondary effects to the glancing angle.

One effect is that a weapon that comes in at an angle is more likely to have its tip bent or broken off by the armor. This is because the long, narrow shape of piercing weapons makes them much stronger in one direction than the other. For example, a drinking straw can be driven through a raw potato if the end strikes the potato perpendicularly (like the arrow striking the plate in Figure 15), but can do no damage to it otherwise. The straw bends sideways, away from the potato, if it hits it at any other angle. Similarly, points or edges that strike armor at an odd angle may bend (if they are soft), or break (if they are brittle). If the point or edge is neither soft nor brittle, it can still ricochet. This is another benefit of the glancing angle.

Ricochet

Ricochet is possible when a weapon strikes a hard, not-brittle target. Hard, not-brittle weapons are the most likely to ricochet. (Softer weapons, like bullets, can ricochet too, but they lose a lot of kinetic energy by deforming on impact.) The arrow in Figure 21 is likely to ricochet. When it does, it does not pierce very far into the armor before bouncing off. The armor's ability to cause a ricochet is a protective feature all by itself. It is part of the reason that good armors had to be hardened: a softer plate won't cause ricochets as well. That is intuitive, but what is the reason for it? What causes a ricochet?

For this, momentum has to be considered again. It is a law of physics that momentum must be conserved in all impacts. What this means is, if you add up the momenta of all the objects (the arrow and the suit) before the impact begins, it will be the same as if you add up all the momenta after the impact is over. There is a trick here, which is that momentum is a vector, and vectors have their own rules of addition. In Figure 22, the red arrows (momentum in) can't be added to the blue arrows (momentum away), because they are at right angles to each other. This isn't a problem with the blue arrows, because they are about the same before and after the impact. The red arrows, however, change direction. In order to conserve momentum, there must be something happening in the armor.

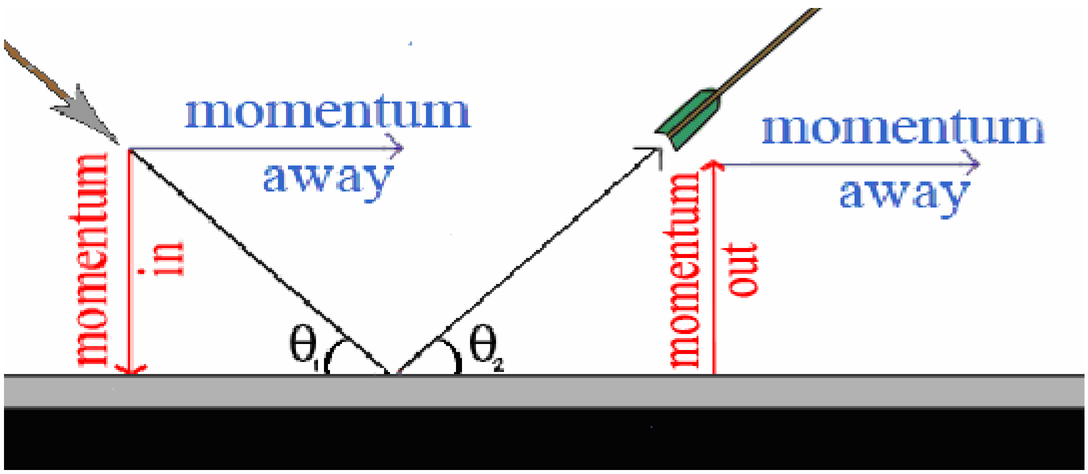


Figure 22: Self-made. Ricochet of an arrow

In the figure above, the momentum of the arrow changes after the impact, but the momentum of the arrow and armor together must be the same. There must be a reaction in the armor. Here, angle theta 2 does not appear smaller than angle theta 1, but in a real impact it usually would be. The arrow shaft would also bend during the ricochet, absorbing some kinetic energy.

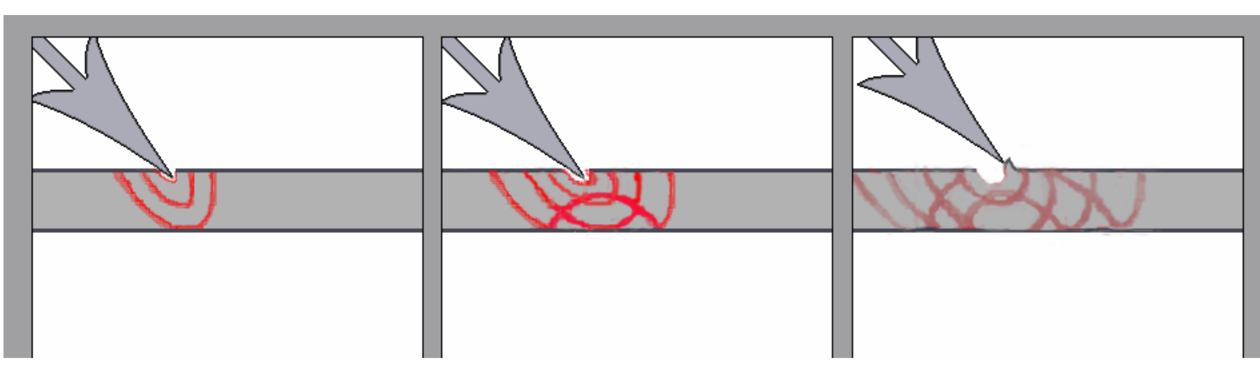
Part of what's happening to the armor, but not the relevant part, is that the armor as a whole is being pushed back by the arrow. If the arrow has a velocity of 40 m/s towards the armor, and a mass of 0.0625 kg, its "momentum in" is 2.5 kg.m/s. (1/16 kg × 40 m/s = 2.5 kg.m/s.) The armor has to take on this momentum itself if it is to stop the arrow.

First, we might try modeling the armor plate as a single, rigid object. That is, after all, what it looks like. If the armor-plate that's struck weighs 5 kg (11 lb), then, in order to take on all the momentum of the arrow, it has to start moving at 0.5 m/s, so that its momentum becomes 2.5 kg.m/s too. (5 kg ×½ m/s = 2.5 kg.m/s.) Furthermore, the plate has to get up to this speed before the arrow gets all the way through it. I'll skip the math, but what it amounts to is that this piece of armor would have to accelerate at a few thousand meters per second per second just to stop the arrow. This is impossible. It means the armor would be running into its rivets, and its wearer, with a few tons of force. It also doesn't account for the fact that the arrow doesn't *stop*; it bounces back again. In order to conserve momentum, the armor would have to accelerate even faster, and it has no reason to do that. Trying to account for the ricochet by looking at the armor piece as a whole is not working. A different model must be adopted: the shock wave model.

Impact Shock Wave Model

Shock waves were first shown in Figure 15. Momentum is not transferred to the whole piece of armor; it is transferred to the waves. (More specifically, it goes to the part of the wave-front moving in the same direction as the arrow. The transverse parts of the wave have a net momentum of zero.) The armor as a whole doesn't move, the waves do. And when the waves hit the far side of the plate, they are reflected. In the figure below, the shock wave is reflected and pushes the arrow away from the armor. The depth of penetration has been exaggerated for clarity.

Figure 23: Self-made. Reflection of impact shock wave



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the armor. These compressive shock waves travel very fast; at the speed of sound in steel. The speed of sound in steel is between 5060 and 5130 m/s, depending on hardness. It is much greater than the speed of sound in air (~331 m/s), and this is the reason that the shock-waves are reflected in the plate. When the wave-front reaches the far side of the plate, it encounters air, in which it cannot propagate as quickly. All waves, when faced with this situation, do the same thing: They partially reflect. (In fact, the propagation-speed difference between air and steel is so great that, unless the arrow strikes within 3.7° of perpendicular, the waves reflect totally. This follows from a formula known as Snell's law.) Any part of the waves that doesn't reflect is heard as sound, and the rest returns to the arrow and can cause it to ricochet.

So why are harder armors better at causing ricochets? Aside from the fact that they're less likely to tear on impact, impacts are more sudden on harder materials. The shock waves have fast, sharply defined, forceful peaks that push the weapon away more effectively. However, these sharply defined, forceful peaks can also do damage to the armor itself. If an armor was hard all the way through, shock waves would wreak havoc on it: Put simply, the armor would be brittle. Solving this problem was part of the armourer's craft.

Material Properties of Armor

Very hard materials are, by their nature, brittle. Glass is the most familiar example of a hard, brittle material. In fact, very hard metals can be noticeably glass-like, with sharp edges and a "tinkly" sound when tapped. (That sound *is* the fast, sharply defined shock waves that escaped into the air.) While hardness is very good against piercing weapons, brittleness was particularly problematic against fast, blunt weapons such as clubs or bullets, which aim to shatter rather than pierce. In good armor, a balance must be found.

What good armor needs is a quality known as "toughness". Toughness was previously mentioned in the "Energy Required to Pierce" section, in conjunction the Izod Impact test. It is not a particularly well-defined scientific quantity, because of all the chaotic, material-based factors which go into it. Creating a tough material, or armor, is in some sense as much art as science.

One very good means of creating toughness in a metal is by varying its hardness at different depths. This limits the ability of shock-waves and cracks to propagate through the armor. Hardness-variation was done in swords as well as armor: High-quality blades consist of folded layers of hard carbon steel and soft iron. Folding techniques in armoring seem to have been used largely to beat out slag, because slag made armor brittle.[181] Hardness gradients in the armor-steel itself were obtained differently.

Good armor was made of iron that was carburized to turn it into steel. The methods used ensured that much more carbon, and hence much more hardness, was found at the surface of the pieces. This was exactly where it was needed.

Armourers carburized iron in their furnaces, by methods that are known today as mock-carburizing (sometimes pack or case hardening) and gas carburizing. In gas carburizing, the piece is heated uncovered in a furnace. Carbon monoxide, a by-product of burning (particularly charcoal-burning), is absorbed by the iron. The temperature and amount of time in the furnace determines the depth and gradient of carbon penetration.[182] In pack-carburizing, the piece was surrounded by charcoal dust or lard before being put in the furnace, to expose the piece to a maximum amount of carbon and prevent cooler air from reaching it while it was being heated.[183] Other methods were used as well, many of which were likely never recorded due to the tendency of armourers to be secretive.

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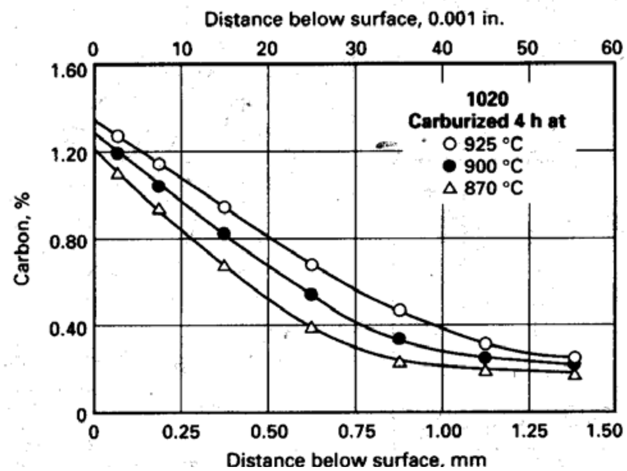
181 "Notes from the Wallace Study Day, 5 December 1998"
182 *Surface Hardening of Steels*
183 Pfaffenbichler

Figure 24: Sample carbon gradient for 1020 steel.

Source: ASM Surface Hardening of Steels,

2002



In the figure above, the 1020 steel has been gas-carburized. Shorter carburization times and lower temperatures lead to steeper gradients. 1020 is a "mild" steel in that it has about 0.2% carbon by weight. However, after gas-carburizing these samples are very high carbon steel at the surface. Actual armor plate will have negligble carbon prior to carburizing and at the center.

The heat treatment of this carburized iron could greatly increase its toughness as well. "Quenching" hot pieces in water or oil causes them to cool rapidly, and maintain some of their high-temperature properties. Steel has a number of different "phases", in which various types of metal crystals are present. These are temperature-dependent. Austenite (Figure 17), one of steel's high-temperature phases, will absorb a great deal of carbon: Just as hot air can hold much more moisture than cold air, hot iron can hold much more carbon than cool iron. When the austenite is quenched, the carbon is locked into place in a super-saturated solution of steel. This thick network of carbon distorts the iron crystals, and keeps them from slipping around, resulting in a harder material. Depending on the exact structures formed, this type of steel may have different names, such as martensite or pearlite.

These structures have internal stresses because of the crystal distortion, which make them more brittle. The solution is tempering: reheating the piece somewhat so as to take most of the brittleness out.. Pack- or gas-carburized steel has an advantage over modern, homogenous steel in this respect: Because the center of the plate is still mostly iron, it cannot become overly distorted.

Armor steel is often compared to modern "mild" steel because of its similarly low carbon content, but this is not practically correct. Good armor steel was highly carburized at the surface and mostly iron in the center. A survey of steels on matweb.com reveals that mock carburizing can more than double the tensile and hardness properties of mild steel without severe detriment to its Izod impact strength.

Hardening may also have been aided by carbonitriding. Steel was sometimes quenched in urine[184], which contains ammonia, a nitrogen compound. Any nitrogen which was absorbed by the steel would increase hardenability while allowing the surface to resist softening during tempering.[185] Whether or not significant nitrogen could be absorbed this way is unknown.

Shock Wave and Gradient

In terms of the ricocheting arrow of a few pages back, in a gradient steel, the arrow is still pushed away from the armor by reflected shock waves. However, in steel that is very hard only at the surface, effects can occur that protect the armor from shock-wave damage. It is possible, for instance, that some of the wave-front can reflect at a boundary between layers of harder and softer steel. However, after some calculations, it seems that this has a negligible effect on the arrow.. Much more important is the refraction of the waves.

