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Modeling the Joust

An Interactive Qualifying Project Report

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by

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1. **joust**
2. **collision**
3. **arms and armor**

Abstract

This project is an exploration into the feasibility of modeling the collision during a medieval joust. Information concerning the history and equipment of jousting is presented, along with an analysis of physical considerations of a joust. Artifacts from the Higgins Armory Museum are examined and used to create the basis for a rudimentary model. An exhaustive model is more within the scope of a MQP, where students have a greater initial understanding of the fundamentals of collisions and material stress.

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1 Introduction

Consider the thought of being a medieval knight about to enter a joust. Imagine donning your armor, which weighs nearly half as much as you, and climbing onto your half-ton-plus warhorse. Feel the anticipation as you look down the course to your similarly equipped opponent and prepare to charge. Hear the thundering as your horse races down the track at great speed; you hold out your lance, attempting to aim a telling blow upon your opponent, while maintaining your very shaky seat. Can you withstand the impact when your lance strikes him, or his strikes you? The questions of the impact force felt by a knight during a joust and the results of that impact are quite intriguing, and just a little unnerving.

The original goal of this project was to develop a complete mathematical model of a joust collision event, and use that model to generate a computer program to simulate a collision. The program would determine the results of the simulated joust: who had been unhorsed, whose lance had shattered, and the impact force felt, compared to something physically knowable, such as a car accident at a certain speed. The ultimate program would have been interactive, allowing the user to choose different armor types from different time periods and geographic locations, and perhaps somehow contribute to the simulation event itself, perhaps by trying to aim the lance with a mouse pointer centered over a target.

Unfortunately, it was discovered that a complete computer model would be extremely difficult to develop, as the mathematics involved are extremely complex; such work is typically done at a graduate level of study. It was determined that attempting to develop such a model would be far beyond the scope of an IQP, and the project was pared down. While a computer model proved impractical for the project time frame, much of the groundwork necessary for such a model could be achieved. As such, this project presents an overview of jousting, its history, forms, and equipment, as well as a qualitative look at some of the considerations to be made when developing a mathematical model of a collision.

This report presents the research and analysis completed to achieve this goal. The first stage of the project involved in-depth research into the history of jousting, its origins and various forms, and the equipment used, the construction of armor and lances and the types and sizes of horses ridden. The chapter following this introduction is a historical narrative, placing in proper historical context the museum pieces that were studied in this project. This is followed by descriptions of the various pieces of equipment used in the joust, as physical characteristics are very important for an accurate model. With a solid understanding of the physical act of jousting and the characteristics of the equipment used, the details and results of an impact would be more readily deduced.

The next chapter, Analyzing the Joust, looks at the actual mechanics of a joust collision, and attempts to reason through all the forces and reactions that must be considered. When the physical events are known and understood, a mathematical analysis can be more easily completed to determine impact forces and event outcomes. To further support a future project group, this chapter also contains a discussion of quantitative methods commonly used to analyze collision, as well as a foray into computer modeling, using pre-existing engineering tools. Rudimentary measurements of example suits of armor were taken to be entered into a general collision analysis program and create a basic simulation of a joust, to provide some feel for the scope of the impact. Unfortunately, due to time constraints, this analysis could not be completed. All of this work is presented with an eye on reducing the time spent by a project group searching for an acceptable collision analysis method, should future attempts to create a computer model use this project.

2 A Brief History of the Joust

The value of martial games was recognized as far back as the days of Sparta and Rome, when youths engaged in mock battle to build skills that would later serve them in their duties as a soldier. Mock combat for practice is far removed from the glorious fairs of knightly times. When, then, did such tournaments become commonplace? It is the purpose of this section to explore the origins of the tournament and place within this history the jousting armors on display at the Higgins Armory.

First, some terms will need to be defined. A 'tournament' is any gathering of warriors for the purpose of martial games of any kind. This is the setting for 'melees' and 'jousts'. Melees are mounted or unmounted combat of competing groups of soldiers. Fights between pairs of warriors, mounted and unmounted, were also known. The joust is competition between pairs of mounted warriors. There are many types of joust, some of which are discussed below. The main focus of this paper is jousting with a lance, its development, and history.

What is considered the first of such affairs occurred in 842, to celebrate an alliance between Louis the German and Charles the Bald. Rows and rows of horsemen would charge at each other, then one 'army' or the other would wheel away as if fleeing, and another charge would begin anew. There was also formation marching, and complex horse dancing. These were displays of horsemanship, however, and there was no actual fighting of any kind. (Barber and Barker 1989: 13)

Tournaments in the 9th century with actual fighting were simply friendly training sessions. Groups of soldiers would compete under the leadership of the lord they would follow into battle during actual warfare. The tourneyers were not mounted, and the contest was a melee, not a joust. The contest would take place on an expanse of fields and farmlands, with no official borders, other than to state that the contest was to take place between two given towns. There were no rules, and no prevented tactics. Often, for instance, several competitors would band together to take down a single opponent. The only concessions were a few safe zones where a competitor could rest, and that the object was to capture the opposing soldiers and ransom them, not to kill them. Mounted combat came later, with the invention of the lance. (Barber and Barker 1989: 15)

At the time of the First Crusade (in the late 11th century), new cavalry tactics appeared in France, centered around the use of a couched lance. Before this time, a horseman would use a spear or javelin, which was very light and designed for throwing. The problems with this were twofold. If a warrior wished to stay distanced from his opponent, he had to throw his weapon, leaving himself unarmed. If he wished to retain his weapon, he had to move forward to close quarters and jab at his opponent with a weapon that was not suited for close-quarters combat, mounted or otherwise. Couched lances were held under the arm, and not designed to leave the hand of the wielder. They could therefore be heavier, and the standard tactic was to arrange cavalry in a line of such lancers, and charge enemy formations. The lances were retained (provided they didn't shatter in the charge) and their length kept an enemy out of reach of most melee weapons. The group tactics all but nullified any need for close combat. The lance was sturdy enough to be used to jab an opponent, but the new tactics emphasized instead the impact of the initial charge, both physically and psychologically, and its power to break enemy formations. This new tactic contributed to the success of the Franks (Western Europeans) in the First Crusade, and the Normans' conquests from south Italy to England. Since these tactics required skill and much training and practice, and only worked when warriors coordinated as a team, it is thought that jousting tournaments may have gotten their start at this time out of necessity, and later evolved into the glorious events of legend. (Barber and Barker 1989: 15)

By 1130, the church had taken notice of the growing popularity of tournaments and evidence is found in church decrees forbidding them. The church had issued decrees starting in the 11th century in an attempt to mitigate the violence and regular combat of the period. These decrees included such things as forbidding fighting on holidays and weekends. (Barber and Barker 1989:16)

From these we can extract some evidence of the fame of organized martial games at that time. The Council of Clermont in 1130 stated in their ninth canon:

> We firmly prohibit those detestable markets or fairs at which knights are accustomed to meet to show off their strength and boldness and at which the deaths of men and dangers to the soul often occur. But if anyone is killed there, even if he demands and is not denied penance..., ecclesiastical burial shall be withheld from him. (Barber and Barker 1989: 17)

The use of the words “fairs” and “markets” suggests that, while jousting was well known in knightly circles, the sport was new enough that its terminology was not widely known, even in France, where most tournaments were thought to have take place. (Barber and Barker 1989: 17)

It was not until 1125-1130 that proof is seen of tournaments taking place outside France. In 1127, Count Charles the Good of Flanders was known to have “frequented tournaments in Normandy and France and outside that Kingdom too and so kept his knights exercised in time of peace and extended hereby his fame and glory and that of his country”. (Barker and Barber 1989:

16) This suggests that tournaments had gained popularity and probably moved to nearby kingdoms in England, and parts of Germany, having already gained popularity in Flanders and Normandy.

In the 1170s and 1180s tournaments began gaining popularity outside military circles. This was due mostly to the demand for literary accounts of knightly valor. Literature in these twenty years went hand in hand with the tournament, with romantic stories of tournament heroes spurring participants to even more impressive deeds, which fueled still more literary acclaim. (Barber and Barker 1989: 21)

One of the most famous of these heroes, as an example, was William Marshall. Marshall rode all through England, France and the Low Countries (Flanders and the Netherlands) participating in tournaments and collecting hefty rewards from ransoming off his captured prisoners, horses and arms. Some of his more unusual exploits also helped increase the popularity of tournaments through literature written by poets and heralds, such as when he was late to receive a prize at one tournament, missing the ceremony because he was at the local smith's, head on the anvil, being hammered out of his helm. (Barber and Barker 1989: 23)

William Marshall, and famous men like him, increased the popularity of tournaments such that in 1194 Richard I of England gave tournaments official sanction. From this action we can deduce that until this time, tournaments were unregulated by any monarchy, and may have even been illegal. Although Richard used these rules to control and tax them, tournaments were now legal, and even had set locations for the events to take place. (Barber and Barker 1989: 25) While jousting and single combat had yet to become the focus of the tournament, by the turn of the 13th century they were certainly part of society and culture in Western Europe. Tournaments were known to take place in German-speaking areas as far east as Austria, but tournaments did not show up in German literature until 1225. In this year, Ludwig of Tuining captured Lebus castle near Frankfurt, the end of the siege was celebrated by what was recorded as "the kind of a tournament called a joust."(Barber and Barker 1989: 25)

Tournaments at this time usually included melees, fought with the same weapons used in war. Injury was possible even when these weapons were wielded without the intent to kill. Accidental injury, and sometimes death, was common. It wasn't until the last half of the 13th century that arms and armor were designed with extra safety during the tournament in mind. Jousts incorporating these new features were called "Jousts of Peace" while those using the sharp lances and standard war armor were called "Jousts of War." (Edge and Paddock 1990:157) Improvements to the arms and armor for Jousts of Peace had to be such that they would still be similar to real arms – retaining the 'training' aspect of the joust – and most importantly, reduce the chance of death or injury to valuable members of the elite fighting class.

Tournament lances were made with blunt heads from the beginning of non-lethal combat games, with the most popular version of this being a three-prong coronal, which spread the impact over a larger area, reducing the chance of impalement. (Edge and Paddock 1990: 157) Two important innovations were made in Italy that not only made the tournament safer, but also split the sport into separate sub-classes of jousting by their inclusion or exclusion. These inventions were the so-called 'Frog-mouth' helm, and a barrier preventing horse collision.

The barrier, known as the 'tilt' was erected between the riders, and they would joust across it (as a consequence, jousting over a barrier became known as 'tilting' or 'running at the tilts'). This was invented in the 1420s in Italy, and tilting migrated to Germany in the 16th century. Horse collisions, which were very dangerous to the horses and the riders, were still possible, as the tilt was sometimes a simple length of rope with cloth hanging over it. Tilts were also made of stouter wooden fences and walls, and while collisions with the walls themselves must have caused accidents, horse collisions were eliminated. (Blair 1958: 158)

The style of helm known as the ‘frog-mouthed’ helm, (see Figure 3.4A) due to the shape of the eye slit, was also invented in Italy around 1420. These helmets were heavier and with a narrower field of vision than helmets used in battle, but still sufficiently light and left enough view for jousting. (Edge and Paddock 1990: 115) The helm allowed the knight to lean forward during a charge, but when he leaned back to properly position his lance for a hit, he would be blind and his eyes completely protected. (Blair 1958: 163)

German jousts were divided into two major variations based around the improvements to the joust. These were the *deutsche Rennen* (“the German run”, a Joust of Peace) that used blunted lances, but no divider; and the *Plankengesteck* (literally: “‘plank’ or ‘board’ joust”, also a Joust of the Peace), which also used blunted lances, but added the Italian-invented tilt. Both utilized the frog-mouthed helm after its invention, but the *Plankengesteck* wasn’t practiced until after 1420, when tilting was introduced from Italy.

The *Stechzeug* (“joust arms”, see Figure 3.2) was used in the *deutsche Rennen* from the early 15th century to late in the 16th. The object in the *deutsche Rennen* was to unhorse one’s opponent. Extra points were given for location of a hit, more points being awarded for a blow landed on the opponent’s helm than on his breastplate, for instance. Additional points were given for the shattering of one’s lance against one’s opponent’s shield. The lances in this joust were blunted and the frog-mouthed helm was used. (Blair 1958: 162) The tilt had not yet been invented when this type of joust became popular. Even after the *Plankengesteck* became popular, many tournaments used the rules of the *deutsche Rennen*. Without a divider, however, a collision of the horses was a very real possibility.

A contrast of the *deutsche Rennen* was the *Scharfrennen* (literally "the sharp run", a Joust of War). The *Scharfrennen* used a pointed lance, a different suit of armor, and like the *Rennen*, no tilt. The helm was a simpler sallet-style, usually with additional breakaway plates on the forehead area to indicate a hit. The armor also had no special shoulder protection, but instead the shield was expanded and shaped to cover the entire arm, shoulder and left torso. (Edge and Paddock 1990: 117)

A slightly altered form of the *Scharfrennen* armor was also used in a joust called the *Hohenzeuggestech* (”high arms joust"). Combatants were strapped to their saddles in a partial standing position. The object of this contest was primarily the shattering of lances. (Blair 1958: 160) With the knights strapped tightly to their saddles and mounts by their legs, being unhorsed would mean breakage of the legs, or worse, the back. This contest declined quickly in popularity in the 1400s, possibly for just that reason.

