Smashing the Bridge between Roman and Medieval Artillery:

The Onager

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Introduction

The study of the military artillery used by a people can reveal much about their society. Because defense is usually of utmost importance, societies spend a lot of time and money on their military and the equipment needed to support it. Artillery, therefore, reflects the technological capabilities of a people and the education level of those involved in defending it. Types of artillery also give information about the aggression level of a people, their mobility and terrain, and the capabilities of their opponents.

This paper will attempt to uncover some information about the technological level of artillery used during the decline of the Roman empire and the beginning of the middle ages (300 AD - 600 AD). Although several types of artillery were used during this time, only the onager seems to have been unique to the period. The onager will therefore be the primary piece of artillery discussed. Since the historical evidence on the onager is extremely limited, statics, dynamics, and computer simulation will be used to aid in reconstruction and analysis. These methods of analysis may serve as a guide for other research where evidence is limited.

Chapter 1 - The Sources

The names used for ancient and medieval artillery varied and were then often misinterpreted when sources were translated and copied throughout the ages. The name onager was given to the one-armed, torsion stone thrower sometime in the third century, "because when wild asses are pursued by hunters, by kicking they hurl back stones to a distance, either crushing the breasts of their pursuers, or breaking the bones of their skulls and shattering them."[1] The term catapult comes from the Greek "kata" and "pallein" meaning to brandish or poise a weapon before hurling. It has been used to describe most types of ancient artillery at one time or another.

Unfortunately, the primary sources on the onager are very limited. While there are excellent technical descriptions given by Heron, Biton, and Vitruvius on two-armed stone throwers, there is no detailed technical description of the onager. Although it was mentioned by Philon around 200 BC and again in the second century AD by Apollodorus of Damascus, it was not described in any detail until the fourth century.[2]

The Roman military officer and historian, Ammianus Marcellinus, described the onager, the ballista, and the ram in a digression during his account of Roman History from 354 AD to 378 AD. In his brief description, he explained that the onager was built by laying down two oak posts in parallel that have been "hewn out and slightly bent, so that they seem to stand forth like humps."[3] After securing the posts, a hole was made in each, and the two holes were spanned with heavy rope. Between the two ropes, one end of a third, smaller beam was placed vertically to form the arm of the onager. This arm could

[1] Rolfe, pp. 329
[2] Marsden, pp. 249

be raised and lowered using cords. A sling made of hemp or iron was attached to the end of the arm using a hook, and a "great cushion of hair-cloth stuffed with fine chaff"[4] was positioned to absorb the blow of the arm.

To fire the onager, four men turned a rod which wound down the cord connected to the arm. When the arm was about horizontal, a stone was placed in the sling, and a bolt was struck with a hammer to release the cord. The tension in the ropes spanning the beams would force the arm forward and the stone would fly out of the sling.[5]

The only other historian of the later fourth century that discussed the onager was Vegetius. He explained that the onager

> "throws stones of different weights according to the thickness and extent of its sinew-bundle; for the larger it is, the bigger the stones it can hurl, in the manner of a thunderbolt. One can find no piece of artillery which is more powerful … the stones thrown by the onager are of such great weight that they no only crush to death horses and men, but they even shatter the siege machines of the enemy."[6]

Vegetius made it clear that sinew (an elastic cord made from animal tendons) was used for the rope that gave the arm its torsion power. He also impressed on his reader the power of the onager.

The last primary source for the onager was Procopius who mentioned that it was used during the Goth's siege of Rome in the sixth century. Although no further description was given, the account did prove that the onager was still in use.[7] It is likely that the onager was being phased out during this period because, as recent studies have

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[3] Rolfe, pp. 327
[4] Rolfe, pp. 329
[5] Rolfe, pp. 327 - 329
[6] Wolfe, pp. 139
[7] Wolfe, pp. 160

shown, the medieval trebuchet had begun to migrate from China.[8] While torsion catapults threw up to 50 pound stones over 400 yards,[9] the simpler and more powerful trebuchet could project 2000 pound objects almost 100 yards, and lighter objects much further![10]

[8] Chevedden, pp. 67
[9] Josephus, pp. 309
[10] Chevedden, pp. 66 - 71

Chapter 2 - Basic Reconstruction

In recent times, reconstructing ancient and medieval artillery has been a challenge for military historians. Reconstructing the onager has presented special problems due to the lack of evidence on its design. At the turn of the century, both Schramm and Payne-Gallwey built large models of the onager based upon the sources discussed above. They also borrowed components from the descriptions of other pieces of ancient artillery and integrated some technology from their own time. Since Payne-Gallwey had more success in his reconstructions, only his research will be analyzed.

Payne-Gallwey built two versions on the onager. The first was more of a generic catapult that did not have a sling, but a “cup” hollowed into the end of its arm to hold the projectile. After reading Ammianus Marcellinus, he modified his original design and added the sling. Although incorrect, the “cup” catapult provided a lot of useful data.