The figure below illustrates shock-wave behavior in a plate with a double-gradient, compared to

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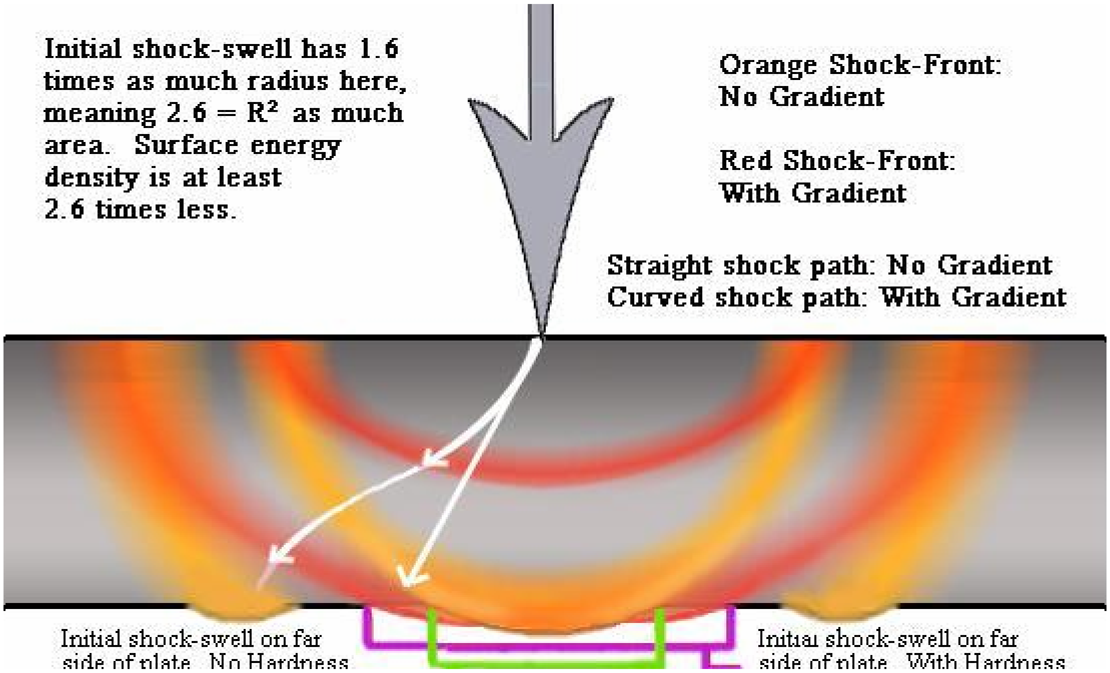
184 "Notes from the Wallace Study Day, 5 December 1998"
185 *Surface Hardening of Steels*

a plate with no gradient. (Reflected shockwave-fronts have been left off for clarity.) The gradient of hardness causes the shockwaves to curve off their original path, and move more along the plane of the armor. At any depth in the armor, the wave-front is more spread out and has a lower energy density. This is illustrated below by the difference in initial shock-swell when the waves reach the far side of the plate. Dimensions are exaggerated for clarity; numbers are for illustration only. An actual shock wave path requires computer calculations to solve; the numbers on this diagram are meant to be illustrative. Note how the gradient causes the shock waves to spread. The shock swell, a bulging of metal on the far side of the plate, is important in terms of the waves' ability to rupture open a path for the arrow. The gradient-plate's shock swell has 2.6 times the area and less than 2.6 times the energy density. The gradient causes the waves to have a longer path-length. Note that this model is theoretical; no experiments have been done.

Figure 25: Self-made. Curvature of shock wave by hardness gradient



The curving effect is especially pronounced for waves that were moving near the plane of the armor to begin with. A wave perfectly perpendicular to the plate would not have its path affected by gradient, and can still reflect and cause the arrow to ricochet. The waves' bending is part of the same phenomenon that causes a straw to appear bent in a glass of water. (In that case, the water's surface is a sharp boundary, not a gradient, so the straw's image bends only once.)

When the wave-front reaches the other side of the armor, the initial shock-swelling it produces is wider and less intense than it would be if emerging from a homogeneous plate. The ripples that follow have a longer wavelength and less energy. They are not as able to rip open a path for the arrow. Furthermore, if they did start a crack on the far side of the plate, the crack would have trouble propagating back through the gradient because of material differences. This resistance to deep cracking is another advantage of surface-hardened metals.

It is worth noting that armors became softer towards the end of their period of use. They were often not hardened or even hardenable. This is usually attributed to a loss of craftsmanship, and that is probably at least partially the case. However, with the increasing use of guns, shattering was much more of a danger than it had been. The tolerances for the hardening procedure would have been much lower than they had been, to ensure that as much impact toughness as possible was retained. If over-hardened, a steel plate would be worse than a wrought iron one. Furthermore, the shock-spreading ability of hardened plate would be less of an advantage against a blunt bullet. Armourers may not have found the difficulty of making properly hardened steel to be worth it. This is particularly likely, given that much of the later demand was for "munitions" armor: cheap protection for large numbers of soldiers.

Weapon Mechanics: The Longbow

The energy-ranges for weapons mentioned in "Energy Required to Pierce" section will be justified in the "Weapon Mechanics" section. It makes sense to begin, as usual, with the longbow.

Since, as mentioned in the "Energy and Momentum in Archery" section, wooden archery equipment deteriorates with time, a lot of educated guesses are needed when talking about medieval archery. The few surviving examples of longbows would break now if ever shot. Their original draw-weights are therefore a subject of debate. Matters are complicated further because longbows require more practice and a different technique than most modern archers develop. My method of determining bow-weight is to start with the arrows.

The total mass of a late medieval or Renaissance arrow was determined in the "Energy and Momentum in Archery" section. It was found that 0.0625 kg, or 962 grains, is a reasonable result.

According to bowhunter.com's Q&A section[186], there is a rule that applies to old-fashioned bows: Your arrows ought to have 9 grains of weight for every pound of draw-weight of your bow. If an arrow is too light it will not fly straight, or may even snap. By this measure, the arrow-weights calculated above would fit a bow between 105 and 110 pounds. The 110 lb draw-weight is a reasonable average, and it was probably common for bows to be two dozen pounds more or less. I will use a 110 lb bow to determine how much energy might be found in an arrow.

The energy of an arrow is not an uncommon topic of interest. There are a great many Internet sites relating to archery in general, and a fair number relating to the physics of medieval archery in particular. Caution should be taken, as they are usually put up by hobbyists, historians, or engineers, but not people who are all three. Additionally, the sites tend to copy off one another, as shown by math errors that appear repeatedly. The formulas and numbers used here are ones that I have vetted or derived myself.

The potential energy of a bow is given by the formula[187]:

$$\text{Potential Energy} = (\text{Efficiency}) \times (\text{Draw Weight}) \times (\text{Draw Length}) \times \tfrac{1}{2}$$

All these numbers are specific to the bow used. While a bow may be underdrawn (not pulled back all the way), it loses power in doing so. My draw length is 0.75 meters (29.5"), because this seems appropriate to the 30" shaft of the arrows used in the "Energy and Momentum in Archery" section. I will use the draw weight of 500 newtons (110 lbs). A good number for the efficiency of a medieval longbow is 0.8, or 80%. The potential energy in this longbow is then 150 Joules.

The potential energy will be converted into kinetic energy when the arrow is loosed. Most of the energy will go into the arrow, but some of it will go into the bow. This is in order to conserve

186 http://www.bowhunter.com/
187 http://www.stortford-archers.org.uk/medieval.htm, http://www.mrfizzix.com/archery/aero.html, http://mysite.verizon.net/tsafa1/longbow/longbow.htm

momentum, which is always necessary in physics. Determining how fast the arrow actually leaves the bow is a classical mechanics problem. The problem is laid out below.

1) **Assume that the bow is 1 kg and the arrow is .0625 kg (~960 grains).**
2) **Momentum = Mass x Velocity. The momentum of the arrow is the same as the momentum of the bow (but in the opposite direction). This is so that final and initial momentum of the system are equal: They are both zero.**
3) $\text{Kinetic Energy} = \text{Momentum}^2 / 2 \text{ x Mass}$. **The kinetic energy of the arrow and the bow together add up to the original Potential Energy.**
4) **These two equations must be solved together:**

$$|\text{Momentum of Arrow}| = |\text{Momentum of Bow}| \ ;$$
$$\text{Potential Energy} = \text{Kinetic Energy of Arrow} + \text{Kinetic Energy of Bow}$$

The solution is that the arrow leaves the bow at 67.2 meters per second, and the bow recoils at 4.2 meters per second. The arrow takes 94% of the energy (141.2 Joules) because it is so light.

According to Williams' tests, having 140 J of energy would make the arrow competitive against homogenous mild steel plate. Unfortunately, the arrow probably doesn't have 140 Joules by the time it reaches its target. Archers were better off shooting at armies that hadn't reached them yet, and air resistance (drag) is a real problem in archery.

Drag is also a real problem in physics. In most circumstances, drag increases exponentially with speed, which in itself changes the speed. For projectiles, the result is a pile of nested equations which only a computer would have the patience for. Additionally, arrows spin, flex and generate lift, and even if they did not, their aerodynamics would be somewhat uncertain. The best way to approach the problem of final arrow velocity may be to adapt a problem that has already been solved.

The graph below shows the trajectory of a thrown baseball, as computer-simulated for Taylor's *Classical Mechanics* textbook.[188] The ball has been thrown at an angle that will just about maximize its range in the presence of drag. This would be similar to the shooting angle of archers for the opening volley of arrows on a battlefield.

Figure 26: This is Figure 2.10 from Taylor's Classical Mechanics textbook

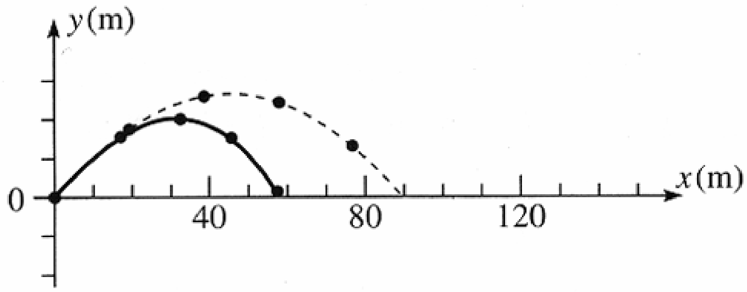


Figure 2.10 Trajectory of a baseball subjected to quadratic air resistance (solid curve). The initial velocity is 30 m/s at 50° above the horizontal; the terminal speed is 35 m/s. The dashed curve shows the corresponding trajectory in a vacuum. The dots show the ball's position at one-second intervals.

This graph will scale up, although care must be taken in doing so. The shape of the trajectory will be similar for the arrow and the baseball. The range reduction due to drag is about 33% here. This is reasonable for an arrow; as shown by the difference between calculated ranges (for a vacuum) and actual reported ranges.[189] Although a baseball's shape is less aerodynamic than an arrow's, a baseball is also symmetric and massive, and less subject to unevenness in flight. Ultimately, motions such as fishtailing and the arrow's lower momentum increase the effect of drag, so the arrow's flight-path may be similar to that of the baseball.

188 Taylor

189 http://www.stortford-archers.org.uk/medieval.htm, "Academy of European Medieval Martial Arts"

Since we are assuming that range-reduction due to drag will be 33%, we should find the range of the arrow in a vacuum. That range, when the arrow is shot at 50° above the horizontal, is given by:

$$\text{Range} = \frac{2 \text{ x } (\text{Arrow Velocity})^2 \text{ x } \sin(50°) \text{ x } \cos(50°)}{\text{Acceleration due to Gravity}}$$

The acceleration due to gravity is 9.8 m/s^2. The range of this arrow in vacuum is 453.8 m, or 492 yards. This range is a factor of 5.04 greater than the range of the baseball shown above. By the assumption that the shape of the trajectories is similar, all physical dimensions on the baseball's graph must then be scaled up by a factor of 5.04.

Flight Path	Range, Vacuum	Range, in Air	Peak, Vacuum	Peak, in Air
Arrow	453.8 m	~297 m	~136 m	~106 m
Baseball	~90 m	~59 m	~27 m	~21 m

Table 9: Flight path of an arrow and a baseball

These numbers are in accordance with an empirical formula for estimating range in air, given in **Range in Air =** $v^2/g\ (1 + cv^2/mg)^{-0.74}$[190]. Here, ***c*** is an aerodynamic constant equal to about 0.0001, and the arrow is shot at 45°. There is a 3% difference in that calculated range (306 m) and my scaled range (297 m). This discrepancy reduces to 1.5% when my 50° shooting angle is accounted for by multiplying by $2\sin(50°)\cos(50°)$. The range-reduction due to drag, as gotten from the empirical formula, is about 33%, as was assumed. So scaling distances in this problem works.

Scaling does not work for the velocities, however. The arrow's velocity is 67.2 m/s, only 2.24 times as much as the baseball's 30 m/s. This is because gravity is the same on all scales. I am going to estimate the final velocity of the arrow by making an assumption: that the drag on the arrow is much

190 http://www.stortford-archers.org.uk/medieval.htm, http://mysite.verizon.net/tsafa1/longbow/longbow.htm

less on the way down than on the way up. While drag is still not really negligible, in doing this I can get the maximum possible speed (and maximum energy) at which the arrow lands. The arrow will "free" fall from a height of 106m. That height is the arrow's peak, where, for an instant, it is neither rising nor falling. The vertical component of the arrow's velocity when it lands (without drag now) is given by:

$$\text{Vertical Velocity} = \text{Acceleration of Gravity}\sqrt{\frac{2 \text{ x (Peak Height)}}{\text{Acceleration of Gravity}}}$$

The vertical velocity of the arrow, when it hits the ground, is 45.6 m/s, downward. The arrow has a horizontal velocity, too, and appears to strike the ground at a 60° angle. Trigonometry can be used to solve for the horizontal velocity:

$$\text{Horizontal Velocity} = \frac{\text{Vertical Velocity}}{\tan(60°)}$$

The answer is 26.3 m/s, to the right. The Pythagorean theorem gives the total maximum speed of the arrow when it hits:

$$\text{Max. Striking Speed} = \sqrt{(\text{Vertical Velocity})^2 + (\text{Horizontal Velocity})^2}$$

The arrow hits at a maximum speed of 52.2 m/s. Its kinetic energy is at most 86.5 Joules, only 61% of what it started with. This is similar to Williams' estimate of 80 J. Even if there were only a 10% range-reduction due to drag, estimates show that the arrow would retain only 80% or so of its kinetic energy, 115 Joules max.