The *Plankengesteck* followed the same rules as the *deutsche Rennen*, but a cloth (stretched over a rope) or wooden divider was used to prevent collision. This form of jousting lasted the longest, until the 17th century, the others declining in the late 15th. (Blair 1958: 162)

	"Frog-mouth Helm"*	Tilt	Rebated Lance	Date
Gestech	Yes (3:160) No (2:95) Yes (4:162)	No(3:160)	Yes (3:160) Yes (2:104) Yes (4:163)	14th – 16th (3:160) 3rd Qtr. Of 15th (4:162)
Hohenzeuggestech	Yes (3:161) Yes (4:163)	No(3:161)	Yes (3:160) Yes (2:104)	Same as gestech(3:160) Author labels this a sub-type of the gestech
Plankengestech (Welschrennen)	Yes (2:104)	Yes (2:104)	Rebated (2:104)	Same as gestech(3:160) Author labels this a sub-type of the gestech
Scharfrennen	No (2:95) Yes (3:160)	No(3:160) No(2:101)	No(3:160) No(4:164) No also implied by name	1460-1530 (3:163) 15th Century (2:97)
Date	Invented early 15th(1:157) Used Late 14th – 1530s(3:157) End of 14th – 1630(4:157)	Estimated invented 1400 (1:157) Migrated from Italy to France 1420, to Germany Early 16th (4: 158)	Invented with the distinction between Joust of Peace and Jousts of War in the late 13th century. (4:156)	NA

Table 2.1 Comparative Table of Sources and Types of Jousts

1 - Barber and Barker 1989
2 - Ffoulkes 1912
3 - Blair 1958
4 – Edge and Paddock 1990

*All four authors use a definitive tone when describing the usage of the helm in the joust in certain points in history. A sentence might say "The so-called 'frog –mouthed' helm was invented in the late 14th century and was utilized in the joust from this point on." (Blair 1958: 157, paraphrased) With no better information to go on, we can draw some conclusions:

1) The new features were required by the rules of the tournament as they were invented.

2) As 'new technology' it may have been considered unsafe to wear a suit of armor to a joust without the helm, the equivalent of seatbelts being incorporated into all new cars today.

3 Equipment for the Joust

In order to create an accurate simulation of a joust, an understanding of the equipment used and its physical parameters is necessary. This section provides an overview of the characteristics of lances and armor commonly used in jousts. A discussion of the physical characteristics of horse and rider is also presented, as these parameters are important factors in the calculation of impact force.

3.1 The Lance

The lance was a horseman's weapon, its design based upon that of the standard spear. Although derived from the spear, a common weapon, feudal nobles held the lance in high regard as the most dignified weapon, and its use by the commoners was generally prohibited. (Kottenkamp 1857: 62) The count of knights' lances was often used as a measure of the strength of armies and lances fixed in the ground outside their tents commonly indicated the ranks of knights. (Kottenkamp 1857: 63)

By the 12th century, the standard spear design had evolved into what is commonly thought of as a lance today. The average spear was approximately 6' 6" in length, much too short for effective use in mounted combat. (Edge and Paddock 1990: 30) The lance had been extended to a length of 10'-12' to provide the necessary reach. The shaft of the lance was constructed of a single piece of wood, typically ash, with a sharply pointed head of iron or steel designed for penetrating armor. (Edge and Paddock 1990: 46) Other sources indicate that cedar, aspen, lime, pine, and sycamore woods were also used in lance construction. (Edge and Paddock 1990: 88; Kottenkamp 1857: 62) Below the head was attached a flag, called a gonfanon or gonfalon, which indicated the rank of the lance bearer. (Edge and Paddock 1990: 31)

In the 13th century, a distinction was made between Jousts of War and Jousts of Peace, resulting in a variation of the lance head. (Edge and Paddock 1990: 157) Typically, during Jousts of Peace, the pointed lance head was removed and replaced with a small crown-shaped head, referred to as a coronal. The new lance design, referred to as "rebated", was designed to spread the force of the impact, for shattering one's lances or unhorsing one's opponent, rather than piercing the opponent's armor. (Edge and Paddock 1990: 160) Another design change sometimes used in tournaments was the hollowing of the lance shaft. These "jointed" lances were designed to make lance breakage much more spectacular. (Edge and Paddock 1990: 160) A hollowed lance would explode in a shower of splinters when compressed beyond its strength, while a solid lance would simply break into two pieces with a few splinters.

The lance was later fitted with a vamplate and a grapper. The vamplate was a round, conical shield affixed just in front of the lance grip for protection of the hand and forearm supporting the lance. The grapper was designed to butt up against the lance bearer's armor when the lance was couched, and prevent it from being forced back during impact. (Edge and Paddock 1990: 88) Figure 3.1 below shows a lance with a vamplate mounted on it and resting in a queue (an armor attachment described in Section 3.2).

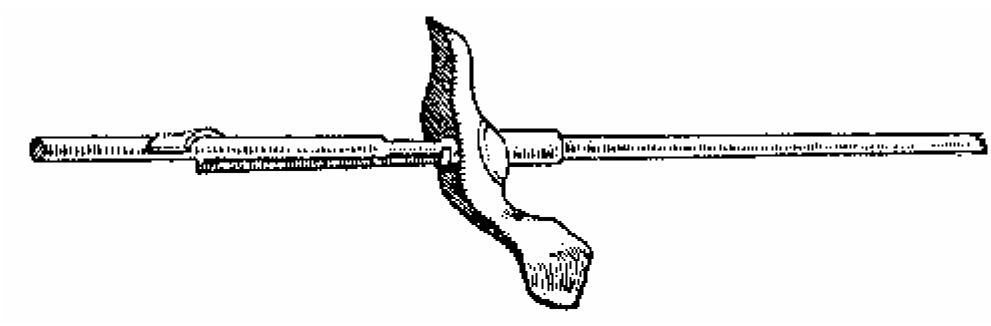

Figure 3.1 Lance with Vamplate and Queue from the Tower of London collection
(Ashdown 1967: 236)

In the 15th century, the lance is said to have reached its peak design. (Edge and Paddock 1990: 146) It was larger than its 14th century predecessor, having swelled in thickness in front of and behind the handgrip, tapering off toward the two ends. (Edge and Paddock 1990: 126) It was equipped with a large steel vamplate and the blunt, three-pronged coronal was affixed to lances for Jousts of Peace. (Edge and Paddock 1990: 163)

3.2 Armor

During a joust, protection of a knight's body was of utmost importance, and armor was the most effective way to achieve this goal. In a Joust of Peace, where the idea was to unhorse an opponent or shatter a lance, armor helped prevent serious injury or death in a situation designed to improve skills and prove one's abilities. In a Joust of War, armor would also provide some level of protection against injury and death, and perhaps give a knight the edge needed to be victorious.

Initially, standard field armor and helm was used for the purposes of jousting. This armor was equipped with certain reinforcing pieces to provide extra protection against injuries caused by jousting. The use of current standard field armor was common in jousting until c. 1440, but also continued to be used for certain types of jousting until the 17th century. (Blair 1958: 159)

One of the first references to specially designed jousting armor was made in an anonymous French manuscript of 1446. (Blair 1958: 159) The main component of this armor was a cuirass, to which a lance-rest, and buckles and straps, for the fitting of other pieces, were attached. The lance-rest was a small, upturned hook mounted on the right side of a suit's breastplate and designed to support the lance to aid the jouster's aim. (Ashdown 1967: 233) The lance-rest also provided some support against impact. It was designed to engage a circular plate mounted on the lance, just behind where the jouster would grip. This would prevent the lance from being forced back during impact. (Edge and Paddock 1990: 75-76) Lance-rests were commonly solid pieces bolted onto the breastplate, but some later examples were spring-loaded and could be folded up when not in use. (Ashdown 1967: 233)

Some suits of jousting armor were affixed with a queue, which was a solid metal bar bolted to the right side of the breastplate with a down-turned hook at the back to hold down the butt of the lance. If there was not already a lance-rest on the armor, then a small, upturned hook was added to the front of the queue to provide the same support as a lance-rest. (Ashdown 1967: 236)

The pieces to be attached to the main cuirass, described in the previously mentioned anonymous French manuscript of 1446, include: a main de fer, a single piece that protects the left hand and arm up to a few inches past the elbow; a pauldron, of a single piece of metal, protecting the left shoulder; a small gauntlet to protect the right hand, probably of leather, called a gaignepain; a polder-mitten, which provided protection from the gaignepain to just above the right elbow; a laminated pauldron, protecting the right shoulder; and a small wooden shield which was suspended from the left shoulder and supported by a poire, a pear-shaped buffer made of wood or leather, which also hung from the left shoulder. (Blair 1958: 159)

Figure 3.2 shows an example of jousting armor very similar to the above description. This form of jousting armor seems to have been used commonly throughout Europe, with minor variations, until c. 1530. (Blair 1958: 159) The suit in the figure is a German suit of armor, which includes a “frog-mouthed” helm, not mentioned in the above French description, but a common piece of jousting equipment (to be discussed in Section 3.3).

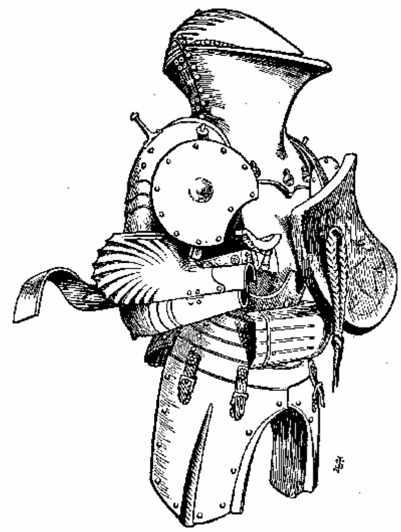

Figure 3.2 Jousting Armor for Das Deutsche Stechen Course from the Wallace Collection, c. 1485 (Ashdown 1967: 309)

One of the variations on this form of armor, which was commonly used in the Italian or "Free Course", was the *Manteau d'Armes*. This was a large, concave shield, which was firmly bolted to the left side of the breastplate, and was designed to protect the breastplate and the left shoulder. It was usually embossed on the surface with raised trelliswork intended to provide a grip for the adversary's lance. (Ashdown 1967: 286) The figure below depicts a *Manteau d'Armes* mounted on a suit of armor.

Figure 3.3 Armor for the Plankengestech (Northern Germany, 16th Century) (HAM 2610.1)

3.3 Helms

Probably one of the most specialized pieces of jousting equipment was the helm. Several forms of jousting helms were turned up in the research for this project; the most thoroughly covered being the "frog-mouthed" helm (seen in Figure 3.2 above). The "frog-mouthed" helm first appeared at the end of the 14^{th} century. (Blair 1958: 156) The helm had a low skull (top) and the front plate curved up and out to form a flat point along the line of sight. A gap was left between the skull of the helm and the bevor (front plate) to allow the wearer to see. This gap was almost completely concealed by the upper edge of the front plate if the wearer sat upright. Adequate sight was only achievable by leaning forward. When jousters leaned back at the moment of impact, their eyes were completely covered. (Blair 1958: 156-157) This design remained in use in Europe, with little variation, until around the 1530s. (Blair 1958: 157) Figure 4A below shows a "frog-mouthed" type helm referred to as the Brocas Heaume, which was from the time of Henry VII. (Ashdown 1967: 273)

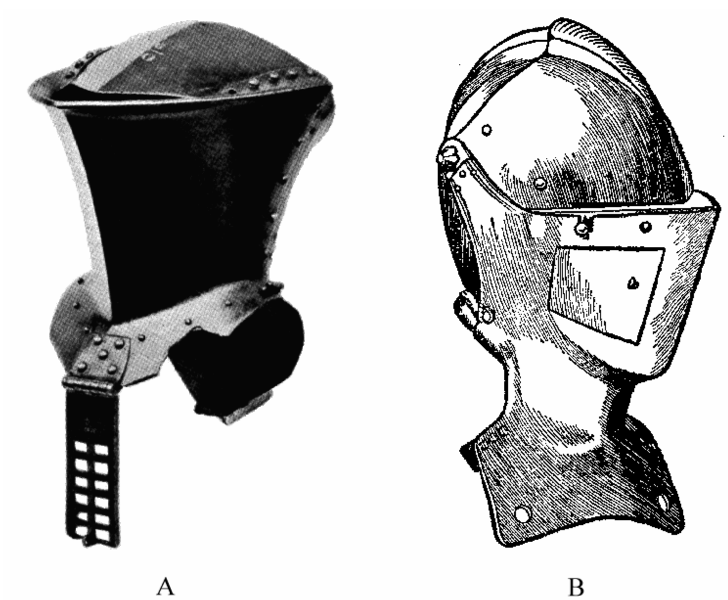

Figure 3.4A The Brocas Heaume (Ashdown 1967: Plate XXXIX)
Figure 3.4B Globular Tilting Heaume from Tower of London (Ashdown 1967: 274)

Another common type of jousting helm was the globular form, depicted in Figure 3.4B. The helm is comprised of a bavière (the front plate) screwed to the backing. The top part of the helm has a visor mounted to it that can pivot up and down. When the visor is down, its lower edge and the upper edge of the bavière form a very narrow gap allowing the wearer to see. (Ashdown 1967: 273) Specimens of these helms in the Higgins Museum and the Wallace Museum Collection all originate from Germany and dated from the late 16th century. (HAM 2548/2586.1/2610.1; Mann 1962: 56/59/61/138/139)

3.4 Horses and Related Equipment

The breeds of horses used as warhorses, often referred to as destriers, throughout Europe between the 13th and 17th centuries varied from nation to nation. The French often used Castilian and Aragonese horses, but also obtained stock from Gascony, Hungary, and Syria. The Netherlands had the Friesian breed, Spain had the Andalusian, and Italy the Mantuan. (Hyland 1998: 2-3)

According to Hyland, "Destriers were of moderate height [approximately 15hh] and robust build." (Hyland 1998: 10) An intact suit of horse barding was placed on a Lithuanian draught mare of about 15.2hh and the suit fit extremely well, indicating that that size of horse is a very close estimation of what would have been common for a medieval warhorse. (Hyland 1998: 10, 30) According to John Waller, Head of Interpretation at the Royal Armouries Museum in Leeds, Great Britain, a close approximation for the traveling speed of a horse during a joust is 20 miles per hour. (Waller: Personal Communication)

Information concerning the weights of such horses is extremely hard to find. Information about some of the breeds that exist today provides some values that can be utilized in a joust model. A modern Friesian ranges from approximately 14.3-15.3hh (57.2-61.2 in/150-160 cm) in height and 1001-1298 lbs (455-590 kg) in weight, while modern Andulusians average around 15hh (60 in/152 cm) and 1199-1298 lbs (545-590 kg). (Amador, 2001) Sources indicate that 1300 lbs would have been an upper limit for horse size, and most medieval warhorses would not reach that size. (Davis 1989: 57)

3.4.1 Jousting Saddles

The design of the jousting saddle is of great importance when considering the impact results of a joust. The design of the saddle, its foot and leg grips, and backing will have an effect on how well a rider can maintain his seat when struck with a lance.

The most common type of saddle used for jousting was referred to as a war saddle, which was the same type of saddle used in actual warfare. These saddles had a raised front grip and back, as opposed to standard riding saddles which had a pommel on the front and a nearly flat seat all the way to the back. (Mann 1962: Plate 95) The raised front and back of the war saddle also continued down the sides, providing some protection to the legs and better purchase to grip one's legs around the horse. The figure below shows the form of a war saddle and a standard riding saddle.

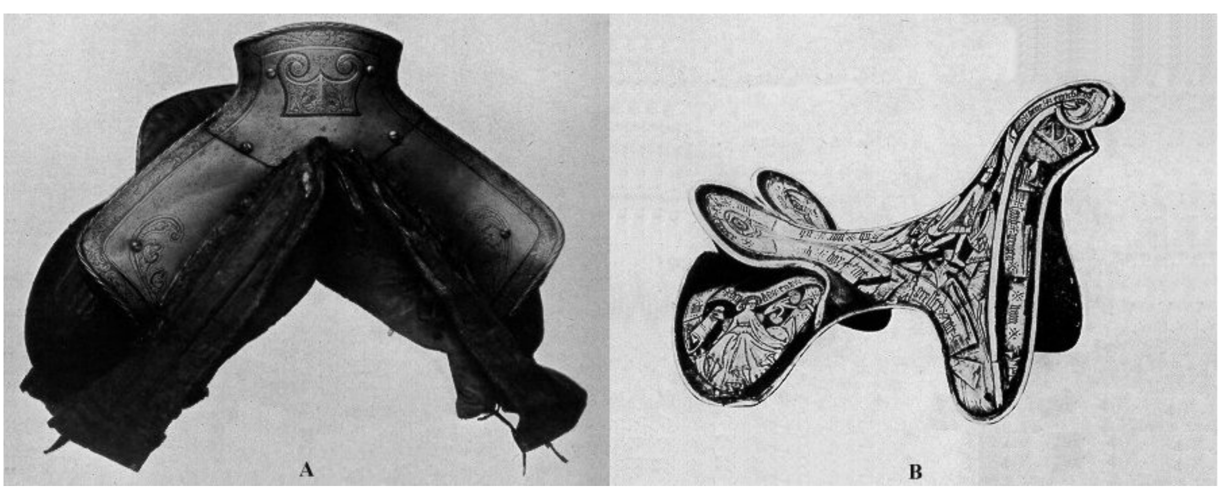

Figure 3.5A War Saddle from the Wallace Collection (Mann 1962: Plate 100)
Figure 3.5B Riding Saddle from the Wallace Collection (Mann 1962: Plate 95)

The Higgins Armory Museum has a reconstructed war saddle, built upon a surviving frame (shown in Figure 3.6 below). The front plate of this saddle (left side in Figure 3.6) rises approximately 7 inches above the seat, placing the top at approximately the abdomen of a rider. The saddle front plate is also quite wide, 11.25 inches across the top and 17.25 inches at the plane of the seat, providing a great deal of protection to the rider. The front plate also continues down the sides, and comes up in front of the thighs of a rider. The plate continues down approximately 11 inches, along the side of the horse, and extends approximately 5 inches outward from the side of the saddle, perpendicular to the side of the horse. This would almost completely cover the rider's legs down to the knee.

Figure 3.6 Reconstructed War Saddle from the Early 16th Century (HAM 2604)

The back plate (right side of Figure 3.6) rises approximately 6.125 inches from the seat, placing it near the waist of a rider. As can be seen in the picture, the back plate is tilted forward slightly, which would place the padding against the pelvis and lower back of a rider. It seems likely that this was done to help provide more support to a rider during an impact from lance or while fighting in close quarters combat. The width of the saddle back plate is approximately 14 inches across the top and 17.5 inches at the seat. The back plate continues down the sides of the saddle for approximately 11.5 inches, and has a width of roughly 3 inches from the sides of the saddle. The back plate must have proved useful for supporting one's self during a joust or battle, providing a decent buttress against being forced back, and lower back support and a hold for a sturdy leg grip to prevent being tipped off one's horse. A war saddle obviously provided a great deal of frontal protection and rear support to a rider, extending from the waist/lower back down the thigh to about the knee of a rider.

A specialized form of saddle was used for the Hohenzeuggestech, a special form of the Gestech. The seat was raised approximately 10 inches above the horse's back, placing the rider in a standing position. (Blair 1958: 160) The front plate of the saddle was much like a shield, split over the horse's back, which protected the rider from the feet to just above the waist. Two bars extended back from the front plate, around the thighs of the rider to prevent him from being thrown from his horse. While such a saddle prevented unhorsing, it is highly likely that it caused severe injuries to the thighs and backs of riders. (Blair 1958: 160)

Compiled List of Jousting Equipment				
Item	**Origin**	**Date**	**Physical Characteristics**	**Source**
Lances and Related Pieces				
Coronel	Germany or Austria	Early 16th c.	3.5 inches long; 1 inch prongs	HAM 2610.7
Lance for the Joust	Germany	16th c.	342 cm long; 4.8-5.7 cm in diameter; 9 lbs 9.5 oz	HAM 894
Vamplate	South German (Augsburg)	16th c.	1 lb 10 oz	HAM 2881.1
Vamplate (A342)	German (Nuremberg)	1549	2 lbs 4 oz Diameter: 11.5 – 11.75 in. Lance opening diameter: 2.5 in.	Mann 1962: 211
Vamplate (A343)	German (Augsburg)	c. 1550	1 lb 4 oz Diameter: 10.25 – 10.375 in. Lance opening diameter: 2.75 – 2.875 in.	Mann 1962: 211
Vamplate (A344)	German	16th c.	1 lb 13 oz Diameter: 12.125 – 12.25 in. Lance opening diameter: 2.6875 in.	Mann 1962: 211
Vamplate (A345)	German (Augsburg)	c. 1580	1 lb 8 oz Diameter: 11 in. Lance opening diameter: 2.25 in.	Mann 1962: 212
Vamplate (A346)	Italian	c. 1570	3 lbs 2.5 oz Diameter: 12 in. Lance opening diameter: 3.875 in.	Mann 1962: 212
Vamplate (A347)	Italian	c. 1560	1 lb 6 oz Diameter: 9.625 in. Lance opening diameter: 2.625 in.	Mann 1962: 212
Armor and Armor Pieces				

Compiled List of Jousting Equipment				
Item	**Origin**	**Date**	**Physical Characteristics**	**Source**
Armor for Das Deutsche Stechen Course from the Wallace Collection	German	c. 1485	96 lbs	Ashdown 1967: 239,309
Armor for the Joust (Gestech)	German (Augsburg)	c. 1500	90 lbs 1.5 oz	Blair 1958: 192
Armor for Plankengestech	North German	3rd quarter of 16th c.	64 lbs 6 oz, (See Fig 3.3)	HAM 2610.1
Armour for the Tilt (A47)	German (Augsburg)	c. 1590	68 lbs 6.5 oz Much like the Armor for the Plankengestech in Fig 3.3, but has a smooth (plain) manteau.	Mann 1962: 56
Armour for the Tilt (A48)	German (Augsburg)	c. 1590	73 lbs 14.5 oz Much like the Armor for the Plankengestech in Fig 3.3.	Mann 1962: 59
Armour for the Tilt (A49)	German (Augsburg)	c. 1590	73 lbs 11 oz Much like the Armor for the Plankengestech in Fig 3.3, but has a smooth (plain) manteau.	Mann 1962: 61
Ballienrennen Armor	German (Saxony)	1590-1600	95 lbs	HAM 2548 & 2586.1
Shoulder Targe (A348)	German	1550-1590	4 lbs 6.5 oz A differently named Manteau d'Armes.	Mann 1962: 212
Stechzeug (tilting armor)	German (Nuremberg)	1500-1540	60 lbs 5 oz	HAM 2580
Helms				
Brocas Heaume	????? (Probably English due to date reference)	Time of Henry VII (1485-1509)	22.5 lbs	Ashdown 1967: 273

Compiled List of Jousting Equipment				
Item	**Origin**	**Date**	**Physical Characteristics**	**Source**
Close-Helmet for Field or Tilt (A169)	German	1560	7 lbs 3 oz Globular form; holes on both sides allow mounting of reinforcing plate for tilt.	Mann 1962: 138
Close-Helmet for Field or Tilt (A170)	German (Augsburg)	c. 1560	12 lbs 14.5 oz 12.375 inches in height. Globular form.	Mann 1962: 139
Close-Helmet for the Tilt (front piece) (A188)	German	c. 1560	12 lbs 6 oz Front piece only.	Mann 1962: 150
Close-Helmet for the Tilt (A190)	German (Augsburg)	c. 1590	12 lbs 8 oz 12 inches in height	Mann 1962: 152
Globular Helm from the Armour for the Tilt (A47)	German (Augsburg)	c. 1590	15 lbs 5.5 oz	Mann 1962: 56
Globular Helm from the Armour for the Tilt (A48)	German (Augsburg)	c. 1590	15 lbs 10.5 oz	Mann 1962: 59
Globular Helm from the Armour for the Tilt (A49)	German (Augsburg)	c. 1590	17 lbs 2.5 oz	Mann 1962: 61
Great Helm (for the Tilt) (A186)	English	c. 1515	16 lbs 10 oz 13.5 inches in height Frog-mouthed form: formed of two pieces ranging in thickness from 0.09375 – 0.4375 inches. *Believed to be the same piece as the "Wallace Heaume" referred to by Ashdown.	Mann 1962: 148
Tilting Helm (A191)	Italian	c. 1570	11 lbs 10.5 oz Globular form.	Mann 1962: 152
Tilting Sallet and Buff (A189)	German (Saxon)	c. 1570	Sallet: 6 lbs 11 oz Buff: 5 lbs 5.5 oz	Mann 1962: 151

Compiled List of Jousting Equipment				
Item	**Origin**	**Date**	**Physical Characteristics**	**Source**
Stechhelm	Augsburg	c. 1500	19 lbs 11 oz	Blair 1958: 192
Wallace Heaume	?????	c. 1515	14 inches in height	Ashdown 1967: 273
Horse Equipment				
War Saddle (A404)	Innsbruck	1549	33 lbs	Mann 1962: 227

Table 3.1 Compiled List of Example Pieces of Equipment for the Joust

4 Analyzing the Joust

There are many factors to be considered when analyzing a collision event such as a joust. The first step is to understand qualitatively the physical events that are occurring, what types of forces are being applied, and the potential results of those force applications. Following an understanding of the physical characteristics of the joust, actual quantitative analysis methods can be applied, which allow for more accurate determination of impact results (e.g. lance breakage). This section begins with a qualitative analysis of the impact involved in a joust, followed by a look at various quantitative methods of impact analysis. The final section covers the use of impact simulation via computer modeling methods.

4.1 Qualitative Understanding

In order to properly model a joust, a basic understanding of the physical events occurring is necessary. The discussion presented here will attempt to list all conditions, forces and potential outcomes of a jousting event. The answers will be sought to such questions as:

What forces would cause a lance to shatter?

What conditions would leave a lance intact and unhorse a rider?

Does the angle of the lance conclusively determine a win or loss?

It is beneficial to approach these questions by analyzing the physical aspects of a joust in stages. First, a very simple model of the situation is created. In this initial stage, many of the more complicated factors of the real-life situation are ignored so that focus can be placed on the most basic aspects of the impact. Then, in successive stages, new elements are added to the analysis model in order to more accurately represent the actual real-life situation. This incremental approach allows more complicated situations to be built on a solid understanding of the underlying aspects.

Stage One

At Stage One the following parameters are assumed:

- The two riders, the Black Knight and the Gray Knight, are of equal size and wearing similar armor. Both horses are also of equal size.
- One rider, the Black Knight, is armed with a lance; the other rider, the Gray Knight, is unarmed, basically a target.
- Both the Gray Knight and the Black Knight are rigidly attached to their horses and cannot be unhorsed or moved.
- The Black Knight has an infinitely strong arm, and his grip on the lance is unshakeable.
- The lance has its normal physical characteristics and is breakable.

Stage One considers the following:

- How does the aim of the lance affect the forces felt by the lance, and its chances of shattering?

Stage One Analysis

Stage One provides one of the simplest analysis scenarios for modeling a joust. Since only one of the jousters, the Black Knight, has a lance, the case of a double hit is removed from consideration. Also, with both jousters rigidly attached to their mounts, unable to be unhorsed, and the Black Knight's unshakable grip on his lance, the focus is placed only on the forces directly affecting the lance.

When the Black Knight comes into contact range with the Gray Knight, his lance may strike the Gray Knight, with results dependent upon the orientation of the Black Knight's lance at the moment of impact. This orientation can be described with two angles, Φ and Θ. The angle Φ is measured down from a horizontal plane, parallel to the ground, placed just below the Black

Knight's shoulder. This angle describes the vertical striking location of the lance. The angle Θ is measured horizontally towards the Gray Knight from the vertical plane, parallel to the direction of travel, aligned with the Black Knight's right shoulder. This angle describes the horizontal striking location of the lance. Φ is shown in Figure 4.1, and Θ is shown in Figure 4.2.

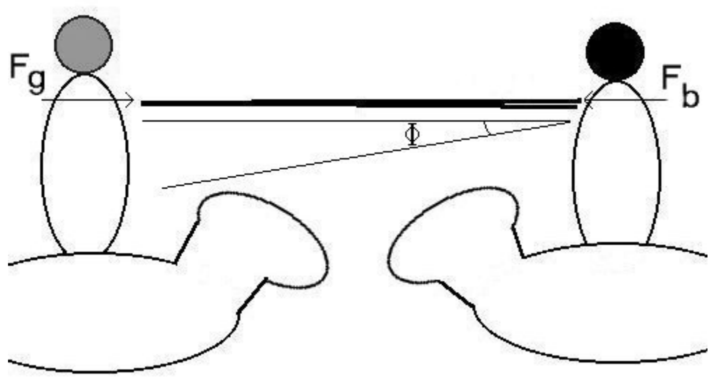

Figure 4.1 Side View of Stage One Scenario

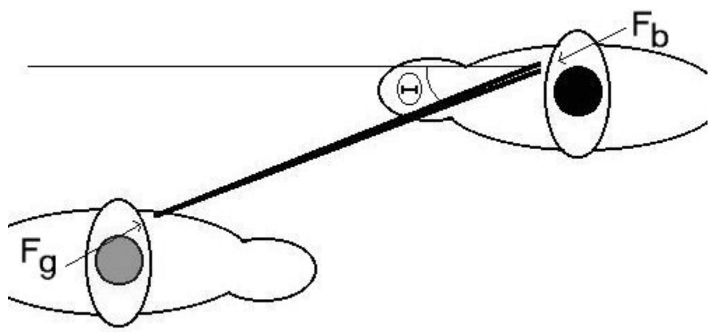

Figure 4.2 Top View of Stage One Scenario

The angle Φ will be assumed to be 0^O for Stage One. This assumption is reasonable as the two knights and horses in this scenario are of equal size, and a lance is couched under a knight's armpit, which is almost directly opposite the upper chest of his opponent, the area most commonly targeted in jousting. Thus, as long as the Black Knight can hold his lance steady, he should strike the Gray Knight's upper chest and his lance will be approximately horizontal ($\Phi = 0^O$). The angle Θ will affect several factors of the joust: whether or not a hit is scored, and how sound the blow is (Was it a solid hit or just a glancing one?). If Φ were allowed to vary, it would have much the same effects, simply in the vertical plane, while Θ affects the horizontal plane.