Given this information, longbows would seem to be ineffective against plate at range. As plate was always worn with padding, and Williams implies that another 50 J of energy is needed to get through the padding (Section 3.0), almost any type of plate would do. However, an arrow traveling at 52.2 m/s (117 mph), is still plenty fast enough to kill an unarmored foot soldier, or wound and panic a horse. The rapid rate of fire of the longbow meant significant damage could be done to an advancing army before the melee began.

Whether or not the longbow could have been effective close up, with 140 Joules of energy and 4.2 kg.m/s of momentum, is a return to the materials question. It may have been, when plate first appeared: Gerald of Wales, writing in 1188, tells of knights being pinned to their horses by longbow arrows that penetrated their armor, legs, and horse. However, this may be misleading: Given the time of writing, the armor may have been leather-reinforced mail. It was definitely possible to proof armor against longbows by the mid-1400s. In 1448, for example, the Guild of Armourers at Angers delineated two qualities of armor: The lower quality was longbow-proof, the higher was proof against the windlass crossbow and some handguns.[191] (As a caution, "proof" does not always apply to sections of a suit other than the cuirass.) Later, pistol proofing, musket proofing, and the complete obsolescence of the bow indicate that arrows were not likely to puncture good armor later on.

The Crossbow

Crossbows are an even stickier subject than longbows. Again, the examples that survive today would break if ever shot, so there is debate about their capabilities. Some unquestionably had massive draw-weights, as demonstrated by the use of mechanical aids to draw them. A draw-weight for a heavy, windlass-drawn crossbow might be 1200 lbs (5455 newtons). There were also crannequin-drawn crossbows, the heaviest of which were probably used for hunting, not war, one- and two-foot crossbows, which were drawn by the legs with the aid of a hook on the belt, and others. Crossbow-like siege engines, often called balistas, were drawn by many men. That balistas penetrated armor is not in doubt, but balistas are weapons a bit like cannons: A knight would usually rely on his ability to get out

191 Bradbury

of their way.[192]

One definite advantage of the crossbow was that it could be held and aimed ready-to-shoot, without effort. This made it easier to use. One disadvantage was its slow rate of fire. These qualities would make it well-suited to defenders in a siege, or to soldiers without as much training as the longbow demanded.

Intuitively, it would seem that the crossbow was much better at puncturing armor than the longbow. However, there is a counterargument: Namely, that the short limbs of a crossbow did not accelerate the bolt very much before loosing it. There is merit to this, but high draw-weights can compensate: An Italian assassin's crossbow with a two-inch, 90-lb draw was known to be lethal at close range.[193]

There are efficiency issues unique to the crossbow. These relate to friction with the crossbow stock, and torque from the trigger mechanism, among others. Efficiency was improved in later crossbow designs.

Such efficiency issues defy mathematical breakdown. Much like drag effects, they are only reliably estimated from experiment and documentation.

An experiment by Stephen V. Grancsay, former Arms & Armor curator for the Metropolitan Museum of Art (1929-64), compared a reproduction longbow with a reproduction crossbow. The results are given below:[194]

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192 Bradbury
193 "The Medieval Crossbow"
194 http://www.thebeckoning.com/medieval/crossbow/cross_1_v_c.html

Type of Weapon	Draw weight	Bolt weight	Speed of bolt
Longbow	**68 lbs.**	**2.5 oz**	**133.7 fps** **(40.75 m/s)**
Crossbow	**740 lbs**	**1.25 oz.**	**138.7 fps** **(42.28 m/s)**

Table 10: Longbow and crossbow comparison

Apparently, the reproduction crossbow was not much of an improvement over the longbow. Experiments are, of course, highly dependent on the conditions under which they were performed. This experiment does have some apparent flaws: For instance, the 2.5 oz (1100 grain) arrow used in the longbow is much too heavy, according to the 9-grains-per-pound-of-draw rule for wooden bows.[195] There may be a similar issue with the crossbow, such as the way it was strung, or a material one: Crossbow steel was processed and tempered just as armor was, although not in the same way.[196] Modern crossbows are certainly capable of much, much higher velocities; e.g. 330 fps (101 m/s, albeit with lighter bolts) for a 200 lb-draw Excalibur Exocet (basspro.com). The experimenter was certainly reputable in his day. However, the experiment was likely published posthumously and may not have been up to standard. Ultimately, what this experiment best shows is the extreme sensitivity of crossbows to efficiency issues.

Documentation indicates that heavy crossbows were much more powerful than longbows. The two qualities of armor offered by the Guild of Armourers of Angers is one example. Another is quoted

195 http://www.bowhunter.com/
196 Bradbury

in Bradbury's *The Medieval Archer*. It is the commentary of Princess Anna Comnena of Byzantine[197] on the crossbows of Franks during the First Crusade (1190s). She describes them as "weapons of the barbarians", and goes on to list things that they have been known to punch through, including shields, iron breastplates, walls and bronze statues, "so irresistible and violent is their discharge." While there may be exaggeration here, it is clear that the Byzantines had nothing comparable to the crossbow at the end of the 12th century, though that region has a history of excellent archery. It is possible Anna Comnena is referring to balistas. Bradbury does not indicate this, though. Additionally, any balistas would have to be shipped to Byzantine or built on site.

The crossbow and the longbow were not exactly comparable in any case, as they were used slightly differently. Lacking speed in reloading, a crossbow was shot for accuracy, versus the longbow's rain of arrows. The actual power of the crossbow remains uncertain. As a result of my research, I consider it to be roughly equivalent to the pistol. Williams' estimate for 13th century crossbow-energies is up to 200 J, while he gives early (14th century) handguns at 250 J.

Guns

A full treatment of guns is beyond the scope of this paper. To derive bullet-energy from first principles, it would be necessary to delve into the chemistry of black powder and the dynamics of explosives. This is aside from any of the numerous efficiency issues, which varied from gun to gun, powder to powder, and soldier to soldier.

To make a rough estimate, I might assume that a decent hand-held firearm could get its bullet up to the speed of sound in air. Guns are loud because the explosions inside them force materials outwards at supersonic velocities; hopefully these "materials" include the bullet. (Modern guns

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197 Bradbury

$$\frac{4}{3}\pi(1cm)^3 \times 11.39\frac{g}{cm^3} = 47.75g = 0.04775kg;$$

$$\frac{4}{3}\pi(\frac{1}{2}cm)^3 \times 11.39\frac{g}{cm^3} = 5.97g = 0.00597kg$$

technically use propellants, not explosives.) The speed of sound in air is 331.3 m/s. Bullet size can obviously vary. I might chose to look at two ball-shaped lead bullets, one 1 cm in radius (~.80 caliber, musket-sized), and one half as wide (~.40 caliber, a common pistol size). The density of pure lead is 11.39 g/cc. The density of an alloy, such as lead-tin, would depend on composition. I will use the pure density. The volume of a sphere of radius *r* is given by $4\pi r^3/3$, so the mass of each of these balls is:

Kinetic energy is obtained in the usual way, and it is found that the musket-ball has 2620 J of energy, and the pistol-ball has 328 J. Williams gives 2300 J for the musket and 250 to 1000 J for the "handgun", depending on period. Both of these estimates are in agreement with the Armourer's Guild of Angers' claim that their good armor could be proof against some handguns, and also the historical fact that plate armor eventually went out of use. (As noted in Section 3.0, Williams states that a bullet's dull shape meant that it needed about 900 J to get through "15th century armor".)

There was still much use for armor, even after the advent of powerful guns. In part, this was because of guns' early rarity, unreliability, and persistently long reloading time. Like bows, they weren't melee weapons. However, they have another similarity to bows which is just as important: Bullets, especially round ones, are extremely vulnerable to air resistance. It is claimed by Sir Henry Douglass, an English scientist during the Napoleonic Wars, that a musket-ball's terminal velocity is 183 ft/s, or 56 m/s. He goes on to say that that such a ball should never be shot at a steep angle (such as long bows were shot at), because at such a low speed the balls could be dealt with by wearing a stiff hat. The effective range of musket-balls is therefore not as great as might be assumed from their high velocity. Musketeers could not fire much before the cavalry reached them, and a melee or standoff began. (Musketeers generally had pikemen to protect them as long as plate armor was in use.)   The great effect of air resistance also means that some of the musket-ball's armor-defeating power is removed. If, like the arrow, it loses 60% of its kinetic energy at useful ranges, it may only have 1500 J to work with when it strikes. This is sufficient to break armor head-on, but is apt to fail if the strike occurs at an angle.

Other "Blunt" Weapons & Padding

Plate armor originally evolved because its ability to protect the knight from blunt impacts was superior to that of chain mail. This section treats why that is.

The chain mail of early centuries was an effective defense against cuts and some projectiles. Any edge or point that failed to get through the links was effectively a blunt weapon. Knights could avoid sword-wounds, but they were still vulnerable to broken bones and other blunt trauma. In the era of chain mail shields were common for this reason. Helmets were also used, and it can be said that they were the first areas of the body to be "plated". Aside from the obvious importance of the head, it is vulnerable to blunt trauma in a way that fleshier areas of the body are not. Being very hard and relatively uniform, impact shocks transmit readily into and through it. Softer, more cut-prone areas will spread the shockwaves out. They effectively cushion the bones beneath them. It is likely that chain-mail era knights would have aimed for the bonier parts of their mailed opponents, where they could do the most damage. In fact, it seems that the knees and shins were the next areas to be plated or reinforced with cuir boulli (hardened leather).[198] Because it was especially important for foot soldiers to not break their knees, even archers were apt to wear poleyns, as shown in images such as the one

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198 Edge & Paddock

below, cropped from a painting of the battle of Agincourt.

Figure 27: Battle of Agincourt, 1415. Unknown artist and date. From http://www.aginc.net/battle

The rigidness of plate armor can protect its wearer from blunt impacts that mail cannot. Plate distributes the force and energy of the blow over the entire plate, instead of allowing it to do concentrated damage in one spot. In Figure 28, a 3-square-inch hammerhead hits the side of a rigid, padded helmet, and loses more than a factor of sixteen (50” divided by 3”) in the pressure it exerts on the head.

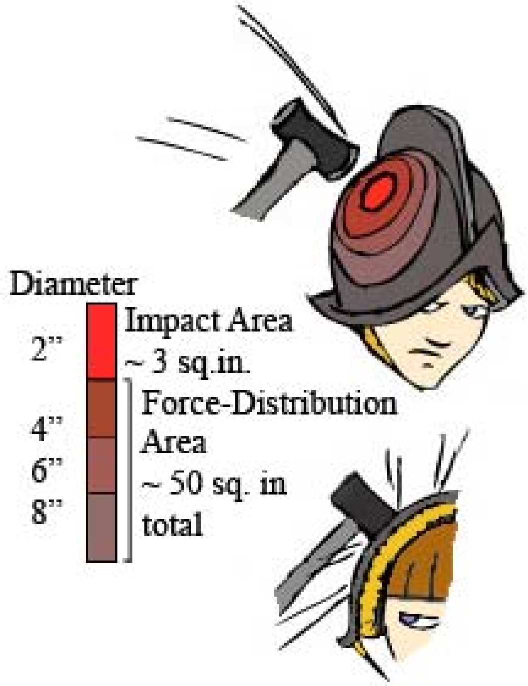

Figure 28: Self-made. Pressure of impact blow

The padding is absolutely essential. It serves a few different functions here. One is a cushioning effect. The hammer actually loses significantly more than a factor of sixteen in pressure it exerts on the head, because the padding is softer than the head. "Force" and "pressure" are concepts I have avoided talking about, because they depend very strongly on how the impacts occur. They become necessary when talking about padding, however.

$$\text{Pressure of blow} = \frac{\text{Force of blow}}{\text{Area of impact}};$$

$$\text{Force of blow} = \text{mass} \times \text{deceleration of weapon}$$

The soft padding causes the weapon to decelerate more gradually, so the force of the blow is less. This is the same concept as an airbag. The padding is also necessary for the plate to create that factor of 16 reduction in pressure. Because the plate is not perfectly rigid and does have shockwaves in it, it doesn't hit the layer beneath it all at once. Without padding, the "shock-swell" shown in Figure 25 could knock the knight out, even if his armor remained intact. Padding effectively doesn't allow shockwaves to be transmitted, so the plate acts as a rigid body. The padding is mostly air, so impact shocks tend to be internally reflected in the plate ("Impact Shock Wave Model" section). Even in a head-on strike, at most 23% of the waves' energy is transmitted as sound into the padding, where it does no damage (except possibly to an eardrum). This follows from what are called Fresnel equations.

For a near-head-on strike, percent energy of shockwaves getting through =

$$\left(1-\frac{(\text{Speed of sound in steel - Speed of sound in air})^2}{(\text{Speed of sound in steel} + \text{Speed of sound in air})^2}\right)\times 100$$

If there were no padding, the relevant speeds of sound would be the speed of sound in water (~1450 m/s) or bone (~2650 m/s), not air. If soft, watery tissue were right up against the plate, it would directly receive 69% of the wave-energy there. If it were a skull right up against the plate, that skull would get 90% of the wave-energy, 91% of which might then reach the brain. Airy padding is a much better option. Shock waves in air are usually referred to as "loud noises", so the greatest danger for the knight might be that getting hit by the hammer will make him fall off his horse.

Handheld Weapons: Lances, Maces, Axes & Swords

In the remaining sections, weapons are modeled that are powered directly by muscle. They are forceful in a different way than projectiles can be forceful. They are being continuously driven forward by the person holding them. In terms of piercing armor, this follow-through is roughly equivalent to a projectile's momentum, but it is even harder to treat mathematically. The weapon models presented are guesses and should be regarded as such.