If Θ is too shallow, the lance is aligned nearly parallel to the direction of travel, and the Black Knight simply will not strike the Gray Knight. If Θ is increased slightly, so as to allow the Black Knight's lance to come into contact with the Gray Knight, then the soundness of the blow must be determined. If the Black Knight's lance strikes the Gray Knight, but Θ is a shallow enough angle, the hit will strike the edge of the left shoulder or arm of the Gray Knight. Striking the edge of the Gray Knight's armor, the Black Knight's lance will not obtain a good purchase, and the lance tip will most likely be deflected. However, if the Θ describing the Black Knight's aim is larger, such that the lance strikes nearer to the center of the Gray Knight's torso, the lance head will be less likely to be deflected and the blow will be much more solid. The more solid the blow is, the greater the forces felt by the Black and Gray Knights and applied to the lance.

When a hit is scored, the Black Knight's velocity and mass translate into a force, F_b, which is applied to the lance through his grip. The Gray Knight also applies a force, from his velocity and mass, on the lance, F_g, which is applied through the contact between the lance tip and his armor. The lance will apply forces back on the Black and Gray Knights. If the lance is stout enough, these forces will be equal in magnitude to the ones applied by the knights. However, if the compression force that the lance can withstand is less than the forces applied by the two knights, the lance ends will be accelerated towards one another and the lance will break.

This breakage could be a shearing break or a snapping of the lance. In the case of a solid shaft lance, the lance cannot bend much perpendicular to the shaft. Thus, when a hit is scored, the forces will press the lance ends together, but the lance will remain generally straight. If there is a defect, such a knot, in the wood of the shaft, a weak point exists there, which could break if the two ends of the lance are compressed together with enough force. The two parts of the lance would slide past each other, creating a relatively smooth, shearing break. If the lance does not have any defect, it will withstand a greater compression force before breaking.

The lance could also potentially be oriented such that it would bend under the compression forces at the two ends. Again, this would create a single break point, but it would be a snapping, like breaking a toothpick in half, creating very jagged, uneven break ends. In the case of a jointed, hollowed out, lance, which has strength less than that of a solid shaft lance, the compression forces are more likely to create a bending, as there is more flex to the shaft. When this bending goes beyond the strength of the lance, it will snap. Since the lance is hollowed, the snapping break causes the lance to explode in a shower of splinters.

Stage Two

At Stage Two the following parameters are assumed:

- The two knights and the two horses are still of equal size.
- The Black Knight is still armed and the Gray Knight is still an unarmed target.
- The Gray Knight is no longer rigidly attached to his horse, but sitting in a jousting saddle, gripping with his legs. The Black Knight is still rigidly attached to his horse.
- The Black Knight still has an unshakeable grip on his lance.
- The Black Knight's lance is now infinitely strong and unbreakable.

Stage Two considers:

- How does the aim of the lance affect the forces felt by the Gray Knight and the chances of him being unhorsed?

Stage Two Analysis

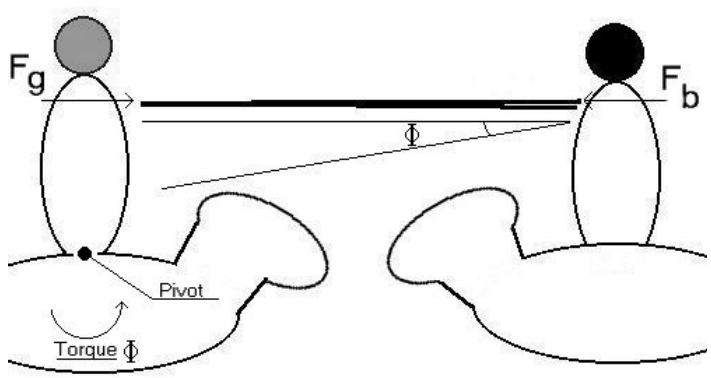

Figure 4.3 Side View of Stage Two Scenario

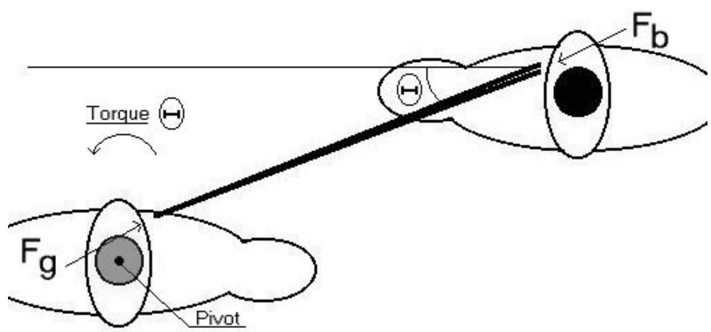

Figure 4.4 Top View of Stage Two Scenario

Stage Two looks at another relatively simplified scenario. The lance has been made unbreakable so that it can withstand any forces applied to it and completely transfer, through its shaft, the forces generated by the two knights. Now that the Gray Knight is no longer rigidly attached to his horse, the focus is moved from the lance, and its breakage, to the Gray Knight and the factors leading to an unhorsing.

As with Stage One, the orientation of the Black Knight's lance will have a great effect on the results of the collision, but the considerations will be somewhat more complicated. The definitions of the two angles, Φ and Θ, do not change, but some of assumptions made in Stage One must be changed or removed. Firstly, the angle Φ is no longer assumed to be equal to 0^{O}. This assumption was acceptable for Stage One because the focus was on the lance, and the vertical striking point of the lance did not have a great effect on the forces applied to the lance.

However, in this stage, the vertical striking location will affect the forces and torques felt by the Gray Knight when struck, as will be detailed later. The value of Φ is assumed positive below and negative above the horizontal plane described in Stage One. Also, the values of Φ and Θ are assumed to be such that the Black Knight's lance always strikes the Gray Knight; the case of a miss was covered sufficiently in Stage One.

When the Gray Knight is seated in his saddle, he can be thought of as two separate bodies, attached by a pivot point. One body is made up of his pelvis and legs, which are gripping the saddle and horse; the other is made up of his armored torso, arms, and head. The two are connected by a pivot point located somewhere near where the Gray Knight's spine is attached to his pelvis. This is where most of the Gray Knight's movement is during the joust, as his upper spine will not bend much due to the rigidity of his armor. The Gray Knight's upper body will be mobile, able to lean to his left, right, front, back, or somewhere in between, such as forward to the left, as well as rotate, such as turning his chest to face left; his legs will stay basically in the same place, gripping the saddle and horse.

When the Black Knight's lance hits the Gray Knight, a force is applied toward the Gray Knight, focused at whatever point was struck. If the Black Knight were somehow able to strike directly at the Gray Knight's pivot point, the force would be applied directly along the direction of the lance and the Gray Knight would be accelerated, pushed, in that direction. However, as was stated in Stage One, the Black Knight is targeting the upper chest of the Gray Knight. The Black Knight's lance will hit at some point away from the Gray Knight's pivot point. The force of the Black Knight's hit will still push back on the Gray Knight, but it will also induce a torque, causing the Gray Knight to rotate about his pivot point.

If it is assumed that the lance hits the Gray Knight in the center of his chest, directly above the pivot point, the torque applied to the Gray Knight will cause him to lean backwards, toward the back of the horse. If the lance hit is assumed to be on the Gray Knight's lower torso, in the area of the pelvis, directly to the left or right of the pivot point, the torque will cause the Gray Knight's body to rotate to one side. Since most lance blows are to the upper left of an opponent's chest, there will be a combination of these two effects. These torques will create a twisting that is likely to create a greater strain on the Gray Knight's grip on his saddle and horse, increasing the chance of unhorsing.

The further away from the pivot point a force is applied, the greater the torque induced. In the vertical case, a larger positive value of Φ will strike lower on the Gray Knight's chest, closer to the pivot point, and cause a smaller torque, while a smaller positive Φ will strike higher and cause a larger torque. If the strike is above the horizontal, a negative Φ, the blow will be even further from the pivot point, causing an even larger torque. In regards to the horizontal orientation, a smaller value of Θ will mean a strike on the edge of the Gray Knight's armor, further from the pivot point, and cause a greater torque, while a larger Θ will be closer to the pivot point and cause a smaller torque. There is a point where Θ will become large enough that the lance strike is at the center of the Gray Knight's torso, aligned with the pivot point. Any increase in Θ will mean a strike on the far side of the Gray Knight's body, his right side, and will cause an increasing torque as Θ increases, but result in a twisting in the opposite direction. This case is ignored however as striking the far side of the Gray Knight would be difficult considering his horse's head would block the Black Knight's aim.

If the vertical torque applied to the Gray Knight is large enough, he will be forced back, with his upper body aligned more parallel than perpendicular to the horse's body. If pushed back far enough, the Gray Knight will be less able to keep his center of gravity over his base, the seat of the saddle, and could more easily fall off the horse. As for the horizontal torque, this will create more of a twisting effect on the Gray Knight, which could loosen the grip of his legs on his horse and saddle. Combining these torque effects on the Gray Knight's ability to maintain his seat on his horse and the force against the Gray Knight's direction of travel, unhorsing becomes more likely. If there were no torque effects, simply a force directed against the Gray Knight, he would only need to be able to overcome that force with his seat on his horse. However, with the torque effects, the Gray Knight must also try to prevent his body from being twisted and turned out of position.

Based on these considerations, a smaller value of Φ and a smaller value of Θ are desirable, as they would describe a blow further from the pivot point in both the vertical and horizontal planes, which would increase the twisting effect mentioned above. However, as discussed in Stage One, a smaller value of Θ, such that the lance hits the outside edge of the Gray Knight's armor, is less likely to obtain a good purchase, and more likely to simply be deflected. This is also true for a Φ that becomes increasingly negative; the strike will hit higher on the armor and could simply clip the top edge of the shoulder, creating another deflected hit. Thus, the ideal target location would fall in the upper left part of the Gray Knight's armor. This would provide a location that is both away from the pivot point, creating a suitable torque value, and that provides good purchase to a lance hit, allowing the force to be fully applied to the Gray Knight. This consideration can be seen in the design of jousting armors, in the leather targets and manteau d'armes used in various forms of armor. (See Section 3.2)

Stage Three

At Stage Three the following parameters are assumed:

- The two knights and the two horses are still of equal size.
- The Black Knight is still armed and the Gray Knight is still an unarmed target.
- The Gray Knight is still unhorseable and the Black Knight is still rigidly attached to his horse.
- The Black Knight still has an unshakeable grip on his lance.
- The Black Knight's lance now has its normal physical characteristics and is again breakable.

Stage Three considers:

- Can a lance be shattered and the opposing rider unhorsed in the same blow?
- Do the conclusions reached in Stage One and Stage Two still make sense when the two situations are combined?

Stage Three Analysis

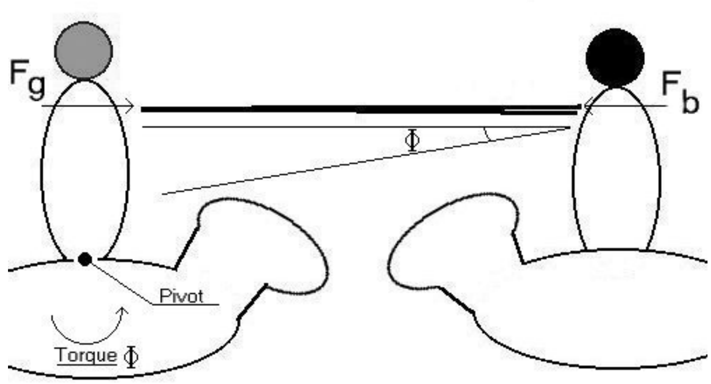

Figure 4.5 Side View of Stage Three Scenario

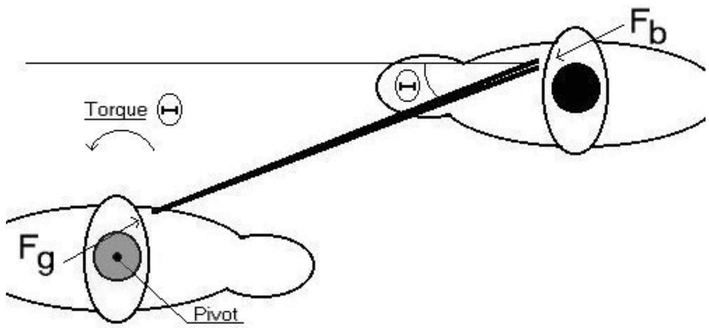

Figure 4.6 Top View of Stage Three Scenario

Stage Three combines the situations studied in Stage One and Stage Two. The focus of Stage Three is to analyze the results when it is possible to both unhorse an opponent and shatter one's lance.

As discussed in Stage One and Stage Two, a lance strike that is on the edge of the armor or a miss will most likely not result in a decisive outcome (shattered lance or unhorsed opponent). With a glancing blow, the forces applied are smaller compared to those possible when a solid hit is scored. Under these circumstances, the lance would need to be rather flimsy to shatter, or the Gray Knight would need to have a weak grip on his saddle to be unhorsed.

One situation where this may not be the case is with a three-pronged coronel and a manteau d'armes. It is possible, with the raised trellis on most manteaus, that the coronel could get caught even it struck the edge of the manteau. In this case, the forces felt would be closer to those of a more solid hit, but since only one or two prongs of the coronel gain purchase, a torque will be created near the end of the lance. Since the Black Knight has an unshakeable grip on his lance, the shaft will be aligned in its initial direction while the tip will be bent toward the Gray Knight. If the torque created is great enough, the lance could be broken somewhere along the shaft, near the tip. Because the torque acts against the diameter of the lance, rather than against the length as compression forces do, a smaller force is necessary to cause a break. Thus, it is unlikely that a well-seated Gray Knight would be unhorsed in the case of a coronel prong caught on a manteau d'armes.

In the more common, and overall more interesting, case of a lance hit that obtains a solid purchase on the Gray Knight's armor, the two important factors are the strength of the lance's shaft and the strength of the Gray Knight's grip on his horse. In most cases, only one outcome will occur, either the lance will be shattered, or the Gray Knight will be unhorsed. This is due to the effects of the Gray Knight's grip on his horse. If the Gray Knight has a sound grip on his horse, and can maintain his position under the force from the Black Knight, then the lance will be compressed between the two knights and is more likely to break. However, if the Gray Knight is unable to maintain his grip on his horse, the force from the Black Knight will be transferred through the lance to the Gray Knight and he will be unhorsed and not able to apply as great a force back on the lance. It is possible, if the force from the Black Knight were great enough and the Gray Knight's seat sound enough, that the Gray Knight would be unhorsed, but also apply enough back force to cause the lance to be shattered. The major question is: which can better withstand the impact force, the Gray Knight or the lance?

Stage Four

At Stage Four the following parameters are assumed:

- The two knights and the two horses are still of equal size.
- The Black Knight is still armed and the Gray Knight is still an unarmed target.
- Neither the Black Knight nor the Gray Knight is rigidly attached to their horses; only their grips on their saddles keep them atop their mounts.
- The Black Knight still has an unshakeable grip on his lance.
- The Black Knight's lance has its normal physical characteristics and is breakable.

Stage Four considers:

- Is it possible for a jouster to be unhorsed by his own lance blow?
- Do the conclusions from previous stages still make sense?

Stage Four Analysis

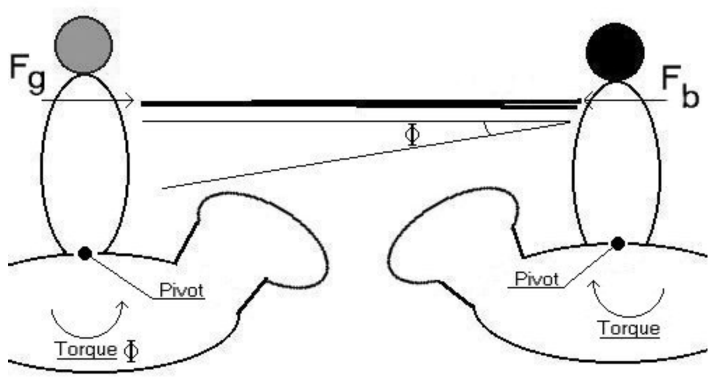

Figure 4.7 Side View of Stage Four Scenario

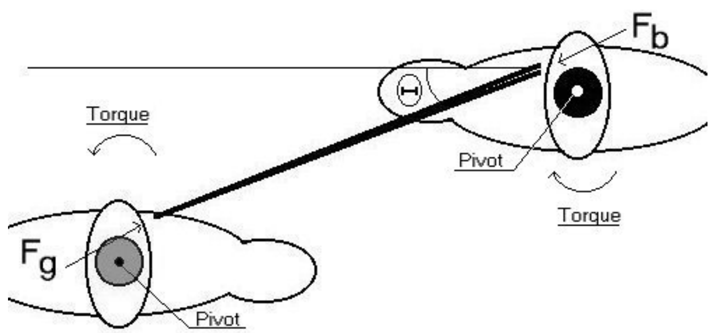

Figure 4.8 Top View of Stage Four Scenario

Stage Four moves closer to the real world situation in that the Black Knight can now be unhorsed as well. Now, the Black Knight's grip on his horse is just as important as the Gray Knight's. Should the Black Knight be unable to maintain his grip on his horse, the same force that would have unhorsed the Gray Knight in Stage Three could now unhorse the Black Knight.

When the Black Knight's lance impacts upon the Gray Knight, the Gray Knight feels a force generated from the Black Knight's momentum and transferred through the lance. The action-reaction law of forces states that the Gray Knight will also create a force that will be equal in magnitude, but opposite in direction, to the one he feels from the lance. Thus, the Black Knight is hit with the same force as the Gray Knight. The major difference between the two hits is that the effectiveness of the one upon the Gray Knight is dependent upon the Black Knight's ability to aim and strike in the proper location, while the one the Black Knight feels is always located in the same place, just under his shoulder where the lance is couched.

Because the Black Knight has his lance couched under his right arm, the reaction force from the Gray Knight will be applied to this area, which is the outer edge of his upper torso, the ideal location for a lance strike, as determined in Stage Two. The force will push back on the Black Knight and create a torque about his pivot point, as defined in Stage Two. Thus, the Black Knight experiences approximately the same unhorsing factors as the Gray Knight, a force pushing him back, off his horse, and a torque twisting him in his saddle.

The Black Knight does gain an advantage due to the fact that he is holding the lance. When the impact occurs, the lance tip is in contact with the Gray Knight for a very short period of time; this means that the Gray Knight feels a severe jolt. Meanwhile, the Black Knight is in contact with the lance for a long period of time before the impact, during the impact, and, assuming he has a sound grip on his lance, a long period of time after the impact. Thus, the Black Knight will feel a less severe jolt, the impact will be spread over a longer time period; the longer an impact lasts, the less extreme the effect. Thus, the Black Knight will have somewhat less of an unhorsing effect to deal with than the Gray Knight, giving the Black Knight an edge. The result of this additional element is that while trying to maintain his aim, the Black Knight must also be concerned with maintaining his grip on his horse, as the Gray Knight had to in Stages Two and Three.

Stage Five

At Stage Five the following parameters are assumed:

- The two knights and the two horses are still of equal size.
- The Black Knight is still armed and the Gray Knight is still an unarmed target.
- Neither the Black Knight nor the Gray Knight is rigidly attached to their horses; only their grips on their saddles keep them atop their mounts.
- The Black Knight no longer has an unshakeable grip on his lance; the lance can be jarred from his hands.
- The Black Knight's lance has its normal physical characteristics and is breakable.

Stage Five considers:

- How does the grip on one's lance affect his ability to unhorse his opponent (or himself) and/or shatter his lance?
- Do the conclusions from previous stages still make sense?

Stage Five Analysis

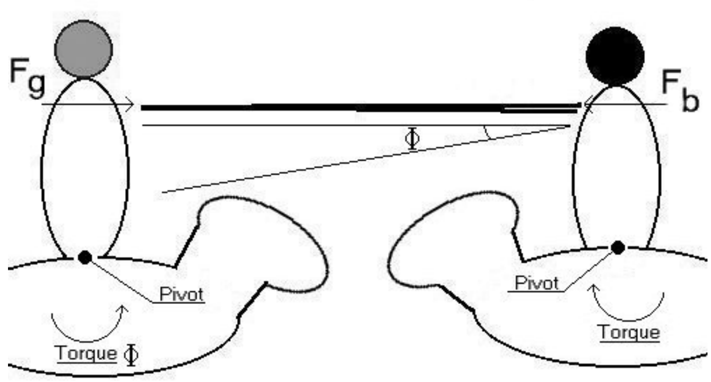

Figure 4.9 Side View of Stage Five Scenario

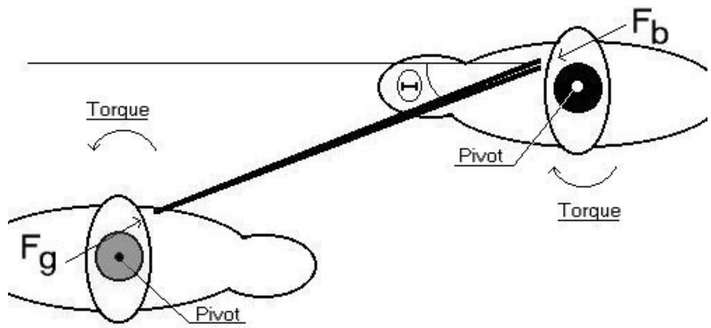

Figure 4.10 Top View of Stage Five Scenario

At Stage Five, the chances of the Black Knight being unhorsed are reduced somewhat as he no longer has an unshakeable grip on his lance. Thus, when the Gray Knight is struck and holds his seat, the return force created may unhorse the Black Knight, if he maintains his grip on the lance, or the lance may simply be jarred from the Black Knight's grasp.

Now that there is the possibility of the Black Knight simply dropping his lance, the chances of his unhorsing are altered. As stated in Stage Four, the Black Knight feels a return force from the impact with the Gray Knight. If the Black Knight can maintain his grip on his lance, the force and torque effects contributing to unhorsing will be as in Stage Four. If, on the other hand, the Black Knight loses his grip for some reason, he may or may not be in danger of unhorsing, which is somewhat dependent upon the equipment used.

First, the Black Knight's ability to hold onto his lance could be aided by additional equipment. If the lance is a simple, straight shaft lance with no extra pieces (e.g. grapper) and the armor is simple, no lance-rest or queue, then only the Black Knight's hand and crux of his arm are holding his lance in place. In this case, the impact could simply force the lance backwards, such that it slides out of the Black Knight's hand. Alternatively, if the Black Knight's hand maintains its hold, the impact force could twist the Black Knight's arm backwards, causing him to simply drop the lance, perhaps breaking his arm as well.

If the Black Knight's armor is using a lance-rest or queue, he needs to worry less about holding the lance horizontal, due to the support of these attachments; they remove the chance of the lance simply being dropped. He can then use more of his arm strength to hold the lance in place, preventing it from being forced back during the impact. The Black Knight's ability to grip the lance with his hand would be improved if the area of the lance near his body were thinner than the rest of the lance, as with the 15^{th} c. design described in Section 3.1. This would allow the Black Knight's hand to better wrap around the lance and hold it steady.

If for some reason the Black Knight does lose his grip, whether or not the hit is still solid will depend on further equipment. The lance could be fitted with a grapper, a circular metal plate mounted on the lance to engage the lance-rest when the lance is forced back during impact, keeping the lance forward. If the lance has such a device, then as long as the it remains in the Black Knight's armpit, as it might if it were supported in a queue, the lance would be supported by the bulk of the Black Knight. The same impact force discussed in previous stages will be felt by the Black and Gray Knights, creating the unhorsing potential. Even a vamplate could prove useful in this aspect, since its large surface area would allow it to be caught by the Black Knight's upper arm and torso armor. If none of these items is attached to the lance, or it fails to accomplish its purpose, then the impact will force the lance backwards, resulting in a reduced impact force being felt by the two knights.

Stage Six

At Stage Six the following parameters are assumed:

- The sizes of the knights and horses may vary and be unequal.
- Both the Black Knight and the Gray Knight are armed.
- Both knights are only attached to their mounts by their grips on their saddles.

- Both knights have shakable grips and could drop their lances.
- Both knights' lances have their normal physical characteristics and are breakable.

Stage Six Analysis

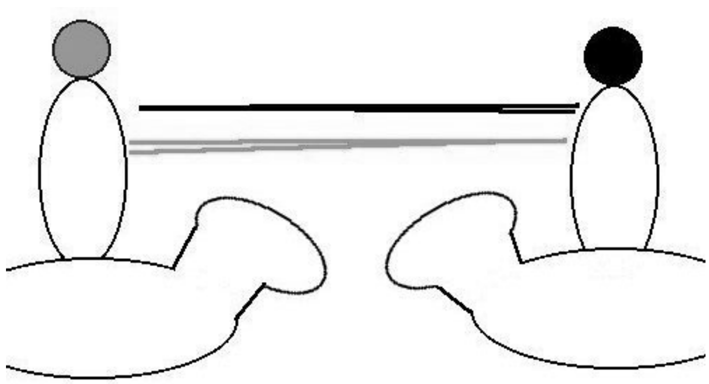

Figure 4.11 Side View of Stage Six Scenario

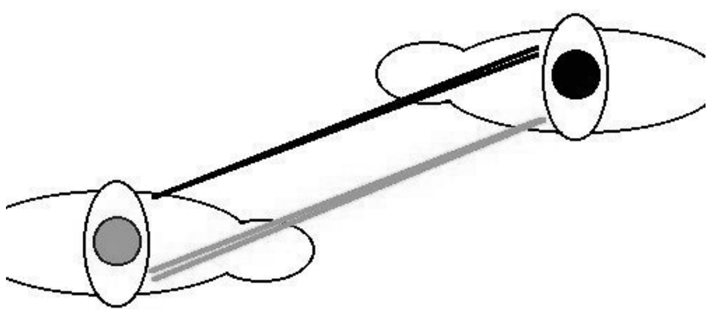

Figure 4.12 Top View of Stage Six Scenario

At Stage Six, the model has reached the level of complexity involved in the real world situation. The results and conclusions of the previous stages can be used to make predictions about the outcomes at Stage Six.

Now that the Gray Knight has a lance and is attacking the Black Knight, the complexity of the situation is greatly increased. The Black Knight not only needs to maintain his grip on his horse under the force from his lance strike upon the Gray Knight, but he must also deal with the possible strike from the Gray Knight's lance. The analysis of two possible lance hits becomes complicated. If both lances are assumed to be the same length, and both knights aim well, both lances will strike at approximately the same time. In this case, each knight would suffer less twisting in the saddle from a torque around his vertical pivot axis. The torque created on the Gray Knight's left shoulder by the Black Knight's hit would be countered by the torque on his right shoulder from the return force from his hit on the Black Knight. The Black Knight would feel the same torque cancellation. This would result in the knights feeling most of the force simply pushing them back out of their saddle, rather than causing them to twist in their seat.

However, this situation is unlikely as variations in lance length, riding position, lance aim, etc will cause the strikes to be offset and different torques generated. The more likely situation is that the strikes, if both knights hit, will occur at different times. For example, the Black Knight could be turned slightly so that he has a small amount of extra reach over the Gray Knight. The Black Knight's lance would strike the Gray Knight first, and the situation would be the same as in Stage Five.