Follow-through was an important aspect of mounted warfare. Knights did not generally use projectile weapons until pistols became common, and those were weapons of last resort. The horse was a major part of follow-through: Even if you couldn't swing your mace hard enough to pierce enemy armor, the horse under you could add to and complete your blow. Jousting tactics were especially reliant on the horse' speed: The couched position of the lance replaced the earlier tactic of wielding it overhead, where only the knight's arm was driving it forward. Lances had the advantage of long range, although they often broke. Since they were driven forward by the galloping horse, they were never decelerated to a stop: One or both riders were unhorsed, the lance broke or was dropped, or one rider was impaled.

The physics of the joust are laid out in detail in the 2002 IQP "Modeling the Joust"[199], but the analysis does not include much numerical data.. Rough calculations can be made using its qualitative information.

It appears that no calculations need be done that involve the horse directly. There is no reason, for example, to find the horse's kinetic energy. For our purposes, it may as well be infinite. The knight will never be able to direct it all into his lance. How much energy he manages to direct into his opponent's armor depends on how rigidly he can stay on his horse, and how rigidly his opponent stays on his. Because of these complications, some tricks will be necessary to estimate the energy of a lance-strike.

A knight would have had to brace himself in the saddle well enough to make use of the horse's power.   He has to withstand the recoiling force of his own lance. I will assume that the knight can brace again 300 pounds of force for a very short time. (The metric equivalent is 1300 newtons.) This is the amount of force that he can use to do damage to his opponent. The number is a little arbitrary; it is maybe what I could brace against standing up. The knight braces against it in the saddle, and under conditions of changing angle: Based on reenactment photos, knights twisted towards each other during

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the collision.

According to *Modeling the Joust*, a fully armored warhorse could be expected to run at about 20 mph (9 meters per second, metric). We can now get the power of the lance-strike.

$$\text{Power} = \text{Force x Velocity}$$

The advantage of working with power is that force and velocity are relatively easy to estimate or measure. Kinetic energy is not measurable here, because there is not a limited supply of energy in the lance. The horse continuously supplies the lance with energy, and the lance pours that energy into the opponent's armor when it strikes. The question is, how much energy does it manage to pour into the armor before point-to-plate contact is broken?

This is where power comes in handy. Power is a rate at which energy is transferred. What is the power of the lance?

$$\text{1300 newtons x 9 m/s} = \text{11,700 Watts} = \text{11,700 Joules / second}$$

The power of the lance-strike is enough to supply nearly a dozen houses! Of course, the strike doesn't last for very long, so not that much energy is transferred altogether.. The bracing force of 1300 newtons is an average: The knight with the lance does recoil, and 1300 newtons is the average impulse-force on him before he recoils so much he's no longer bracing the lance very well.

To get the amount of energy transferred, we need to know how much time the collision took to occur. Without measurements, it can be hard to say how much time that is. However, we could calculate a ballpark figure..

If each horse is running at 20 mph, then they are running at each other with a combined speed of 40 mph (18 m/s). I will assume that the knight holding the lance doesn't visibly recoil yet, and the knight struck by the lance is thrown a half-meter backwards before he loses contact with (or suddenly has too much contact with) the lance. This gives me the time it takes the collision to occur:

$$\text{Time of Collision} = \frac{\text{Distance of Recoil}}{\text{Speed of Collision}} = \frac{\frac{1}{2}\,\text{m}}{18\,\frac{\text{m}}{\text{s}}} = .028\ \text{seconds}$$

With the time known, I can now determine the total energy put into the armor of the struck knight:

$$\text{Energy} = \text{Power x Time} = 11{,}700\ \text{Joules / second x } .028\ \text{seconds} = 325\ \text{Joules}$$

According to this calculation, the lance is equivalent to a small pistol when it is rebated; that is, blunt like a bullet. This puts the danger of the joust into perspective a bit: Aside from the danger of getting trampled, the knights may as well have been shooting at each other. When the lances were not rebated and did not break, they were certain to pierce all but the thickest or hardest armor. This is based on Williams' assertion that the energy needed for a point to pierce mild steel plate rises exponentially with the thickness: About 5 mm, or 1/5", of mild steel would be the minimum needed to protect the wearer from a sharp, well-aimed lance.

It might do to make a further comparison with maces. Maces were very short-range weapons with limited versatility. Nonetheless, flanged or spiked maces were choice weapons against armored knights. Maces have unusual mechanics. They are point-impact weapons, but are swung instead of thrust. This makes it much easier to get them up to high speed, even when on foot. Also, their momentum can help tear and crush armor that has already been slightly penetrated by one of the spikes. Mace-blows can be quantified with some educated guesses.

Major league pitchers can hurl fastballs at 90 mph. Pitchers have a highly specialized skill, but it is reasonable to assume that a strong man is capable of 66 mph (30 m/s), and an armored man might manage half of that (15 m/s). This is the speed that a knight can move the end of his arm. It includes any extra velocity he gets by whipping his wrist, so the mace can be regarded as a stiff extension of his arm. (The same is not true of the flail, which would move much faster if used well.) To find out how fast the mace head is moving, I assume the knight's arm is a little over 27" (0.7 m) long. I am going to treat it as if it were one spoke of a large wheel:

$$\text{Circumfrence} = 2\,\pi\,(\text{Arm Length}) = 4.4\text{ m}$$

Since the end of his arm (rim of the wheel) is moving at 15 m/s, his arm would make 3.41 revolutions per second if it could actually move like a wheel. This would be true no matter the length of his arm. Suppose now that his arm is about 20" longer (0.5 m). That is, he's holding the mace. His arm is still making 3.41 revolutions per second, only now the end of his arm has to go the distance

$$\text{Circumfrence}' = 2\,\pi\,(\text{Arm Length} + 0.5\text{ m}) = 7.54\text{ m}$$

In order to complete its revolutions, the mace head must be moving at 3.41 rps × 7.54m = 25.7 m/s. This would correspond to ball pitched at 57 mph in full arm harness. What kind of kinetic energy does the mace have, if it weighs 2 kg (4.4 lb)?

$$\text{Kinetic Energy} = \frac{1}{2}\text{ x (mass) x (velocity)}^2 = 660\text{ Joules}$$

(For a mace swung at full speed)

Considering the 325 Joules of the lance and even less for the longbow, it is easy to see why the mace remained popular despite its disadvantages. Its points, even when they were not as obvious as those of a morning-star mace, were able to put a hole the armor, which the mace's momentum could then widen easily. Furthermore, being handheld like the lance, the mace was not entirely limited by the energy and momentum it had during the swing. The follow-through available to handheld weapons would also have been available to the mace. It should be noted that a mace without points would not be such an effective weapon, unless the armor was slaggy and inclined to shatter: According to Williams, the amount of energy needed for a dull weapon to get through armor was around 900 J. This is logical, since plate evolved to counter dull-impact weapons.

Swords and axes might be modeled much like the mace. However, as edged weapons, they are at a disadvantage: The edges have much more area than points, and are effectively duller. Furthermore, Williams gives sword and axe energies at a maximum of 160 J, although this may be for slower, two-handed weapons. It is not clear whether or not Williams has considered follow-through in these weapons. The speed that may be added to a strike if the combatants are mounted is also important. A 2 kg axe whose edge had 100 J of energy when swung on foot may have 360 J if swung from horseback. (For a warhorse galloping at about 9 m/s and a horizontal swinging motion.)[200]

It is notable that edge-shaped dents seem to be rare on surviving suits: The only edge-dent I observed in the Higgins' collection was on the thin steel cladding of a gun-shield, c. 1540. The points of swords may have been more effective, but since thrusting is slower than swinging, a sword-point that pierced armor was probably being driven by a horse, like a lance. It seems that in the era of plate, swords and axes were probably most useful against foot soldiers, slaggy armor, and during speedy mounted combat.

Report Conclusion

The physics of armor is complex on many levels. It is a matter of the craftsmanship of armourers and the skill of soldiers who tried to defeat the armor. It remains relevant today, as better vehicle armor and armor-piercing weapons continue to be developed. It may never be known exactly what each suit was capable of withstanding, because the artifacts cannot be tested and are no longer in their original condition. However, by analyzing them scientifically, we can come to a better understanding of warfare in the age of plate armor.

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Project Conclusion

The Classic Suit of Armor IQP project spanned the 2006-2007 academic year. The project team consisted of four group members and was advised by Professor Jeffrey Forgeng of the Humanities and Arts Department at WPI. It was conducted in collaboration with the Higgins Armory Museum located in Worcester, Massachusetts. This IQP continued and expanded upon the efforts of previous teams' work on this particular project. In the research portion of the project, each group member read some general sources on medieval armor to obtain a background and then focused on his/her specific topic areas. During the hands-on component of the project, HAM Harness 429 was carefully examined from head-to-toe by the team. The harness was photographed and footage was taken of its individual components as well as the full harness assembled on a mannequin. A video containing the pertinent points of our investigation of the harness was made as the final product of the project, in addition to the compiled report of the previous terms' research.

The project began with a PQP component. The main purpose of the PQP was to produce a project proposal that included an introduction to the relevant topics to be researched, a project plan of work for the upcoming three terms, and an annotated list of sources to be used in the research phase. During this phase, the team examined the previous Classic Suit of Armor IQP as well as other Higgins IQP projects to get a better idea of what was expected for our project. It was decided that the four main areas of research to be divided up amongst the team would be: the manufacture of armor, the history of armor collecting, the biomechanics and functional aspects of wearing armor, and the physical investigation of armor's protective capability. For the annotated list of sources, the team started by pulling relevant sources from the previous Armor IQP. The George C. Gordon Library at WPI and libraries at nearby colleges were utilized in obtaining most of the sources for the biomechanics and physics of armor protection sections. One difficulty faced by the team was coordinating all the various drafts and edits to the project proposal components made by each group member. To overcome the obstacle, the team used a version control software and housed the files on a member's server. Although we got off to a slow start in the first term, we eventually pulled together a viable project proposal.

The first term of the IQP proper was the research and writing term. The main goals of the term were to gain a background of armor in the medieval period, explore the existing armor database at the museum, and perform the majority of the research into the four main topic areas. In terms of gaining a background, armor manufacture, the social and historical context of medieval Europe, the rise of plate armor to the Maximilian era, and the decline of armor were investigated by a team member using general sources in the Higgins Armory library. A Powerpoint presentation was made by each group member and they were presented at a group meeting.

The goal of exploring the existing armor database was two-fold and included both making suggestions as to how it could be improved and the generation of new content for it by looking in books, collection catalogues, art books, and on the web. In terms of improving the database, the team determined that the existing format (Microsoft Access) was too difficult to work with and suggested that the data be transferred into a MySQL database. Furthermore, the team started using a wiki to coordinate the group's research activities. We thought about placing the existing database into the wiki format because the wiki format is easier to use. The team also considered pursuing the creation of the wiki site as the final interactive deliverable of the project, but discarded the idea by the middle of the second term. With respect to content generation, a respectable amount of database worthy content was found in the web sources and the art books. Unless one was visiting a high-quality museum's website, such as the Metropolitan Museum of Art, the free web was found to be an unreliable source on armor.

The major component of the first term of the IQP was the composition of each member's research documents. Each week the team was supposed to perform research on the topics listed for that week in the plan of work and then submit a write-up to Prof. Forgeng for editing. The idea was for a constant cycle of drafts and revisions to occur between each team member and Prof. Forgeng. However, by the end of the term, only the biomechanics topic was close to lining up with the plan of work. Work had been done on the other three topics, but the work was a few weeks behind the original project plan of work.

Near mid-term, an artifact handling session was conducted to prepare the team for the hands-on component. Near the end of the first term, the team began looking through the catalogue of the museum's harness to choose a harness for the hands-on component. The team wanted to examine a full harness, but it was hard to find a full harness in that hadn't already been thoroughly studied or was not on tour. It seemed that most of the harnesses in the catalogue were ¾ or ½ harnesses. The team eventually found a few candidate harnesses and chose Harness 429 because it had not been thoroughly studied and was the most convenient to pull out of storage.

The second term of the IQP consisted of finishing the previous term's research documents and the hands-on investigation of Harness 429. In terms of the research documents, more progress was made on all of the major topic areas. By mid-term, the research for the biomechanics section was complete and the physics of armor section was not far behind. Only a little more progress was made on the armor manufacturing and armor collecting areas. The highlight of the second term was the rare opportunity to handle historical artifacts. Each week a two-hour meeting was held to investigate Harness 429 component by component. Each team member took notes on his/her respective harness components and took lots of photos of each of them. Prof. Forgeng was very helpful in pointing out details of the armor that may have otherwise been missed. Midway through the term, the existing database-to-wiki idea of a final deliverable was abandoned in favor of producing a video of our investigation of the harness. Due to the limited amount of time left in term and the upcoming term, it was decided that the video would be component based in that each piece would be filmed with the interesting features pointed out and narration added later. The team came together by the end of the term and produced a draft of the storyboard for our video and the armor component investigation was pretty much finished as well.

The final term of the IQP consisted of filming Harness 429, editing the video, and compiling the project report sections into a cohesive entity. Early in the term, all the raw footage of the harness components was collected using a Sony MiniDV camcorder borrowed from the WPI ATC. We decided to film the harness stop motion style being assembled on a mannequin in the proper order: from toe to head. While on the mannequin, the harness was photographed and filmed from various angles. The video was edited in the following weeks using Adobe Premier Pro. The raw footage was cut into manageable clips and relevant sections were stitched together to form the final video. The audio recording program, Audacity, was used to capture the narration for the video. Write-ups on the most important findings of our investigation of the harness and the suggestions for the improvement of the existing database were made. The introduction of the project proposal was reworked to form the project report introduction and the conclusion section was written. The abstract, table of contents, and works cited were added in to form a final compiled project report.

Overall, this IQP was a unique experience and much was learned from it. It isn't every day that one gets the opportunity to handle historical artifacts and to use resources from a collection as unique as that of the Higgins Armory Museum. We learned how large of a commitment a project such as this IQP requires. Some aspects of the project flowed smoothly whereas other parts were less graceful. The group got along well with each other and there weren't any group dynamics problems. One suboptimal aspect of the team's performance was that we had some difficulty in scheduling weekly meetings: both amongst ourselves and with our advisor. This usually resulted in the team starting the term's work a few weeks behind and thus deviating ever more from the plan of work. It also felt like the team's progress had stagnated at certain times during the project. At some points, Prof. Forgeng could not believe how far behind the team had become. He let it be clear that his responsibility was to point us in the right direction and provide us with meaningful feedback on research drafts and that it was our responsibility to schedule meeting times amongst ourselves and perform the work. The museum's limited open hours also made it somewhat difficult for research to be done in its library. Although some sections of the four main research topics didn't get written, the team did pull through for the most part.

Throughout the course of the project, we pursued some routes that we ended up not following anymore. Therefore we have several suggestions for future project teams:

- For the investigation of Harness 429 in particular, a future team could focus its research specifically on the determination of where each of the components came from and their specific year of origin or modification. Future teams could also investigate the variety of etchings on the harness and elaborate on the irregularity of its decoration.
- In terms of the physics of armor's protection component, a future team could expand upon the research we began to include models of more of the weapons of the day. We wanted to test actual samples of sheet steel, but did not have the time or the preparation to do so. A future team could perform such tests or even carefully examine the material properties of the metal in the historical artifacts. Such research could also supplement an investigation of the manufacturing process for plate armor.
- For the biomechanical and functional aspects of wearing armor, various experiments were planned, but never carried out due to time constraints and organizational difficulties. We

wanted to perform experiments involving physical activities such as climbing stairs, jogging, and getting up from the ground both with armor on and without it. A future team could probably perform such experiments as well as examine other areas such as heat exchange through armor, how armor affects one's range of motion, armor's effect on respiration, and the effects of a helmet's style on one's field of view.

- In the functional aspects section of our report, modern body armor was used to provide a context for further investigation into medieval armor. A future team could expand upon that concept to draw parallels and point out differences between each body armor type with respect to their historical and technological contexts. Another possibility is the investigation of the scientific tools and models used by modern armor manufacturers.
- A future team could transfer the existing database into a MySQL database to make it easier for the average user to operate. Also, much more information and pictures could be added to the database. The entire database could also be converted into a wiki format. The wiki format is easy to use and edit.
- A future team could produce a video on the construction of plate armor: from the mine to the finished harness. The team could contact modern practicing armorers to gain better insight into the craft.

In terms of the course of the project, the team believes that future teams would benefit from earlier access to and handling of the historical armor artifacts. We also believe that forming a strong background in the historical contexts of plate armor is fundamental to any investigation of the components later on. To start out with, books by Blair and Edge and Paddock are excellent choices. We found that it became easier to understand more about the history of plate armor once we actually handled the parts of Harness 429. In terms of project organization, some of the most important considerations are clearly defined goals and good communication amongst the team. Also it is good to ask the advisor questions and bring up concerns whenever the team is unsure of how to proceed rather than wait till later on because less time and energy will be wasted in the long run.

Figure 29: The Authors (Left to right: Ryan Meador, David Sansoucy, HAM 429, Caroline Mallary, Eric Van Dyke,

About the Authors

About the Authors

Caroline Mallary

Caroline is a graduating Physics major. Her attentiveness to the physical model helped to present an important perspective on the analysis of armor.

Ryan Meador

Ryan is an Electrical and Computer Engineering major, expecting to graduate in May 2007. His interest in photography and digital media led him to be a part of this IQP.

David Sansoucy

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Appendix

Investigation into the Existing Armor Database

Overview of Database Technology

Nearly all modern databases fall under the category of "relational databases", which simply means that they store tables of information. The columns of the tables are the different attributes of a record, and each row is an individual record. In a well-designed database, every table will have a column or set of columns designated as the *primary key*, which means that for each record, the value in the column(s) must be unique. The primary key is a way of uniquely identifying a particular row. The "relational" part of "relational database" comes into play when one considers that a column in one table might contain a reference to a primary key in another table. Such a column is known as a *foreign key*. Foreign keys provide a means to associate records in different tables with each other. With attributes of a record that are columns, there can only be one value of that type for each record. For example, a table with the columns "name" and "phone number" would be able to store peoples' names and phone numbers. But what if someone has more than one phone number? The solution is to break the table into two tables. One table will be a primary key (usually an integer) and the name field, the other table will be a foreign key and the phone number field. Thus, you can associate two phone numbers with the same foreign key value, which in turn will associate them both with the same name.

ID (primary key)	*Name*
0	Ryan
1	Eric
2	Dave
4	Caroline

ID (foreign key)	*Phone Number*
0	123-456-7890
0	234-567-8901
1	345-678-9012

In the above example, Ryan has two phone numbers associated with him, Eric has one, and Dave and Caroline both don't have any phone numbers.

The language one uses to communicate the table structure and data to the database, as well as to perform queries on the database, is known as Structured Query Language (SQL). A full discussion of SQL is far beyond the scope of this document, but it is a simple enough language so that with a bit of knowledge, it reads almost like English. The most important aspect of SQL to understand for the purposes of this document is the SELECT statement. A SELECT statement is the command used to retrieve information from the database. It consists of the word “SELECT” follow by the list of columns one wants to retrieve, the table to retrieve them from, and an optional condition that must be satisfied in order for the row to be returned. For an example of the condition, consider a table with a column that stored the year an artifact was produced. The condition could be “year < 1600” to retrieve only information about artifacts manufactured prior to 1600. When working with records that have data spread across multiple tables, as in the foreign key example above, an additional clause known as a JOIN clause is used to instruct the database to also include relevant data from other tables. The graphical interface of Microsoft Access takes much of the “pain” of writing SQL out of the process by allowing the user to choose options off of menus, but it also takes away nearly all of the expressiveness of the language. Behind the scenes, Access is using SQL, and it is possible to expose those details through the user interface if you find the appropriate control panels.

Description of the Current Database

The current database resides in a Microsoft Access file and an accompanying folder of images. There are a number of tables in the databases, many of which have no apparent function. Some of them seem to be a rudimentary form of keyword matching, which groups certain terms together by relatedness (this is especially evident in the table that has all the geographical information in it). Few, if any, of the database tables contain primary keys (as explained earlier, a primary key is necessary to uniquely identify a record; without one, it is impossible to edit a record and be 100% sure you aren't actually editing multiple records). The artifacts in the database are uniquely identified, however, but not through the built-in protection a primary key affords. The unique value is the file name of the image the record is about. The dialog boxes used to insulate the user from the SQL queries are poorly made. Not only do they look bad, but they are only partially functional. The queries they internally perform are ludicrously inefficient and often accomplish their goal through techniques that will no longer work if any significant change to the database is made. For example, the primary artifact search query performs a JOIN operation on itself at least four times. There is absolutely no need for this, as a

JOIN is only relevant when it is between tables, and if the columns being joined in this manner are changed, the query will fail.

Microsoft Access' number one achilles heel is scalability. This means that as more entries are added to the database, it becomes increasingly difficult to maintain it. Also, as more users work on the database, it becomes nearly impossible to keep all the changes synchronized (with everyone changing their own copy of the database file, it's impossible to automatically merge the changes), as Microsoft Access does not easily lend itself to a multi-user environment. It is entirely possible to set up such a system, however, and many companies do just that despite the drawbacks. Microsoft Access is widely regarded as a “toy” database for quick-and-dirty small projects or for use by the non-computer saavy. It should be noted, however, that of all the products in Microsoft Office, Access is probably the most difficult to use, meaning that a user capable of using Access doesn't have to make much of a leap to be able to use a more advanced solution.

It is also worth noting that Access costs a large amount of money as part of Microsoft Office. For anyone who doesn't get Office with their computer or through WPI's CCC, it will be prohibitively expensive for them to purchase it on their own. Access is also (ironically, considering its name) unavailable for non-Windows operating systems such as Linux and Mac OS.[201]

Proposal for an Improved System

An improved system would embody a number of things:

- Centralized storage, so there's only ever one copy of the database that all users work with simultaneously
- A database engine that supports full SQL and executes queries more efficiently

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201 http://en.wikipedia.org/wiki/Microsoft_Office

- A fully functional user interface for adding entries as well as searching and viewing them
- A database table design that is understandable and easily extensible (for future changes)

An example setup that meets the above criteria would be the omnipresent “LAMP” server setup: Linux, Apache, MySQL, PHP. This means simply that there is an internet-connected computer (exposed to the outside world via the firewall) somewhere running Linux, with the Apache web server, a MySQL database server, and PHP software for the user interface. PHP and Apache work together to produce dynamic web pages. The user interface would be through a web browser. The MediaWiki software that our IQP group investigated is exactly this. MediaWiki is a program written in PHP that is intended to produce easily-edited web pages with the data stored in a MySQL database. We used this wiki technology quite successfully, but it was deemed too informal for a final project. A large number of ready-to-use plugins exist for the MediaWiki software, permitting it to be expanded to do nearly anything (Wikipedia is the classic example).

Any reasonably modern desktop computer (even one that is a few years old) could be converted into a LAMP setup for zero cost and approximately 2 hours of time by a knowledgeable person. It would then just be a matter of creating or installing a suitable user interface, copying the existing Access database into the new system. To achieve a fully automatic copy, some programming would be required both for the conversion to the new database, probably by exporting it from Access as CSV (Comma Separated Values) and then doing an import on the new database, which would likely have been redesigned to a more sane structure, and would require a mildly intelligent program to rearrange the data. A user interface would also need to be written in a language such as PHP to provide a friendly way to access that information once it is in the new system. Using a ready-made solution like a wiki removes the burden of creating a user interface, but adds the workload of adding all the current database entries by hand, as it would be very difficult to create (and impossible to find ready-made) a way to convert the Access database into a wiki as an automated process. This may sound like a lot of work, but for a reasonably experienced web developer, it would only take a few hours and the benefits could be reaped for years to come in terms of increased productivity and usefulness.

Plan to Implement Keyword Search Functionality

The current database provides no method of associating multiple keywords with an object, so searching by keyword is a very hit-or-miss proposition. An improved implementation would add two new tables to the system. The first table would be an integer primary key and a keyword, and the second a table that maps between artifact entries and keywords by use of a foreign key for each. Much as the phone number example at the beginning of this document, multiple keywords would thus be able to be associated with a single artifact entry. The reason the phone number example used only one extra table and this uses two is purely to save space; if only one table were used, many keywords would be redundantly stored in it. That isn't a problem for phone numbers, as there's a reasonable expectation that they are unique.

Once such a system were in place, searching for a single keyword would be a matter of retrieving the desired keyword's ID (primary key) through a SELECT statement, then using that value in another select statement on the keyword map table to find the ID's of all the relevant artifacts. The artifact ID can then be used in a SELECT statement to get the details of each artifact. Note that it is possible (and, in practice, one would never do it any other way) to condense these three operations into a single SELECT statement by use of two JOINs. Searching based on multiple keywords would require a sub-SELECT, which is beyond the scope of this document, but fairly easy to learn from web-based tutorials.

Conclusion

It is both highly desirable and relatively painless to replace MS Access with a more robust database solution that will make the database more accessible to a larger number of people and also will scale well with future changes that may be desired. Assuming an old computer can be found for free and someone donates their time, the conversion would cost no money (it can be accomplished entirely with free software). A switch away from MS Access would bring the artifact database in line with the standards currently in use with commercial database.

Recommended Reading

- www.mysql.com -- To learn more about SQL, relational databases in general, or the MySQL database software in particular, including tutorials on how to set up a database, this website is a comprehensive reference.
- www.php.net – Home page of the PHP programming language, potentially useful for creating a user interface to a custom artifact database system. Also the language used by WikiMedia to create their famous MediaWiki software.
- www.linux.com – A good guide to linux in all its various forms. Includes tutorials (HOWTO's) that will get even a beginner up and running with a LAMP setup.
- http://www.kitebird.com/articles/access-migrate.html – A discussion of reasons MySQL (or any true database) is better than Access in different situations and advice on how to convert data between an existing Access database and a new MySQL database.

Web Sources (David Sansoucy)

There are a multitude of websites that come up when one simply Google searches armor, "Medieval armor", full plate armor, and similar terms. Many of them are for companies that specialize in the production of replication armor based on real artifacts for use in movies, TV shows, re-enactments, and for other modern day uses of medieval armor. In general, most of the dates for modern-day replicate harnesses and pieces are broad, such as "17^{th} century armor". While these sites contain nice photos and such, the accuracy of the photos and their associated caption may not be as high as photos of pieces found in museum collections which are available on the internet. It didn't take long to figure out that the best way to obtain quality pictures of armor with accurate descriptions was to search the websites of well-known museums. Various museums such as the Metropolitan Museum of Art, the Art Institute of Chicago, the Art History Museum in Vienna, and the Royal Armouries at Leeds Museum showcased some of their harnesses and armor pieces. Data and pictures were collected for about thirty artifacts and most of the pictures were in color and of good quality.

One stand-alone website, linked to from Wikipedia, was a large picture of a poster made by Dr. Alan Williams. The poster contained research into the metallurgical aspects of plate armor and a good black and white picture of full plate armour from around 1500. Since the author of the poster was Dr. Alan Williams, the data can be assumed to be credible.

Thirteen photos were obtained from the website of the Metropolitan Museum of Art in New York City. The photos were of a selected number of museum artifacts and there were informative descriptions for each picture. The photos were in color and of high resolution. On the website, there was an interactive Zoom In/Out and Move View feature that allowed closer inspection of the artifact without sacrificing the high quality of the picture. The majority of harnesses photographed for the website were the complete originals and only a few have had modern parts added. In the descriptions, there was good height, length, and/or weight information concerning most of the artifacts as well as credible information concerning the armorer who made the artifact. The majority of date ranges were more accurate and of a smaller range than would be found in less credible sources.