Then, a very short time later, the Gray Knight's lance hits the Black Knight. By this point, the Black Knight's lance will have had most of its effect on the Gray Knight. However, even if both knights held their seats against the force, they will have moved somewhat. Perhaps the Black Knight's hit lifted the Gray Knight out of his saddle somewhat, but the Gray Knight was able to remain atop the horse. This means that the Gray Knight will not be in the same position when his lance hits the Black Knight, as he was when the Black Knight's lance hit him. Thus, it could be easier for the Gray Knight to unhorse himself, if the Black Knight can manage to hold his seat during the Gray Knight's hit. The Black Knight could also have been lifted out of his seat by his own lance strike, giving him a somewhat weaker hold on his horse. Here, it is easy to see where a knight's skill and strength play an important role, in both his ability to strike his opponent and to withstand a strike himself.

Another interesting element is the effect of varying sizes of knights, horses, and equipment. If the Black Knight has a larger mass, heavier armor, a larger horse, and/or a faster horse than the Gray Knight, he would have some advantage. Additional mass and velocity result in a greater momentum, and greater momentum results in the ability to apply a greater force. Thus, the impact force from the Black Knight would be greater than that from the Gray Knight. Also, if the Black Knight has additional body or armor mass, he has a greater inertia. This greater inertia makes it harder to accelerate, or move, the Black Knight. Thus, if the Gray Knight were just barely able to unhorse the Black Knight with some impact force F_g when the Black Knight were his initial mass, he would need a force greater than F_g to unhorse the Black Knight at an increased mass. Else, if the Gray Knight applied the same force F_g to the heavier Black Knight, the Black Knight would not be accelerated as much, and possibly no longer unhorsed by the blow.

There are many factors to be considered when analyzing a collision such as a joust. The location of the lance strike has a great effect on the impact forces felt by both combatants. Additionally, the abilities of each jouster affect their response to the impact force, and how well they maintain their position on their horses. However, by reconstructing the scenario through the six stages laid out above, beginning with a simple model and adding elements until the real-life situation is achieved, a solid understanding of the situation is gained. With this understanding in hand, analysis methods can be selected to determine specific details about the collision. The next section describes some of the possible methods to use, and their pros and cons.

4.2 Quantitative Analysis

Several methods/models are available to analyze the details of collisions, many designed for specific types of collisions. Two of these methods, rigid body collision and wave propagation, seem to be appropriate for a joust situation. Rigid body collision analysis is used to describe and determine the forces during a collision of two basically spherical bodies, or one spherical body against a rigid shell; for the purpose here, the shell would be the suit of armor surrounding a knight. Wave propagation is used to describe and determine the forces when a rod-shaped object is hit on the end, such as a hammer striking a nail, or a lance against an armored knight.

A rigid body collision model alone is inadequate to describe an entire joust collision event, as the equations fail when a rod shaped object is used, i.e. a lance shattering. A wave propagation model must be used to analyze the effects on the lance. However, wave propagation alone is also inadequate to describe the whole event, as the equations break down when the object striking the end of the rod is not the proverbial immovable wall.

The total situation must then be split into two parts. The first would describe the forces applied by the lance against a jouster's armor. The rigid body method of a sphere against a shell would be used to determine forces acting on the target jouster. In this case, the lance is simplified to be a spherical object colliding with the jouster's armor, assumed to be a rigid shell. The second part of the situation would describe the force applied by the jouster back on the lance, as if he were an immobile wall, onto which the lance, a rod-shaped object, had been thrust. The wave propagation model would then be used to determine the effects on the lance.

Another useful analysis method to consider is impulse and momentum balancing. Impulse is the quantity of force multiplied by time and is equal, on each body, for any two colliding bodies. For the model being developed here, this is especially important, as a knight with a short collision time, such as the knight on the receiving end of a lance strike, feels much more force than a knight with a long collision time, the knight holding the lance, with which he never loses contact, unless he drops his lance. Momentum balancing, on the other hand, would be an oversimplification of the model. Momentum is used to determine the ending, after the collision, velocities of two colliding objects, given their masses and velocities before the collision. However, simplifying the model to a basic momentum-balancing problem may be useful, especially when the lance is assumed unbreakable, as an extra check against the accuracy of the results of a more complicated model; momentum balancing can provide a rough idea of the forces that can be expected.

Impulse and momentum balancing would be computationally simple, and would yield basic information about the collision, such as forces acting on the knights, and a probable outcome of the collision, but all in a very simplified sense. The suggested rigid body/wave propagation model would yield much more specific information, such as deformation of the armor and lance breakage, and would provide a much more accurate picture of the results of the collision. This more complex model, however, can be tedious and very complicated, and may require several hours of compute time to complete analysis for just one collision.

4.3 Computerized Joust Collision Model

One tool available for collision analysis is computer simulation. The purpose of this project is to develop a computer model of a joust to provide a feel for the collision to someone interested in a more qualitative sense, such as a museum visitor. There are already software packages on the market that can provide detailed quantitative analysis of impact forces and object deformations during a collision. As discussed in the previous section, many of the analysis methods for collisions are very computationally intensive. Using simulation software, the grinding work of the calculations is automated and results are somewhat more reliable.

However, the calculations are still rather time consuming, depending upon the complexity of the situation; even a "simple" scenario can take an hour or more for analysis to complete.

Dr. Malcolm H. Ray, an Associate Professor of Civil and Environmental Engineering at WPI, made available for use in the project some of his department's collision simulation resources. With the help of one of Dr. Ray's assistants, Charles Plaxico, three-dimensional representations of jousting armor and a lance head were created. The intention was to create three-dimensional models of pieces of jousting equipment, then enter the masses of the suits of armor, lances, and riders into a simulation program, and compute some of the details of a joust collision. This simulation would have provided some idea of the forces that are present during the impact. Unfortunately, due to time constraints, the entire simulation could not be setup and completed in the timeframe of this project.

4.3.1 Measurement Methodology

In order to create three-dimensional representations of the jousting equipment for a collision simulation, example pieces needed to be measured. A coronel and lance, representative of those common to jousting, and two suits of jousting armor were chosen to be measured for the basis of the simulation. Detailed measurements of the lance were already on file at the museum; the other pieces had to be measured manually. Since the coronel was small, its characteristics were measured extensively with relative ease. However, the suits of armor, being much larger, required more involved methods. For the scope of this project, the simulation required only a rough model of armor, allowing the measurement methods to be kept relatively simple. A more simplified armor model would also reduce the complexity of the scenario and simulation time.

Initially, a reference point was chosen on each suit of armor. For both pieces, this was the most forward point on the helm, point 1 on Figure 4.14B and a similar point on the helm in

Figure 4.15B. A string was attached to this point, dropped straight down the front of the armor, and fastened at the bottom to make a reference line. Then using a carpenter's level and a ruler, each point was measured with respect to the reference point and line. The "height" of a measurement point was measured as positive down from the reference point. The "width" of a measurement point was defined as positive to the right of the reference line, when facing the front of the armor. Finally, the "depth" of a measurement point was taken as the distance from the plane of the reference line, in front of the armor, to the surface of the armor. As an example, point 8 on Table 4.3 is *above* the reference point, to the *left* of the reference line, and *in towards* the armor from the reference line.

The measurement methods used created rather crude shapes for the suits of armor, which were adequate for this project's purpose, but far from completely accurate. The reference line was a simple string, which was not very rigid, creating a reference that tended to move when trying to take accurate measurements. Additionally, the rulers used were made of flexible plastic, and the odd angles, created by the shapes of the armors, between the reference line and the measurement points made it difficult to determine if measurements were being taken properly with respect to the reference line. Also, the suits had to be measured while on their display stands, which meant holding measuring tools in mid-air at odd angles. The measured values were most likely skewed by the fatigue induced in one's arms by this awkward orientation.

At the very basic level, measurements would have been more accurate if the armors were measured with a rigid ruler and some sort of rigid reference line. Measurements could have been further improved if the armor were measured while off its display stand, allowing the armor to be oriented so as to allow a rigid reference point to be placed in a more appropriate spot, such that the angle of the armor's surface does not create difficult measuring situations. This would have also removed the fatigue factor as the armor could be placed on a table at waist level

Another method to achieve more accurate measurements of the suits of armor would be to use a device designed specifically to measure objects for three-dimensional recreation in a computer model. Such devices are computer controlled, multi-jointed mechanical arms, with a probe on the end. The probe is placed at a location to be measured on an object. The computer then places the point in a local coordinate system based on the orientation of each joint in the arm. This provides a much more accurate measurement than manual measurement with a ruler, and the data is stored immediately in digital format and can be easily loaded into modeling software.

While this project was in progress, WPI's Civil Engineering department obtained such a device, the FaroArm, produced by FARO Technologies, Inc. Dr. Ray also made offered this as being available for use in relation to this project, but unfortunately, the device arrived too late in the project to be utilized. The arm is highly portable, so it could be easily taken to the Higgins Armory Museum to measure pieces, which would remove the need to take the artifacts out of the museum, ensuring their safety. Additionally, the probe on the end of the arm is used only for location selection, and does not need any actual contact with the surface of the object being measured. This means that it can have a rubber or cloth cover placed on the end, preventing any possible damage to museum pieces. Use of WPI's FaroArm would provide a fast, accurate, and safe way to create three-dimensional models of objects for the sort of simulation work on which this project is focused.

4.3.2 Measured Pieces

The first item selected was a coronel, a lance head. The selected piece (HAM 2610.7) was a three-pronged coronel with points that flare out from the center. It originated in the area of Germany or Austria, sometime during the early 16th century. The Figure 4.13A and 4.13B are photographs of the piece and depict the major measurements taken.

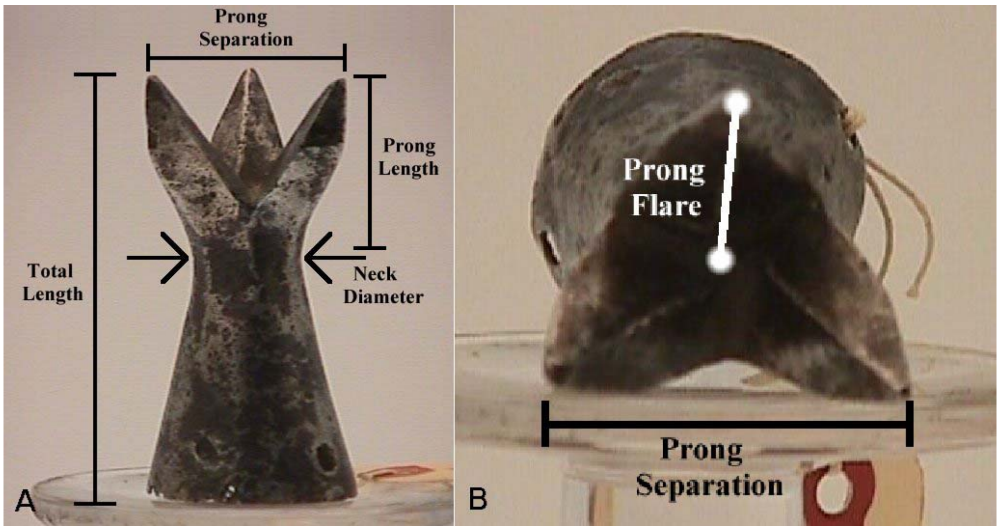

Figure 4.13A Side view of lance coronel (Higgins Armory Museum, 2610.7)
Figure 4.13B End-on view of lance coronel (Higgins Armory Museum, 2610.7)

Total Length	3.5 inches
Prong Length	1.5 inches (approximate from top of neck to tip for all prongs)
Prong Separation	1.625 inches (approximate separation between all adjacent prong pairs)
Prong Flare	1 inch (approx. distance from center of coronel to tip of prongs)
Width of Prongs	1 inch at base tapering to a point no more than 0.125 inches or so wide.
Neck Diameter	1.0345 inches (calculated from neck circumference of 3.25 inches)
Base Diameter	1.75 inches by 1.875 inches (oval shaped bottom)

Table 4.1 Lance Head Data (Measured)

To go with the coronel, an example lance was selected from the Museum's collection. The lance selected (HAM 894) was a jousting lance from 16th century Germany. It was equipped with a different type of lance head designed for a Joust of War, more pointed than a Joust of Peace coronel, but the shaft itself served as an excellent example lance.

Overall Length	134.65 inches (Including a lance tip)
Length of Lance Tip	3.27 inches
Diameter of Shaft	2.24 inches
Diameter of Lance at Base of Lance Head	1.89 inches
Weight of Lance	9.59375 lbs (4.36 kg) (Including lance tip.)
Type of Wood	Unknown (For simulation, will assume one of the common types of wood mentioned in Section 3.1.)

Table 4.2 Lance Data (Obtained from HAM Records)

Two pieces of jousting armor were also measured for the simulation software. The pieces chosen were the Stechzeug Suit (HAM 2580), from Germany (Nuremberg) during the period of 1500-1540, and the Armor for the Plankengestech (HAM 2610.1), from Northern Germany during the 3rd quarter of the 16th century. Figures 4.14A and 4.15A show the suits themselves, while Figures 4.14B and 4.15B show the locations of measurement points.

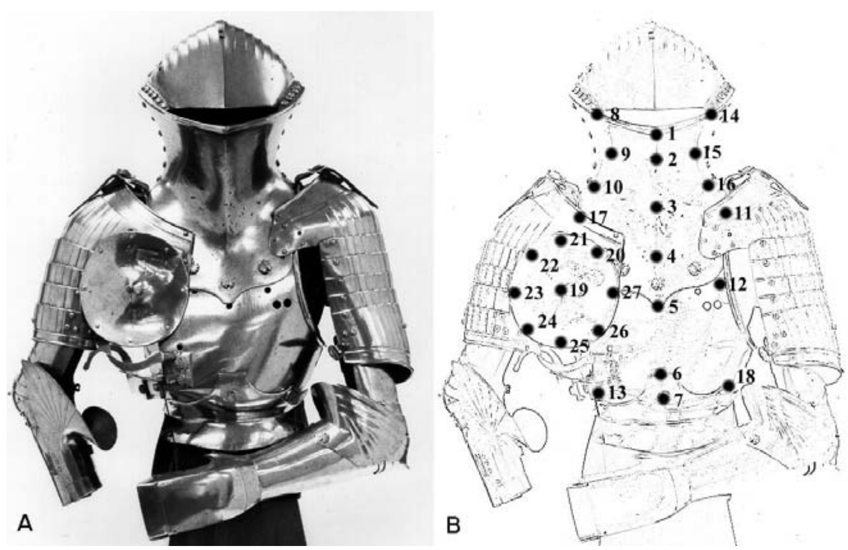

Figure 4.14A Stechzeug Armor for the Joust (Higgins Armory Museum, 2580)
Figure 4.14B Location of measurement points on the Stechzeug (Higgins Armory Museum, 2580)

Figure 4.14A depicts the Stechzeug in an alternate configuration than was measured. The small disk place on the left shoulder in the figure was actually mounted to the right shoulder when measurements were taken. The points 11, 12, 17, and 19-27 are shown above as mirrors of their actual location on the measured piece. Table 4.3 lists the measurements taken from the Stechzeug (See the Section 4.3.1 for an explanation of the meanings of "Height", "Width", and "Depth").