Five photos were obtained from the Art Institute of Chicago website. The website contained good pictures of certain selected artifacts. There were informative descriptions and good date ranges for each artifact. There was only one artifact (the ¾ harness) that didn't have a given date range. There was good height or length information for most of the artifacts, but not too much about the particular armorers who made the artifact.

Ten photos were obtained from the Kunsthistorisches (Art History) Museum in Vienna website. Overall the museum had good color pictures of its selected armor artifacts. There were brief, informative descriptions and good date ranges for each artifact. Good height or length information also accompanied most of the artifacts.

Five photos were obtained from The Royal Armouries at Leeds Museum website. The site contained a few high quality photos, but a very brief description accompanied each photo. There was also no sign of the armor's physical parameters such as its weight, length, and/or height in the description.

One notable observation that was made was that the Wallace Collection website did not contain any useful pictures of any of the harnesses or other armor pieces in their collection. This was a little bit surprising because of how well-established the Wallace Collection is in terms of arms and armor.

In the course of searching the web for credible sources, people's individual websites and "collections" of armor were sometimes found. In these websites, people typically posted photos that were taken from various museum trips or other experiences involving plate armor. The credibility of the information in some of the captions that accompanied the pictures is hard to gage, as such depends heavily on what type of person actually took the photo. In terms of the actual photos, some of the individually-made ones were not of as high quality as the ones displayed on the various museum websites listed above.

Overall, the web is generally not a reliable source when it comes to finding good pictures of armor artifacts that have credible accompanying information. This observation is especially true because when one searches the web, the websites of the aforementioned museums are seldom at the top of the search list. Therefore, unless one already knows specifically what museums' sites to look for or can find another site where a series of links to those museums exists (such as with the Higgins Armory site under the "Research Resources" page), the chances of finding credible information from the web are not very good. Good photos and credible descriptions are definitely out there, but are generally hard to come by. One thing to keep in mind is the time when this research took place because the websites of some of the aforementioned museums may have changed since then. The investigation into web resources for plate armor was conducted in mid-November of 2006.

Project Proposal

During the course of *The Classic Suit of Armor,* a survey of the historical evolution of plate armor from its origins in the fourteenth century to its decline in the late seventeenth century will occur. The Higgins Armory Museum houses over one hundred complete suits of armor, as well as nearly a thousand single pieces that demonstrate the evolution of armor from Greek helmets of the ancient era to ornate full harnesses of the 1600s and the eventual decline of armor as new firearms emerged. This project will build upon the combined efforts of "The Classic Suit of Armor," a project pursued by two previous IQP research teams. During this project, our team will examine the main points of existing research in more detail, and expand into further areas of research. Particular focus will be paid to the history of armor collecting, manufacturing process, biomechanics, the physical properties and fashion of armor, and their respective historical contexts. The team will also examine an individual (as yet undocumented) suit of armor of the Higgins collection in detail, and place it in historical context.

Initially, body armor was developed in order to defend against the blows of hand-to-hand combat. One type of body armor was essentially a robe made up of small interlocking chain, links known as mail armor. Over time, armor evolved into full suits of plate steel that provided the wearer with impressive protection. However, the more efficient training of infantry, combined with the necessity for increased mobility, caused the bulky, restrictive suits to be left behind. As more powerful weaponry came into play, the popularity and appeal of armor dropped significantly, and eventually armor became obsolete. Today armor is largely a collector's item.

Armor collecting actually began in the late Middle Ages--about the time that armor was no longer being used for its intended purpose: protection in battle. The collected pieces were largely armor passed down through families and descendants of the original wearer. Many of these were later acquired by royal houses for political reasons and as status symbols, and some eventually found their way into private collections. The suits were often refashioned together from mismatched parts before being sold to new owners. Armor purveyors sold these composites to increase revenue because full suits of armor fetch higher commissions. For this reason one of the difficult jobs of curators is to determine which parts are original. Today museums own the vast majority of the world's remaining European, armor with the Higgins Armory Museum as one of the premiere arms and armor museums in the United States.

Before one can understand the historical context of armor as a defense mechanism and later, a fashionable symbol, one must first understand how the armor was created. Plate armor was manufactured by skilled craftsmen and artisans in trade organizations called guilds. The guilds provided both training and economic protection similar to today's workers' unions and became the focus for armor output.

Manufacturing methods of armor progressed in order to meet new demands and take advantage of new materials and technologies. These demands sprung both from new military realities and client desire for impressive armor. The evolution of armor manufacture will be studied in depth including advancements in the knowledge of metallurgy, metal shaping, and movement with respect to human anatomy. It can be said that given the technology of the time, the production of high-quality plate armor stands as an impressive accomplishment. This project seeks to document the changes in armor production and the trip a typical suit took from the ore mine to the owner (and ultimately, the museum).

The biomechanics of wearing armor will be investigated in depth with regards to protection provided to the wearer, mobility, and overall comfort. Consideration will be given to how the armor was constructed to fit the user's unique form and how the body naturally moves. The team will expound upon the effects on vision, breathing, heat exchange and mobility during battle. It can be said that the creation of metal plate armor conforming to a person in motion during battle was a considerable feat.

Both the form and function of armor will be examined during this research project to further understand their concurrent evolution. Plate armor grew from previous armor styles in response to the battle style and offensive weapons of the day. Plate armor later became a decorative status symbol for the wealthy and influential. The form and function of armor was dictated by both advances in manufacturing methods and materials as well as concurrent evolution of weaponry and military tactics. In addition, as customers became more obsessed with high quality armor as a status symbol, intricacy, detail, and uniqueness supplanted durability on the battlefield. The team will document a historical timeline treating functional and decorative changes.

The Higgins Armory Museum collection contains many suits of armor that have never been thoroughly studied. The core of this IQP project will be examining one of these suits in detail. The team will endeavor to determine where and when it was manufactured, and if possible, by which armorer. The team will also attempt to determine if all the pieces in the suit were intended to go together or if the suit has been created piecemeal from other suits. We will attempt to find and document modern restorations of the armor and paths of ownership. This valuable information will then be compiled into a final comprehensive document and be used to develop some useful internet presence. The scope of other deliverables including museum armor database entries and multimedia will be assessed by the team at a later time.

Term 2 Plan of Work (B Term)

"The first term's work will usually flesh out the background research begun in the PQP and write up the general documentation on the subject. Plan on at least 2 submitted drafts of any text, plus an integrated full draft of all texts at the end of term. By the end of the term the team should also have drafted its provisional plans for the format of the final product, including architecture and sample components (e.g. webpage layout, animations). During this term the team will also receive orientation on artifact handling protocols at the museum. By the end of the term, the team will need to have identified the technical resources it will be using to fulfill the next term's work (e.g. cameras), and obtain the training it needs to use them".202

1. **Week 1**
    a. *Team*
        i. Goals
            1. Gain a preliminary understanding of the chronology of armor.
                - Early Armor 1350s - 1550s.
                - Late Armor 1550s – 1650s.
            2. Gain a preliminary understanding of historical and social context of armor.
            3. Gain preliminary understanding of manufacture and use of armor.
            4. Organize research information and prepare to present findings to the team.
        ii. Resources
            1. Blair, Claude. (1972). *European armour* circa *1066 to* circa *1700*. London: B.T. Batsford, Ltd., 1958; 2nd ed. New York: Crane, Russak and Co.
                - Detailed descriptions
                - Good for researching our suit of armor since it includes drawn-out discussions of particular designs
                - Key source
            2. Blair, Claude, and Leonid Tarassuk, eds. (1982). *The Complete Encyclopedia of Arms and Weapons*. New York: Simon and Schuster.
                - Names, history, and pictures of arms and weapons are included in this book.
                - Explains who used what type of weapon and where they used it.
                - Contains detailed info on swords, spears, axes, lances, bows, etc.

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202 Forgeng, Jeffery. "Higgins Armory Museum PQP/IQPs: Prospectus for Students." Worcester Polytechnic Institute. 2006.

3. Edge, David and Paddock, John. (1988). *Arms and armour of the medieval knight*. Greenwich, CT: Crescent Books.
    - Thirteenth to sixteenth century history of armor
    - Good illustrations
4. Morrison, Sean. (1963). *Armor*. New York: Thomas Y. Crowell Company.
    - Not a lot of pictures
    - Not very specific
    - Easy reading and good for a quick overview
5. Pfaffenbichler, Matthias. (1992). *The Armourers. Medieval Craftsmen Series.* Toronto: University of Toronto Press.
    - Describes how the armorers had their own unique design for the pieces they created
6. Stone, George Cameron. (1961). *A glossary of the construction, decoration and use of arms and armor in all countries and in all times, together with some closely related subjects.* New York: Jack Brussel Pub.
7. A weapons and armor dictionary.

iii. Deliverables
1. Draft of oral report and presentation.
2. Updated annotated resources.

b. *Ryan Meador*

i. Major areas for study
1. Gain a preliminary understanding of the historical and social context of armor.

ii. Goals
1. Prepare group oral presentation

iii. Resources
1. General resources (above)

c. *Eric Van Dyke*

i. Major areas for study
1. Context of manufacturing
2. Gain preliminary understanding of manufacture and production of armor.

ii. Goals
1. Gain working knowledge of above focus area
2. Prepare group oral presentation

iii. Resources
1. General resources (above)

d. *David Sansoucy*

i. Major areas for study
1. Investigation of Post-Maximilian era armor to the decline
2. The reasons for the decline of armor in the late 1650's

ii. Goals
1. Gain working knowledge of above focus area
2. Prepare group oral presentation

iii. Resources
1. General resources (above).

e. *Caroline Mallary*

i. Major areas for study
    1. Evolution of plate armor from the rise of plate armor to the early 1500s
        - Investigation of rise of plate into the Pre-Maximilian era
        - The reasons for the rise of plate armor

ii. Goals
    1. Gain substantial knowledge on above focus area
    2. Begin making a presentation for the rest of the group

iii. Resources
    1. General resources
    2. Edge and Paddock. *Arms and armour of the medieval knight.*
    3. Stone. *"A glossary of the construction, decoration and use of arms and armor in all countries and in all times, together with some closely related subjects."*
    4. Art books: Possible sources: Libraries of WPI, Higgins, Holy Cross, Assumption, Clark, Worcester Public

2. **Week 2**
    a. *Team*
        i. Goals
            1. Make oral presentations to the team on the four main bodies of information. Workload and research will be divided between team members. This discussion gives the opportunity to present preliminary research in general areas. The divisions are as follows:
                - Ryan: Historical context in which armor was developed
                - Caroline: Evolution of plate armor into the mid 16th Century ("early armor")
                - David: Evolution of armor until its decline ("late armor")
                - Eric: Manufacturing overview.
            2. This discussion will summarize the existing scholarly research in major areas.
        ii. Resources
            1. General resources (above).
        iii. Deliverables
            1. Group oral report (2 hour meeting minimum)
            2. PowerPoint presentations
    b. *Ryan Meador*
        i. Major areas for study
            1. Historical context
        ii. Goals
            1. Finish researched
            2. Give oral report
        iii. Resources
            1. General resources (above)
    c. *Eric Van Dyke*
        i. Major areas for study
            1. Context of manufacturing
            2. Gain preliminary understanding of manufacture and production of armor.
        ii. Goals
            1. Gain working knowledge of above focus area
            2. Prepare group oral presentation
        iii. Resources
            1. General resources (above)
    d. *David Sansoucy*
        i. Major areas for study
            1. Post-Maximilian era evolution of armor
                - The changing styles and decorations
        ii. Goals
            1. Finish introductory research
            2. Finish and present topic presentation to rest of group
        iii. Resources
            1. Ashdown, Charles Henry. (1967). *European arms and armour*. New York, NY: Brussel & Brussel.

2. Extensive information about evolution of armor
    - Old source; first published in the 1800s
3. Blackmore, Howard L. (1965). *Arms and armour.* London: Studio Vista.
    - Information on early plate armor with illustrations
    - Follows evolution/decline of armor

e. Caroline Mallary

i. Goals
1. Find specific suits that exemplify evolution (making case for reasons for change.)

ii. Deliverables
1. List of typical & atypical suits by era and geographical origin.
2. Possible map or ImageReady animation.
3. Make presentation

iii. Resources
1. John Woodman Higgins Armory. (1961). *Catalogue of armor: The John Woodman Higgins Armory.* Worcester, MA.
    - Catalogue of armor for the Higgins Armory.
2. Hammond, P. T. (1986). *Royal Armouries: Official guide*. London.
    - Trustees of the Royal Armouries with Philip Wilson Publishers. The official guide to the Royal Armouries in London.
3. Nickel, Helmut. (1991). *Arms & Armor from the Permanent Collection*. New York: Metropolitan Museum of Art.
    - Pictures of arms and armor from the Metropolitan Museum of Art.
    - Tells where each arm or armor was acquired and where they were used in Europe and in which period of time.
4. Ffoulkes, Charles John. (1916). *Inventory and survey of the armouries of the Tower of London.* London, H.M. Stationery off.
    - Inventory and information on the London armouries.
5. Stone. *"A glossary of the construction, decoration and use of arms and armor in all countries and in all times, together with some closely related subjects."*
6. Karcheski, Walter J., Jr. (1995). *Arms and Armor in the Art Institute of Chicago*. Boston: Bulfinch Press.
    - Basic categorical listing of the arms and armor acquired by the Art Institute of Chicago.
    - Dates, brief backgrounds, and pictures of most items.

3. Week 3

a. Team

i. Goals
1. Develop armory database hands on.
2. Become familiar with existing information databases and make contributions.
3. Evaluate existing IQP database structure.
4. Consider data structure modification (i.e. don't use Microsoft Access!)
5. Team to discuss final product.

ii. Resources
1. General resources (above)
2. Databases
3. Journals
4. Web
5. Museum catalogs
6. Art books
7. Blair. *European armour* circa *1066 to* circa *1700*.

iii. Deliverables
1. Preliminary discussion of final product.
2. Significant contributions to databases.

b. *Ryan Meador*

i. Major areas for study
1. Database

ii. Goals
1. Persuade the team to abandon MS Access and provide preliminary plan to smooth transition
2. Add to existing database in the interim.

iii. Resources
1. Trapp, Oswald. Translated by James Gow Mann. (1929) *The Armory of the Castle of Churburg*. London : Methuen & Co. Ltd.
2. *Royal Armouries Yearbook*. Volume 1. (1997) Royal Armouries Publications.

c. *Eric Van Dyke*

i. Major areas for study
1. Database development

ii. Goals
1. Make significant contributions to existing database resources

iii. Resources
1. Williams, Alan.
2. Ffoulkes, Charles F. (1912). *The armorer and his craft.* London: Methuen & Co. Ltd.
3. Blair.
4. Edge & Paddock.

d. *David Sansoucy*

i. Major areas for study
1. Database development

ii. Goals
1. Evaluate the existing database
2. Contribute to the new database

iii. Resources
1. Existing Database
2. Web sources (to be determined)

e. *Caroline Mallary*

i. Goals
1. Find suits where physical data like thickness is available.

- Based on abundance of data, refine focus of physical study (e.g. if there is most data on armor of 1600s, plan to make more study of guns from that era.)

ii. Deliverables

1. List of suits or time periods with adequate data.

iii. Resources

1. Higgins database
2. General resources
3. Blair. *European Armour* circa *1066 to* circa *1700*.
   - Detailed descriptions
   - Drawn-out discussions of particular designs

4. Week 4

a. Team

i. Goals

1. Begin in-depth research on individual topics.
2. Orientation and preparation for artifact handling, documentation, and inspection.
3. Each team member will choose one candidate suit (before this meeting).
4. A specific suit of armor will be agreed upon (during this meeting).

ii. General resources

1. See individual sources.

iii. Deliverables

1. Four subdocuments on weekly areas of study
2. Written discussion of reasoning for suit choice.

b. Ryan Meador

i. Major areas for study

1. Research general context of knights and chivalry.
2. Armor as a symbol of knighthood and chivalry – gives the collection its appeal

ii. Goals

1. Gain working knowledge of above focus area

iii. Resources

1. General resources (above).
2. Ross, James Bruce and Mclauglin, Mary Martin, eds. (1955). *The portable medieval reader*. New York: Viking Penguin Inc.
   - Contemporary writings
   - Good social context source
3. Barber, Richard. (1974) *The Knight and Chivalry*. New York.

c. Eric Van Dyke

i. Major areas for study

1. Armorers
   - Training
   - Skill sets
   - Royal armorers
     i. Few, high quality suits

- Military armorers
    i. Mass production
    ii. Interchangeable parts
- Role in society
- Role in chivalry

2. Famous/important armorers and guilds
3. Famous/important suits of armor made by specific armorers

ii. Goals

1. Finish introductory research
2. Finish and present topic presentation to rest of group

iii. Resources

1. Williams, Alan.

d. *David Sansoucy*

i. Major areas for study: Vital human anatomy

1. Important human anatomy
    - Important body zones
        i. Head
        ii. Visceral region
        iii. Chest
    - Associated vulnerabilities of the body zones
        i. Internal organs
        ii. Blood vessels
        iii. Tissues
2. Areas where natural protection may be lacking
    - Under arms
    - Visceral region (abdomen)

ii. Goals

1. Understand the vital body zones and why they need protection

iii. Resources

1. Behnke, Robert S. (2006). *Kinetic anatomy.* Champaign, IL: Human Kinetics.
2. Easterby, Ronald, et al. (1982). *Anthropometry and biomechanics: theory and application.* New York: Plenum Press.
3. Erven, Lawrence W. (1976). *Handbook of emergency care and rescue Revised Edition.* Beverly Hills: Glencoe Press.
4. Leonard, Robert J. (1995). *Human gross anatomy [electronic resource]: an outline text.* New York: Oxford University Press.
5. Marieb, Elaine N. (2005). *Anatomy and physiology 2nd Edition.* New York: Pearson Benjamin Cummings.
6. Marshall, Robert. (2001). *Living anatomy: structure as the mirror of function.* Victoria: Melbourne University Press.
7. Netter, Frank H. (1989). *Atlas of human anatomy.* Summit, N.J.: CIBA-GEIGY Corp.
8. Spence, Alexander P. (1986). *Basic human anatomy.* Menlo Park, CA: Benjamin/Cummings Pub. Co.

            9. Tortora, Gerard J. (1989). *Principles of human anatomy*. New York: Harper & Row.
    e. *Caroline Mallary*
        i. Goals
            1. Obtain good data on various weapon types and how they were used.
            2. Focus on those weapons most prevalent at era determined by Week 3B's research, and those likely to do the most damage.
        ii. Deliverables
            1. Short write-up and data ranges for weapons to be addressed.
        iii. Resources
            1. Internet sources
            2. Library-order resources: e.g. books on the *Mary Rose*, Henry the VIII's flagship, which was raised in 1982 and on which many wooden parts of weapons were preserved.
            3. Oakeshott. (1980). *European Weapons and Armor.* Beinfeld Publishing Inc.
                - Various weapons descriptions
            4. The John Woodman Higgins Armory Museum, Catalogue of Armor. 1961
                - Pieces featured are accessible.
            5. Stone. *A glossary of the construction, decoration and use of arms and armor in all countries and in all times, together with some closely related subjects.*
            6. Blair and Tarassuk. *The Complete Encyclopedia of Arms and Weapons*.

5. **Week 5**
    a. *Team*
        i. Goals
            1. Perform preliminary hands-on interaction with the suit of armor including detailed documentation.
            2. Continue individual research.
            3. Discuss suit first impression.
        ii. General resources
            1. Artifacts.
        iii. Deliverables
            1. Four subdocuments on weekly areas of study.
            2. Written discussion of first impressions of the suit.
    b. *Ryan Meador*
        i. Major areas for study
            1. Early armor collecting
        ii. Goals
            1. Finish introductory research
            2. Give group oral presentation
        iii. Resources
            1. *Castle Churburg Armory* <www.churburg.com>.
            2. Churburg Catalog
    c. *Eric Van Dyke*
        i. Major areas for study
            1. Guilds

- Guild structure
- Economic protections
- Legal regulations of guilds
- Quality of work/quality control
- Important guild locations (armor centers)
- Location in terms of proximity to raw materials

2. Similarities to modern workers' union structure

ii. Goals

1. Understand social context of guilds and armorers

iii. Resources

1. Williams, Alan.

2. Ffoulkes, Charles F. (1912). *The armorer and his craft.* London: Methuen & Co. Ltd.

d. David Sansoucy

i. Major areas for study: Human body parameters

1. Investigate the average historical body characteristics

- Height
- Weight
- Build
- Mass distribution
- Senses
    - i. Vision
    - ii. Hearing

2. Physiological processes

- Breathing
- Heat exchange

3. Examine basic human physical abilities and limits

- Locomotion
    - i. Walking
    - ii. Running
    - iii. Climbing
    - iv. Balance
    - v. Horse riding
- Lifting loads
    - i. Average strength required to do certain tasks
    - ii. Sustained loading conditions (endurance)
- Rotational motion
    - i. Throwing and swinging objects
    - ii. Generation of torque
- Flexibility
    - i. Range of motion

4. Discussion of biomechanics

- How the discipline can be applied to armor research

ii. Goals

1. Understand human range of motion and physical abilities

iii. Resources

1. Bassett, Steven E. (2005). *Anatomy & physiology [electronic resource].* Hoboken, N.J.: Wiley.
2. Behnke. *Kinetic anatomy.*
3. Burton, R.F. (2000). *Physiology by numbers [electronic resource]: an encouragement to quantitative thinking.* Cambridge, UK; New York: Cambridge University Press.
4. Easterby. *Anthropometry and biomechanics: theory and application.*
5. Frievalds, Andris. (2004). *Biomechanics of the upper limbs: mechanics, modeling, and musculoskeletal injuries.* Boca Raton, FL: CRC Press.
6. Kreighbaum, Ellen. (1996). *Biomechanics: a qualitative approach for studying human movement.* Boston: Allyn and Bacon.
7. McArdle, William D. (2001). *Exercise physiology: energy, nutrition, and human performance.* Philadelphia: Lippincott Williams & Wilkins.
8. Ozkaya, Nihat, et al. (1999). *Fundamentals in Biomechanics 2nd Ed.* New York: Springer.
9. Spence. *Basic human anatomy.*
10. Winter, David A. (1979). *Biomechanics of human movement.* New York: Wiley.
11. Winter, David A. (1991). *The biomechanics and motor control of human gait: normal, elderly and pathological.* Waterloo Ont.: University of Waterloo Press.

e. *Caroline Mallary*

i. Goals

1. Refine mathematical basis for damage done by various weapons.
2. 3 basic types likely to do much damage: pointed thrust (projectile & held), overhand (pointed and blunt), firearm (blunt but fast)

ii. Deliverables

1. List of formulas and their physical justifications.
2. Explain why excluded damage-types were excluded.

iii. Resources

1. *efunda .com*
   - A resource site for engineers
   - Has a section on force need to stamp through sheet metal
2. *hectorcoleironwork.com*
   - Information on historical arrows from a practicing reproduction arrowsmith
3. *bowhuntinginfo.com*
   - kinetic energy calculator for weight of arrow and draw of bow. Good for quick comparisons.
   - Talks about hunting big game and the considerations of a forceful arrow strike.
4. Taylor, Classical Mechanics. Sausalito, CA: University Science Books.
   - Physics textbook with information on calculating air resistance.
5. Smith. (1960). *A History of Metallography.* University of Chicago Press.
   - Historical metals resource

- Has scaled contemporary drawing and description of 1700s shaving razor…useful for estimating point size and hardness of earlier blades and points.

6. **Week 6**
    a. *Team*
        i. Goals
            1. Team to determine final product.
            2. Photograph, measure, weigh, describe suit.
            3. Prepare contacts list and appointments.
            4. Continue individual research.
            5. Decide on final product form and content.
            6. Draft task list for final product.
        ii. General resources
            1. Artifacts.
            2. Acquire media recording technology from WPI ATC.
        iii. Deliverables
            1. Four subdocuments on weekly areas of study.
            2. Rough photographs and video footage of hands-on sessions.
            3. Analytical data on suit.
    b. *Ryan Meador*
        i. Major areas for study
            1. Royal Collecting
        ii. Goals
            1. Document royal collecting habits and motives.
            2. Persuade the team to abandon Microsoft Access and provide a preliminary plan for smooth transition to a new database
        iii. Resources
            1. Hewitt, John. (1845). *The Tower: its history, armories, and antiquities.* London, Pub: ?
            2. Books on Vienna
            3. Ffoulkes, Charles John. (1912). European Arms and Armor in the University of Oxford.
            4. *Royal Armouries Yearbook.*
        iv. *Eric Van Dyke*
            1. Major areas for study
                - Armor clients
                    i. Client needs and wants
                    ii. Knights specifications
                    iii. Military specifications
                    iv. Armor production timeline
                    v. Patrons for specific guilds and armorers
            2. Goals
                - Relate plate armor clients to modern personal protection needs
            3. Resources
                - Williams, Alan. *The Knight and the Blast Furnace.*

        - *Battelle Armored Secturity Division. Retrieved from* <http://nationalsecurity.battelle.org/clients/inno_defense.aspx?id=30 >.
        - Barber, Richard. *The knight and chivalry.*
        - Oakeshott, R. Ewart. *Knight and his armour.*

c. *David Sansoucy*
   - **i.** Major areas for study: Modern Body Armor Manufacturers
      - **1.** Major Manufacturers
         - Ceradyne Inc.
         - PointBlank Body Armor Inc.
      - **2.** Classifications of Armor
         - 5-6 Internationally recognized classes
      - **3.** Major Armor Materials
         - Metals
            - i. Hardened steel plate
         - Polymers
            - i. KEVLAR
            - ii. Other plastics
         - Ceramics
         - Composites
      - **4.** Modern Body Armor Systems
         - Interceptor vest
   - **ii.** Goals
      - **1.** Gain background of modern body armor manufacturers
   - **iii.** Resources
      - **1.** Ceradyne Inc. (2006). *Personnel protection systems.* CA: Ceradyne Inc.
      - **2.** Dean, Bashford. (1920). *Helmets and body armor in modern warfare.* New Haven: Yale University Press.
      - **3.** GlobalSecurity.org. (2006). *Military: Body armor.* Retrieved October 5, 2006, from http://www.globalsecurity.org/military/systems/ground/body-armor.htm.
      - **4.** Harris, Tom. (2006). *How body armor works.* Retrieved September 27, 2006, from http://science.howstuffworks.com/body-armor.htm.
      - **5.** Marconi, Debbie. (2001). Body armour offers police officers a second chance. *REINFORCEDplastics*, 44-45, Retrieved September 29, 2006, from ScienceDirect Database.
      - **6.** Military.com (2004). *Isaac newton and the assault rifle: body armor innovations.* Retrieved September 27, 2006, from http://www.military.com/soldiertech/0,14632,Soldiertech_Armor,,00.html.
      - **7.** National Institute of Justice (U.S.) (2001). *Selection and application guide to personal body armor.* Rockville, MD: National Institute of Justice's National Law Enforcement and Corrections Technology Center. Retrieved September 27, 2006 from http://www.ncjrs.gov/pdffiles1/nij/189633.pdf.
      - **8.** Peleg, Kobi et al. (2006). Does body armor protect from firearm injuries? *Journal of the American College of Surgeons*, 202, 643-648, Retrieved September 29, 2006, from ScienceDirect Database.

- **iv.** Contacts
  - **1.** Police, SWAT, Army body armor expert
    - Soldier Systems Center (Natick)

d. Caroline Mallary

- **i.** Goals
  - **1.** Scale previous mathematical models against historical documentation and reproductions
- **ii.** Deliverables
  - **1.** Write-up pairing models with practical evidence
  - **2.** Explanation of revised models and assumptions
- **iii.** Resources
  - **1.** Snook, George. *The Halberd and other European pole-arms 1300-1650.* California: Museum: Restoration Services.
    - This book describes the Halberd and other European pole-arms.
    - Contains detailed descriptions and illustrations of these weapons.
  - **2.** Wilkinson, Fred. (1978) *Arms and Armour*. London: Hamlyn Publishing Group Ltd.
    - Contains information on different types of spears and bows.
    - Has the efficiency of each type of spears and bows. May contain draw-weights, etc.