Point	Height	Width	Depth
1	0	0	0
2	0.4375	0	1.375
3	5.9375	0	4.3175
4	7	0	5
5	11.875	0	3.9375
6	15.875	0	2.5
7	18	0	2.9375
8	-0.75	-4.125	4.375
9	3.125	-3	6.4375
10	5.125	-3.75	7.25
11	7	-5.625	5.5
12	11.875	-5	3.9375
13	15.875	-4.75	2.5
14	-0.75	4.125	4.375
15	3.125	3	6.4375
16	5.125	3.75	7.25
17	7	5.625	5.5
18	15.875	5	3.9375
19	11.375	6.625	4.375
20	8.125	4.625	5
21	7.875	7.25	5.5625
22	9.6875	8.5625	6.625
23	12.5	8.875	6.875
24	14.75	7.5	5.625
25	13.875	5.75	3.9375
26	13.375	3.625	3.25
27	10.25	3	3.875
Weight	60.3125 lbs (27.415 kg)		

Table 4.3 Stechzeug Armor Measurements - Units: inches

For the Plankengestech Armor, only the Manteau d'Armes was measured. The manteau was designed to be the primary target for the lance when such armor was used, and would be the most likely location the impact would take place. Thus, only the manteau needed to be specifically modeled as an object in the crude simulation being constructed. The mass of the rest of the armor would simply be added to the characteristics of the manteau in the simulation. While not an accurate distribution of mass, this simplification would provide reasonable numbers when only considering impact forces.

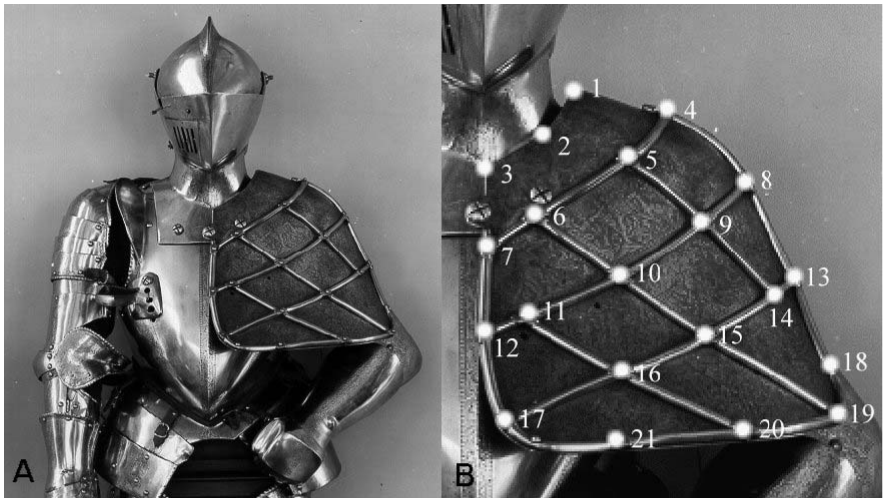

Figure 4.15A Armor for the Plankengestech (Higgins Armory Museum, 2610.1)
Figure 4.15B Measurement points on Manteau d'Armes (Higgins Armory Museum, 2610.1)

Table 4.4 lists two sets of data for the Plankengestech armor. After sketching a two-dimensional model of the first set of measurements on paper, it was found that the shape was entirely unlike the manteau, and the data had to be scrapped. Due to the limitations of the measurement methodology, discussed in Section 4.3.1, the original set of measurements had a great deal of error. A second set of measurements was taken with extra care and double-checked for accuracy; the new set produced a much more acceptable model.

	First Set			Second Set		
Point	Height	Width	Depth	Height	Width	Depth
1	0	3	9.375	5.25	4.1875	9.125
2	1.25	2.875	6.3175	6.8125	2.5	6.375
3	2.8125	0	5.25	8.1875	0.25	5.1875
4	3.6875	6.25	10.125	6.25	7.4375	9.75
5	6.3175	4.5	6.25	7.875	5.3175	6

6	4.8125	2	4.5	9.75	1.9375	4
7	5.9375	0	3.75	10.75	0.375	3.125
8	6.4375	9.25	10.625	9	10.4375	10.1875
9	8.6875	7.25	7.5	10.25	8.0625	6.9375
10	10.5625	4.125	4.75	12.125	4.6875	4.125
11	8.4375	0.5	2.5	13.125	1.625	2
12	9.375	0	1.875	13.75	0.375	1.375
13	10.3175	11	10.25	12.75	12.0625	9.8125
14	10.6875	10.125	8.375	13.125	11.3175	8.0625
15	12.8125	7	5.25	14.375	8.125	4.9375
16	13.9375	3.75	2.625	15.375	5	1.75
17	12.6875	0.75	-0.125	16.625	1	-0.875
18	13.5625	11.125	9.75	16	13.3175	8.4375
19	15.1875	12.3175	6.5	17.25	13.6875	6.0625
20	14.6875	9.1875	2.125	17.625	9	1.9375
21	14.4375	4.6875	0.5	17.625	4.75	-0.75
Weight	64.375 lbs (29.261 kg)					
Manteau Thickness	0.116 inches					
Lattice Thickness	0.375 inches					

Table 4.4 Plankengestech Manteau Measurements – Units: inches

Figures 4.16, 4.17, and 4.18 show a graphical comparison of the two sets of data. On the left is the first set, and on the right is the second set. It can be easily seen that the second set much more accurately represented the shape of the manteau d'armes.

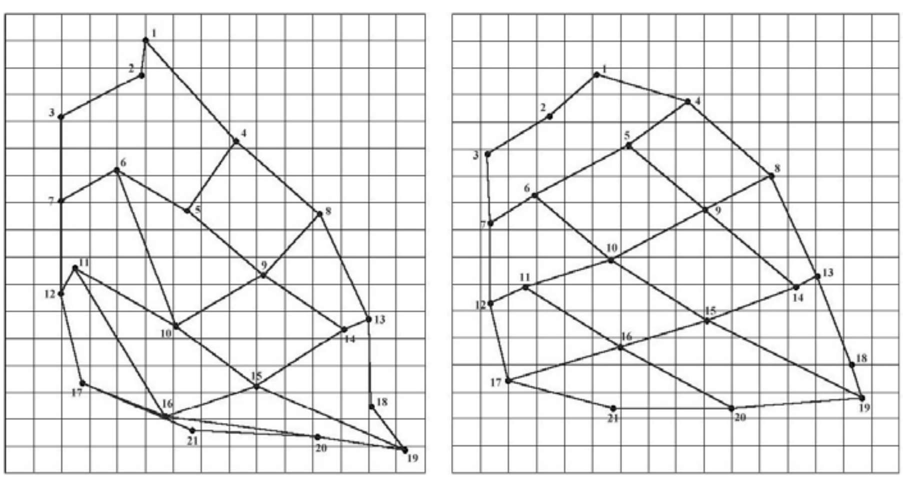

Figure 4.16 Graph of Width vs. Height Data (View of Manteau from the Front)

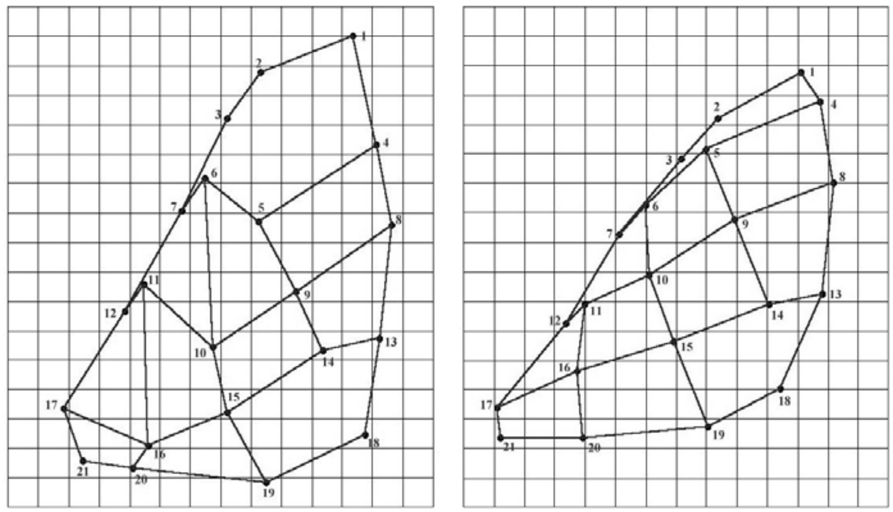

Figure 4.17 Graphs of Depth vs. Height Data (View of Manteau from the Left Side)

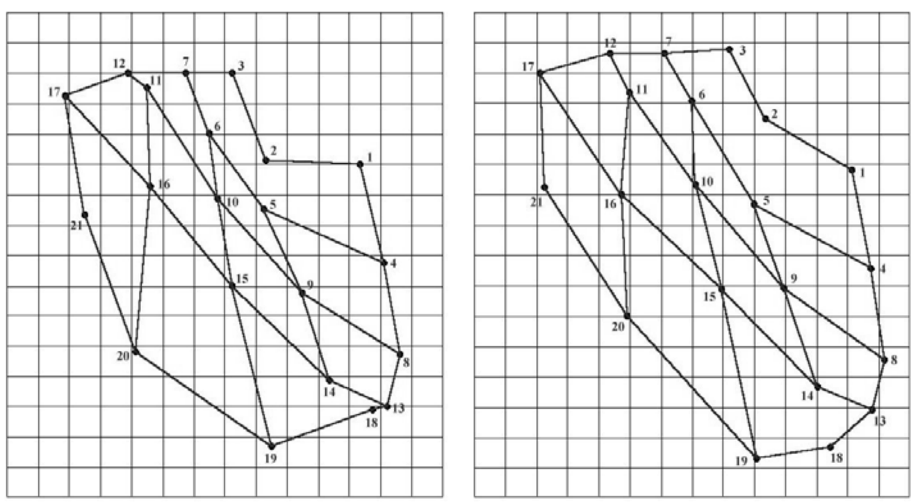

Figure 4.18 Graphs of Depth vs. Width Data (View of Manteau from the Top)

4.3.3 Model Creation and Computer Analysis

After obtaining measurements for the pieces from the museum, another meeting was held with Professor Ray and one of his assistants, Charles Plaxico; Charles was to aid in most of the work for modeling the joust collision. The set of measurements for the Stechzeug armor was not extensive enough to provide a complete three-dimensional model; many more points were necessary, to properly recreate the armor's shape, which would be difficult with the crude measurement method used. However, the manteau from the Plankengestech piece was complete enough to be used, with the rest of the armor being modeled as a basic form, such as a sphere, onto which the manteau is mounted.

Charles used a mesh and grid generation program named TrueGrid®. TrueGrid® is designed to generate meshes and grids that define the form of structures and fluids. These meshes and grids can then be used for engineering analysis and design. During the object creation process, it was discovered that the manteau shape was not quite correct. The piece appeared to be shaped to fit over the right shoulder rather than the left. The problem turned out to be that the coordinate system in which the measurements had been oriented was not right-handed, as is the standard for graphing. The problem was resolved by simply inverting the y-axis values of the data; all "Depth" measurements were multiplied by a factor of –1. Once this was done, the manteau had the proper orientation.

Upon further discussion with Charles, it was found that there are many pre-designed models in collision software that can be used. One of these was for that of a human body. The major parts of the body (torso, head, upper arm, lower arm, etc) were modeled as specific types of elements, rigid or beam, and connected with joints that could be given parameters limiting motion. For example, a human elbow is designed to bend through a 180^{O} range. One of these joints is placed at the waist of the human model. By setting parameters on the waist's range of motion, it may be possible to determine whether or not a knight is unhorsed, simply by determining if his upper body is forced beyond a certain angle with respect to his lower body.

The legs are assumed to be part of the horse, as they are gripping it, and are somewhat ignored. When the impact occurs, there will potentially be some backward force on the torso, causing the waist to bend back, from a vertical alignment towards the horizontal. If the waist is observed to bend back beyond a certain angle, say 60-70 degrees from the vertical, the rider will be nearly horizontal on top of the horse. At this point, it could be assumed that the rider is no longer able to grip the horse well, and is thus unhorsed. The exact details and effectiveness of this will not be known until some actual simulations can be executed.

Unfortunately, due to constraints on his time, Charles was unable to finish the object models and complete collision simulations within the time frame of the project. He was able to create basic shapes of the manteau d'armes and the lance coronel. However, the placing of the beam object, defining the lance shaft, and of the jouster behind the manteau were incomplete; both of these are necessary for even a crude simulation and obtain relevant information. The TrueGrid® file containing the objects completed, the manteau d'armes and the coronel, *armor3a.tg*, will be made available to any future groups wishing to continue the work begun in this project. (Contact Professor Jeffrey Forgeng for information.)

5 Conclusion

The resources available in the Higgins Armory Museum's library allowed extensive research concerning the historical development of the joust and characteristics of jousting equipment. This information provided a general historical context for jousting, its various forms, and the physical details of relevant equipment that would affect the collision involved in a joust. However, after the preliminary research portion of the project was completed, it was determined that modeling a joust collision was far more complicated than first anticipated. Discussions with people knowledgeable in collision modeling and general physics indicated that such simulations are non-trivial, and require extensive knowledge and analysis, beyond the capabilities of the students involved.