7. Week 7

a. Team

- **i.** Goals
  - **1.** Update Term 3 schedule to reflect progress and details of production.
  - **2.** Prepare annotated list of artifacts to compare our suit against to point out specific similarities and differences.
  - **3.** Summarize individual Term 2 research.
- **ii.** General Resources
  - **1.** Artifacts.
  - **2.** Team document portfolio.
- **iii.** Deliverables
  - **1.** Four subdocuments on weekly areas of study.
  - **2.** A full spreadsheet of comparison artifacts to be examined, sorted by location in the museum.
  - **3.** Documentation of provisional plans for final product.
  - **4.** Portfolio of materials submitted during the term.
  - **5.** List of any items under copyright which the team may need permission to reproduce.

b. Ryan Meador

- **i.** Major areas for study
  - **1.** Private Collecting
- **ii.** Goals
  - **1.** Document private collecting practices, especially the use of cobbled-together suits
- **iii.** Resources

1. Wallace Collection www.wallacecollection.org
    - Detailed info on how and when it was collected as well as what is in the collection
2. *Peterson, Harold L. (1975). How do you know it's OLD?*.Major areas for study

c. *Eric Van Dyke*
    - i. Major areas for study
        1. Metallurgy
            - Early mining practices
            - Smelting methods
            - Metal compositions used
            - Advancements in the understanding of metals
        2. Manufacturing technology
            - Blast furnaces
            - Forging
        3. Trace raw material production from ore to billet production
        4. Fuels for furnaces
        5. Progression of metals
            - Failed metal compositions
            - Properties
    - ii. Goals
        1. Understand path of raw materials from the mine to the anvil
    - iii. Resources
        1. Williams, Alan. (1978). *The metallurgy of muslim armour*. Manchester: University of Manchester.
        2. *Arms, armour and base-metalwork: The James A. de Rothschild Collection at Waddesdon Manor* : [Catalogue] / Claude Blair ; publ. for the National Trust [for Places of Historic Interest or Natural Beauty, London].
        3. Williams, Alan and de Reuck, Anthony. *Royal Armoury at Greenwich, 1515-1649: a history of its technology*.
        4. Bacon, John Lord. (1919). *Forge-practice and heat treatment of steel.* New York: Wiley.
        5. Bacon, John Lord. (1904). *Forge-practice (elementary).* New York: Wiley.

d. *David Sansoucy*
    - i. Major areas for study: Models Derived from Modern Body Armor
        1. Main Body Armor Components
            - Helmets
            - Vests
            - Elbow
            - Knee Pads
            - Steel-toe boots
        2. Body Armor Characteristics
            - Overall weight of the body armor
            - Range of motion allowed/restricted
            - Amount of protection offered

- Modular vs. rigid design

3. Evolution of Modern Body Armor

- Better materials
  - i. Better protection
  - ii. Decrease in weight
  - iii. Greater flexibility

ii. Goals

1. Create model of modern armor characteristics for later use.

iii. Resources

1. Dean, Bashford. (1920). *Helmets and body armor in modern warfare.* New Haven: Yale University Press.

2. Marconi. Body armour offers police officers a second chance.

3. Harris. *How body armor works.*

4. Horsfall, I. et al. (2005). The development of a quantitative flexibility test for body armour and comparison with wearer trials. *Applied Ergonomics*, 36, 283-292, Retrieved September 29, 2006, from ScienceDirect Database.

5. Majumdar D. et al. (1997). Physiological effects of wearing heavy body armour on male soldiers. *International Journal of Industrial Ergonomics*, 20, 155-161, Retrieved September 29, 2006, from ScienceDirect Database.

6. Military.com. *Isaac newton and the assault rifle: body armor innovations.*

7. National Institute of Justice (U.S.) (2001). *Selection and application guide to personal body armor.*

8. Peleg et al. Does body armor protect from firearm injuries?

iv. Contacts

1. Police, SWAT, Army body armor expert

- Soldier Systems Center (Natick)

e. Caroline Mallary

i. Goals

1. Separate out suit characteristics that were purely stylistic; compare to civilian clothing.

2. Understand methods & motifs of surface decoration

ii. Deliverables

1. Write-up overview of armor and style.

iii. Resources

1. Pfaffenbichler, Matthias. (1992) *The Armourers*. Medieval Craftsmen Series. Toronto: University of Toronto Press.

- Armourers are named in for their suits made and other arms they have developed.
- Describes armourers' unique designs, which will have common stylistic traits.

2. Weigly, Russell F. *The Age of Battles*. Indianapolis, IN: Indiana University Press, 1991.

- Deals with development of battles apart from raids and siege warfare.
- Will help delineate functional characteristics by era.

3. Art books: Potential sources: Libraries of WPI, HAM, Holy Cross Clark, Assumption, Worcester Public, Worcester Art Museum.

Plan of Work (C Term, 2007; *tentative*)

"This term will chiefly be given to artifact study and photo documentation; after each photography session the images will be reviewed and edited as necessary. Each team member will also be individually finalizing the content of their draft, and writing up a part of the report of the selected harness."203

Week 1:

- Gather all photos and documents on selected suit.

- Further artifact study

- Input information into database.

- Arm, hand & shoulders.

- Helmets

- Leg & foot & miscellaneous

- Torso.

- **Term 3, Week 1**
  - Team
    2. Goals
    3. Resources
    4. Deliverables
  - Ryan Meador

  iv. Major areas for study
    1. American Collecting

  v. Goals
    1. Document American armor collecting practices

  vi. Resources
    1. Higgins Armory Museum
    2. Metropolitan Museum of Art

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203 Forgeng, Jeffery. "Higgins Armory Museum PQP/IQPs: Prospectus for Students." Worcester Polytechnic Institute. 2006.

- Eric Van Dyke
    2. Major areas for study
        - Shaping armor techniques
            - Skills and training required (armorer section)
            - Special concerns for specific armor pieces
        - Tools used for production
            - Molds, templates, jigs
            - Forges, hammers, anvils
        - Production timeline
        - Evolution of production techniques
        - Increased anatomical understanding improved fitting and articulation of armor
        - Joint types
        - Adjustability
    3. Goals
        - Discuss methods for forming plate armor from raw metal to ready to wear piece.
    4. Resources
        - Price. *Techniques of medieval armour reproduction: the 14th century*.
        - Williams. *The Knight and the Blast Furnace.*
        - Fliegel, Stephen. (1997). *The Making of Armor*. Cleveland: The Cleveland Museum of Art.
            - Describes all major manufacturing techniques used by armorers
            - Describes certain suits of armor and how they were designed uniquely for individuals and troops
            - Richard, Thomas. (1960). *Metalsmithing for the artist-craftsman*.
- David Sansoucy
    2. Major areas for study: Structural features of historical armor
        i. Fitting the body's anatomy
        - What organs and tissues need the most protection?
        - Is there evidence of anatomical consideration?
        - What were the "rules of thumb," if any, when it came to fitting armor?
    1. Investigate possible "conventions" concerning the armor
            - Why was the total weight around 45-60 lb?
            - What components did all types and styles of suits have?
            - To what extent were pre-formed pieces of suits used?

    Integrating with the body's motions: articulation
        - How were the components connected to the body?
        - How were joints done in the armor?
            i. Sliding rivets
            ii. Other mechanisms to allow range of motion

- How adjustable was the suit if the user's body size changed?
- Consideration of physiological issues
  - Adequate vision for battle
  - Breathing: adequate ventilation
  - Heat exchange: heat flow from underneath and through the armor
  - Hearing: Effects, if any, of helmets on hearing and locating sources of sound
- Goals
  - Understand the structure of historical armor
- Resources
  - Blair. *European Armour* circa *1066 to* circa *1700.*

1. Ffoulkes. *The Armorer and His Craft.*

i. Fliegel. *The Making of Armor*.

i. McArdle. *Exercise physiology**:** energy, nutrition, and human performance.*

ii. Pfaffenbichler. *The Armourers. Medieval Craftsmen Series.*

iii. Sherwood, Lauralee. (2004). *Human physiology: from cells to systems 5th Ed.* Belmont, CA: Thomson.

o Caroline Mallary

2. Goals

1. Investigate physical metals properties and how they are measured.

2. Investigate feasibility of measuring these properties in chosen suit.

a. Crystallography via X-ray diffraction

ii. Deliverables

1. Write-up

2. List of potential experiments and facilities at which they could be

conducted

iii. Resources

1. **Sauver. *Metallography and the heat treatment of steel***

a. Textbook of metals and their properties

b. Molecular-level information may be useful for examination of armor

2. **Williams. *The Knight and the Blast Furnace***

- a. Recommended by professor

Week 2:

-Artifact study.

- Team
  - Goals
  - Resources
  - Deliverables

8. *Ryan Meador*

a. Major areas for study

i. Armor Today

1. production, modern armorers

ii. Modern collecting

iii. Museums

b. Goals

i. Document modern collecting, use of replica armor, and museum practices

ii. Look more in-depth at the database and/or transition plan if it is going to be part of our final product

c. Resources

i. Price, Brian R. *(2000). Techniques of medieval armour reproduction: the 14th century. Boulder, Colo.: Paladin Press.*

ii. Higgins Armory Museum

- Eric Van Dyke
  - Major areas for study

Armor finishing

Final fitting for comfort, mobility, etc.

Decoration

Reasons for decoration

Status symbol of wealth and influence

To show off craftsman's skill

Methods (etching, embossing, etc)

Styles (chronologically and geographically)

If the suit was being manufactured as a work of art rather than a means of protection, were there any shortcuts taken or alternative materials used?

Surface effects

Bluing

Guilding

Are there any parallels between ancient and modern armor production?

Armor care and upkeep

Skilled artists performed detailing

Armor as a work of art.

What extra costs were involved in various types of decoration and embellishment?

Goals

Finalize term 2 documentation.

Contacts

Practicing armorer

Practicing blacksmith

Metalworker's Union

Military, police, or SWAT protection manufacturer

○

- David Sansoucy

5. Major areas for study: Apply previously developed models to a specific historical harness
    - Historical Harness (TBD)
        - Measure important characteristics
            - Total weight
            - Dimensions
            - # of components
        - Investigate protective capability
            - What body zones were covered
            - How was the protection of the suit distributed
        - Other features
            - Freedom of movement allowed/restricted

        - Field of vision
        - Breathing allowance
        - Heat exchange
      - Conduct experiments involving human movement without wearing armor versus the same movement while wearing armor
        - Tests may include:

- # of times walk up flight of stairs in a time period: without armor then with armor
- Jump up: without armor then with armor
- Try swinging an object with arms in a controlled fashion: without armor then with armor
- Debunk myth about not being able to get up from ground while in armor

        - Analyze results
      - Take any pictures and/or footage.
    - Tie up loose ends

6. Goals
    - Apply the models generated in previous 5 weeks
7. Resources
    - Horsfall, I. et al. The development of a quantitative flexibility test for body armour and comparison with wearer trials.
    - Majumdar D. et al. Physiological effects of wearing heavy body armour on male soldiers.
    - HAM Harness (TBD)
    - HAM replicate suit (If possible)
    - Media recording devices
    - Experimental equipment
        - Timer
        - Statistical analysis program (Excel)
        - Measuring devices

- Caroline Mallary
    - Goals
        1. Make arrangements for chosen experiments

    ii. Deliverables

        1. Detailed plan of experiments

        2. Preliminary schedule for the experiments and their reports

    iii. Resources:

        1. **Sauver.** ***Metallography and the heat treatment of steel***

a. Textbook of metals and their properties

2. **Taylor, Classical Mechanics. Sausalito, CA: University Science Books**

   a. General Physics textbook.

3. Contacts:

   a. Forgeng

   b. Machlouf & Jianyu Liang (Materials Science)

   - c. Iannochione (Physics)

Week 3:

- Begin artifact write-ups

Week 4:

- Suit write-up and study guide

Week 5:

- Deadline for updated versions of individual research documents and draft documents on selected harness.

-Produce sample final product components

Week 6:

- Team to submit updated SOP for hardware and software used (e.g. camera).

- Discuss tasks for term 3.

- Due this week: complete final draft of the IQP product and report in electronic format (typically on a CD-rom).

Week 7:

- Return all loaned material.
- Each team member to submit finalized research document.
- Each team member to hand in a portfolio of materials submitted during the term.
- Team to submit all artifact documentation materials generated during the term (e.g. artifact photos).
- Update plan of work.
- Finalized write-up on harness.

Plan of Work (D Term, 2007; *tentative*)

This term will be spent finalizing the product in electronic and hardcopy format.

Week 1:

- Team to finalize format for the database

- Submit final draft of suit write-up

- Brainstorm introduction

Week 2:

- Draft introduction

- Brainstorm conclusion

Week 3:

- Draft abstract (80 words maximum)

- "About us" text and photos

- Database documentation (including images) for project report

Week 4:

- Full draft of project report and updated database.

Week 5:

- Updated project report

- Complete draft of the IQP product and report (including title page, abstract, etc.) due.

- All materials to be submitted on CD rom, including website, electronic version of the project report (MS Word and pdf versions), final project proposal (MS Word only), and any electronic material created by the team (e.g. photographs, programs, etc.).

Week 6:

- Due this week: complete final draft of the IQP product and report in electronic format (typically on a

CD-rom).

Week 7:

- One CDR form from each team member, with personal information and abstract filled in.
- 3 bound hard copies of the project report for the whole team (1 in color).
- 2 CD-ROMs containing an electronic version of the project report (MS Word and pdf versions), project proposal (MS Word only), and any electronic material created by the team (e.g. photographs, website).
- Portfolio of materials submitted during the term.
- Documentation of all permission letters sent and received.
- All loaned material.

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