Based on the responses of people interested, from a historical standpoint, in jousting and the medieval period in general, the originally intended result of this project, a complete computer model of a joust, would be of much interest to the historical community as a whole. With that in mind, the project was refocused to provide as exhaustive a basis as possible for the computer model. If it were not possible to create the computer model within the constraints of the project, at least a solid foundation would be laid for later project groups that continued the work.

Thus, the final form of the project became as detailed coverage as possible of the forms and equipment for the joust. This would provide necessary background information, and leave the meat of the computational work for a future project. To further aid future project work, a qualitative analysis of the situation was completed to aid in some of the conceptual aspects of the work. Additionally, specific pieces of equipment were studied to provide a basis for the physical characteristics necessary to being a model.

Appendix A

<u>Notes from a Discussion of Collision Modeling w/ Dr. Malcolm H. Ray</u>

<u>WPI September 13, 2001</u>

Many ideas came out of the meeting offering a broad range of options. Dr. Ray indicated that the events to be modeled have a very straightforward side and a very complex side.

Straightforward Side

- Calculation of impact force and momentum transfer
- Determination of mechanical events (i.e. rider unseating, lance shattering, etc.)

Complex Side

- Determination of physical deformations that could occur in the armor (these problems are mathematically non-linear and very event-order dependent, making their simulation a detailed and complex process, typically focused on by graduate level studies in civil and/or mechanical engineering)

Dr. Ray suggested that the majority of the modeling be kept simple, with cursory looks at the more advanced elements. He offered to provide access to some advanced collision force analysis software the Civil and Environmental Department uses. With the physical characteristics of the elements involved (equipment piece materials, masses, and shapes), simulations could be run to determine the forces resultant from the impact of a lance hitting a breastplate as in a joust.

The most complicated part of this is obtaining a 3D coordinate representation of a breastplate. Dr. Ray said that a method often used is a masking tape grid laid out on an object, which marks changes in the surface plane. An origin is selected and the location (in a 3-D coordinate system) of key points is measured. He also suggested that perhaps a foam model of the inside of a breastplate could be made; the foam could be cut up and measured, making the task easier and more accurate. How exactly this information is gathered would be something to be cleared with the museum, but once it is obtained, the simulations would not be a problem.

There was also a discussion of computation time. Since the final product is intended to be something a museum visitor could look at, the response time must be relatively short. Dr. Ray indicated that complete simulations, determining all forces and deformations of objects, could take approximately an hour, depending on the complexity. He suggested that a table be created that cross references lance, armor, and other joust details involved in order to provide the specific collision results. These results would be generated via simulation as discussed above, and the table could be easily updated as new situations are analyzed. The information could then be looked up quickly when the museum program is run. Simple force and momentum calculations would be done on the fly, but the more advanced results would be looked-up.

Dr. Ray also offered the possible use of some physical impact testers the department uses. These testers vertically drive a narrow tip into an object placed at the bottom of the device frame. A special measuring device immediately behind the tip measures the force of the impact and the information can be read into a computer providing a graph of the impact event. The tips are very similar in size and shape to a lance tip, and special heads could potentially be produced to be more coronal shaped, the three-pronged lance head mentioned in the Equipment for the Joust section. A piece of steel similar in thickness to a breastplate could be placed in the device and an impact run. This would provide an actual physical specimen to look at and use as a reference.

Dr. Ray also identified several sources of information that could be useful for an overview of impact mechanics. These included *Introduction to Impact Engineering* by M. A Macaulay and *Impact Mechanics* by W. J. Strouge.

Print and Electronic References

Amador, Armondo G. Ed. *Kingdoms Project.* http://www.il-st-acad-sci.org/kingdoms.html Illinois State Academy of Science and the Weizmann Institute of Science. Last updated: May 5, 2001.

A compilation of animal information; provides information on the average height and weight of various breeds of horses.

Ashdown, Charles Henry. *European Arms and Armour.* New York, NY: Brussel & Brussel, 1967

Contains extensive information about the design of tilting armor, including images and diagrams, with some limited information about lances.

Bannantine, Julie A., Jess J. Comer, and James L. Handrock. *Fundamentals of Metal Fatigue Analysis.* Englewood Cliffs, NJ: Prentice Hall, 1990.

Provides an introduction and overview of metal fatigue analysis, which may prove useful in developing more advanced model/program features.

Barber, Richard and Juliet Barker. *Tournaments: Jousts, Chivalry and Pageants in the Middle Ages.* New York: Weidenfeld and Nicolson, 1989.

Source provides an excellent overview of the Middle Ages. Contains a detailed history with specific, cited examples of jousting accounts. Also provides illustrations, which reinforce the descriptions. Focuses on the customs and rules of jousting, with little detailed information about equipment.

Blair, Claude. *European Armour: Circa 1066 to Circa 1700.* London: B.T. Batsford LTD, 1958

Contains detailed descriptions of armor, including weights, which seems to be hard to find information. Includes many drawn-out, sometimes tedious, discussions of particular designs, down to the last rivet placement. Provides useful information about tournament armor, with images & sketches; a supplement to other sources for equipment information

Bratley, Paul, Bennett L. Fox, and Linus E. Schrage. *A Guide to Simulation.* New York, NY: Springer-Verlag, 1983.

A somewhat more advanced text than Kreutzer or Graybeal & Pooch, focusing on effective and efficient simulation. Also provides a discussion of modeling principles.

Referred to by Kreutzer; should be useful in the design of a more advanced modeling program.

Bull, Stephen. *An Historical Guide to Arms & Armor.* New York, NY: Facts on File, 1991.

Provides limited information about tournaments and tilting armor. Useful as a secondary source to supplement and verify the information of others.

Clephan, R. Coltman. *The Tournament, its Period and Phases.* London: Methuen & Co. Ltd., 1919.

Source provides a detailed history of jousting. Contains information about rules and the development & refinement of the joust. It separates the terms 'Joust' and 'Tournament'; covers all tournaments, so there is lots of information on melee tournaments as well as jousts.

Cripps-Day, J. *History of the Tournament*. London: Roberts & Leefe, Ltd Printers, 1918.

Source provides a detailed history of the joust, arranged by event. Contains information and images about general jousting rules and forms, but is almost too detailed to sift through for information on specific equipment. The text is also very old and fragile, somewhat limiting its general usability.

Davis, R.H.C. *The Medieval Warhorse.* London: Thames & Hudson Ltd., 1989.

Provides an overview of horse breeding in medieval times. Offers very limited information concerning horse breed sizes.

Dieter, George E. *Mechanical Metallurgy.* 3rd Ed. New York, NY: McGraw-Hill, 1986.

A more advanced text on metals and their response to forces (stress, strain, impact). More focused and advanced than "Mechanics of Materials 1"; the information should prove useful for improvements to a basic program to create a more advanced final product, which more accurately simulates a joust.

Edge, David and John Miles Paddock. *Arms and Armor of the Medieval Knight.* New York, NY: Crescent Books, 1990.

Provides history of the development of the lance, as well as information about tournaments and tournament armor.

Emmet, William T. et al. *The Tournament*. Worcester: WPI IQP, 1979.

Illustrations and plans for a joust exhibit that was assembled in the Higgins Armory Museum. Provides very detailed drawings and descriptions of some equipment. Another IQP was involved restoring a few pieces for the display. Also contains a bibliography of useful sources, most of which in the Museum's library.

FaroArm. http://www.faro.com/Products/FaroArm.asp FARO Technologies Inc., 2001.

Company website providing information about the FaroArm mechanical measurement tool, for use in Computer-Aided Manufacturing Measurement.

Ffoulkes, Charles F. *The Armorer and His Craft*. London: Methuen & Co. Ltd., 1912.

Source provides a detailed discussion of armor design and construction. A good source for information as to why armor was designed like it was, but reads like a collection of essays on certain design aspects.

Fishman, George S. *Principles of Discrete Event Simulation.* New York, NY: John Wiley & Sons, Inc., 1978.

Provides a more advanced treatment of simulation and modeling, with an added emphasis on statistical analysis of simulation results.

Referred to by Kreutzer; should be useful in the design of a more advanced modeling program.

Forsyth, P. J. E. *The Physical Basis of Metal Fatigue.* New York, NY: American Elsevier Publishing Company, Inc., 1969.

Provides information that should fill-in/clarify some of the details of metal fatigue that may be missed in the other mechanical texts. Due to the age of this source and the potential advancements in this area of engineering science, the information may be out-of-date and inaccurate; a more current reference should be found.

Graybeal, Wayne J. and Udo W. Pooch. *Simulation: Principles and Methods.* Cambridge, MA: Winthrop Publishing, Inc., 1980.

Provides an overview to computer-aided simulation and modeling. May be useful as a supplement to the other modeling sources.

Hearn, E. J. *Mechanics of Materials 1.* 3rd Ed. Woburn, MA: Butterworth-Heinemann, 1997.

Source provides an introduction to material structure and response to stress and strain, including impact deformations. Provides mathematical foundations, which will be useful to the core of a simulation program.

Hyland, Ann. *The Warhorse: 1250-1600.* Gloucestershire, Great Britain: Sutton Publishing Ltd., 1998.

Source provides an overview of the horse industry in Europe. Covers limited information about different breeds of horses used as destriers (war horses), and the average size of such horses.

Karcheski, Walter. *Stechzeuge of the German National Museum, Nuremberg*. Worcester: Higgins Armory Single Copy (unpublished), 1988.

Source contains photographs of various stechzeuge armors and pieces of stechzeuges. Reproduction of the pictures is not permitted, so this severely limits the usefulness of an all-photograph work. Some pieces have scale indicators, making the source useful for measurement information. No reference to exact pieces or time period is given, so the pieces could not be placed in their correct historical reference.

Kottenkamp, Dr. F. *History of Chivalry and Ancient Armour.* Translator: Rev. A. Löwy. London: Willis & Sotheran, 1857.

Provides information about the history of lances and armor, including structure, materials, and usage. Should prove useful in determining how to model these objects. Also provides some information about tournaments. The source is quite old, making some of the information potentially questionable, but it can be confirmed with other sources.

Kreutzer, Wolgang. *System Simulation: Programming Styles and Languages.* Reading, MA: Addison-Wesley, 1986.

Provides an overview of system simulation techniques and ideal languages, presenting specific examples. Being slightly outdated, in technology terms, the book focuses on programming languages that would not be used, and does not mention the one originally envisioned for the project (C++). However, its object-oriented focus should still provide useful information and guidelines. The book also references several other sources that may be useful, nearly all of which are available at the WPI Library.

Laking, Sir Guy Francis. *A record of European Arms and Armor (5 Volumes)*. London: Chiswick Press, 1920.

Source discusses examples of armors and where they were used. Organized by piece, containing an entire section on a single type of helmet, for example. Possibly useful in placing museum pieces in proper time periods and geographic locations.

Macaulay, M. A. *Introduction to Impact Engineering*. New York: Chapman and Hall, Ltd., 1987.

Provides an introduction to theories and methods of analyzing collisions. Offers a basic overview of collision analysis and detailed information about various aspects. Compliment to Strouge text.

Mann, Sir James. *Wallace Collection Catalogues, European Arms and Armour*. Vol. I Armor. London: Willam Clowes & Sons, Ltd., 1962

Provides data about the physical characteristics of pieces of jousting equipment contained in the Wallace Museum collection.

Mitrani, Isi. *Probabilistic Modeling.* New York, NY: Cambridge University Press, 1998.

Provides background and methods for modeling systems affected by certain levels of randomness. Covers more mathematical background to help improve the usefulness and validity of simulations involving randomness and when several assumptions are used to simplify the simulation. Could be useful in a more advanced simulation program.

Oakeshott, Ewart. *European Weapons and Armour.* North Hollywood, CA: Beinfeld Publishing, Inc., 1980.

Contains information about both general and tournament armors. More limited than other sources.

This source as been identified as undesirable for the project's purposes by Professor Jeffrey Forgeng. As such, it will not be used in the report, and it only here for completeness.

Payne, James A. *Introduction to Simulation: Programming Techniques and Methods of Analysis.* New York, NY: McGraw-Hill, 1982.

Provides an introduction to simulation study utilizing computers. Provides specific examples to illustrate general concepts.

Referred to by Kreutzer; should provide a solid foothold for initial design of the simulation program.

Strouge, W. J. *Impact Mechanics*. New York, NY: Cambridge University Press, 2000.

Provides coverage of theories and methods of impact analysis, including object deformations. Compliment to Macaulay text.

TrueGrid® - Quality Hexahedral Mesh Generation. http://www.truegrid.com/Welcome.html XYZ Scientific Applications, Inc., 2002.

Company website providing information about the TrueGrid® program for generating meshes and grids that define structures and fluids for engineering and design purposes.

Young, Alan. *Tudor and Jacobean Tournaments*. London: Sheridan House, 1987.

Source focuses on the social aspects and effects of the tournament. Provides some equipment description. Useful as a supplement to other sources and to crosscheck historical information.

Personal References

Deane, Andrew. Royal Armouries Museum. Armouries Drive. Leeds, Yorkshire, LS10 1 LT UK.

Member of the Royal Armouries Museum Program of Live Interpretation, including jousting. Mr. Deane has taken part in re-enacting actual jousts, providing him with insight into what a jouster is experiencing during the event.

Hick, Steve. Email Contact: Hick_Steve@prc.com

Mr. Hick has information on sources and references dealing with jousting, especially rules and techniques.

Ray, Dr. Malcolm H. Associate Professor of Civil and Environmental Engineering at WPI. Email Contact: mhray@wpi.edu. Phone Contact: 508-831-5340

Dr. Ray specializes in automobile collision modeling. Provided information on concepts in modeling, a few sources about impact engineering, and help in some of the more detailed analysis of the collision effects for the project.

Reed, Robert and Jennifer. Email Contact: jlrr@mindspring.com

The Reeds can provide information about horse breeds used in tournaments and serve as points of contact to persons knowledgeable in jousting equipment and armor in general.

Waller, John. Royal Armouries Museum. Armouries Drive. Leeds, Yorkshire, LS10 1 LT UK.

Head of the Royal Armouries Museum Program of Live Interpretation, including jousting, with 40 years experience in reconstruction of historical combat and equestrianism. Able to provide some of the physical details of a joust not generally covered, such as average horse speeds during impact.