The “cup” catapult was approximately a half-scale model. Its main beams were 10.5 feet long and the distance between them was 4’. The arm was 7’ long 4.5” thick and an average of 7.25” wide. It used horse hair instead of sinew to create the torsion skein. The horse hair was made into 0.5” rope and wound to form a skein 8” in diameter. Payne-Gallwey used modern ratchets to tighten the skein and wind down the arm. He used a metal slip hook to release the arm. After fine-tuning, the “cup” catapult was able to hurl a 10 pound rock about 350 yards. Based on his experience with his first model, he estimated that the frame of the largest Roman catapults had been about twice the size of his model with a 10’ to 12’ arm. This full-scale catapult would require a skein 2’ in diameter, but would have a range of around 400 yards using a 50 pound projectile.

Apparently, the frame of the half-scale model was larger and stronger than necessary. The relationship between skein diameter and projectile weight will be discussed later.

Payne-Gallwey's second catapult was more like a true onager and utilized a sling. He did not give exact dimensions of all components as he did with the "cup" catapult. However, he made numerous comparisons between the two models and provided sketches which lead the reader to assume that he either used the same frame or one built to the same scale. The only differences were the design of the arm, and the addition of the sling. The arm of Payne-Gallwey's second model was much thinner and lighter since the tip did not have to be hollowed out to receive the projectile. According to his diagrams, the arm was about 8' long and tapered from about 6" in diameter at the bottom to 3" at the top. The sling was made of leather and sized to hold an 8 pound stone. The ropes used to attach the sling were 1/3 the length of the arm or about 2.5'. A rope was attached to each of the four corners of the sling, and two of the ropes were tied to the end of the arm. The other two ropes were tied together and hung on a hook at the end of the arm. This was done so that the later two ropes would come free as the arm swung forward, releasing the projectile.

Payne-Gallwey ran tests on both his original and modified onagers using an 8 pound weight. The "cup" catapult would "throw a round stone 8 lb. in weight, from 350 to 360 yards, but the same engine with the advantage of a sling to its arm will cast the 8 lb. stone from 450 to 460 yards, and when its skein is twisted to its limit of tension to nearly 500 yards."[11]

[11] Payne-Gallwey, pp. 11 (appendix)

The only other published reconstruction of the onager was in 1971 by Marsden. Although primarily concerned with other types of ancient artillery, he did devote a chapter to the onager. He built a small model based on Schramm and Payne-Gallwey's work, but did little more than summarize and verify the earlier works.

Chapter 3 - Unresolved Issues

With all of the work done to reconstruct the onager, there are several major issues that remain unresolved. Some of these issues have been debated before and even resolved for similar types of artillery, but others have apparently never been addressed.

The composition of the skeins for the onager and other artillery is one of the most challenging problems to those attempting a reconstruction. The material chosen to make the original skeins had to meet several criteria. First, it had to be of a material that could be woven into rope or cord. It had to very elastic with a minimal amount of elastic deformation. This means that after the rope was tight, all of the force of the machine had to be obtained by twisting the rope an additional 90 degrees. This additional twisting could not permanently stretch the rope or it would render it useless. The material used also had to be durable - able to endure constant use, harsh weather, and age. The primary sources explain that animal sinew was the best material for skeins with horse or women's hair as alternatives. Sinew probably referred to tendon because of its elasticity and the fact that other material that might be interpreted as sinew (like muscle) was probably consumed as food. There is no evidence as to how sinew was woven into rope because that was a tradition passed on through those in the trade and never written down.[12] Reconstructions of ancient artillery have had to utilize the second choice horse hair because sinew rope and mass quantities of women's hair were simply unavailable! Regardless of the material chosen, the skeins had to be treated with oil to prevent them from drying out and fraying, to bond the cord, and to make the skeins weatherproof.

[12] Landels, pp. 107 - 111

Since both materials were used, but sinew was obviously preferred, I think a conservative estimate would give sinew a 10% performance increase over hair.

Determining the dimensions of the onager has been another major problem for historians. While exact dimensions were given for two-armed catapults by the original sources, none were given for the onager. There was a formula, that utilized a cubic root to determine the diameter of the skein for a two-armed catapult based on the weight of the projectile to be used. All other dimensions for the catapult were then given in terms of that diameter. The formula, $D = 1.1 * \sqrt[3]{(100 * M)}$, gave the diameter in dactyls (1 dactyl = 0.76 inches) and the projectile weight in minae (1 mina = 0.96 pounds). It was proposed by Marsden that this formula could be applied to the onager, but the effective number of minae must be doubled since only one skein and one arm would be used to throw the projectile.[13]

This was a start, but following that logic, Payne-Gallwey's onager should have had a maximum capacity of 5 pounds when it actually worked fine with an 8 pound stone. This can be attributed to the shorter arm and longer sling used on the two-armed catapult. A better approach would be to multiply the desired weight by about 1.6. A revised formula in inches and pounds would be $I = 0.834 * \sqrt[3]{(167 * P)}$, where P was in pounds and I in inches. Unfortunately, this formula can not be verified without test or simulation so doubling the weight and using the original formula might give a better safety margin.

As stated above, all other dimensions can be given in terms of the spring diameter. Marsden used this approach to give the layout for a generic onager, but following his approach for a skein of 8" yields a shorter frame than that built by Payne-Gallwey.

Every onager reconstruction that has been attempted has utilized a large vertical framework to stop the arm of the catapult after the projectile has been released. There has been a considerable amount of dispute as to what angle the framework should assume to release the projectile at the proper time without breaking the onager's arm. The idea for this framework came from Ammianus Marcellinus' description of the bumper used to stop the arm. I feel that his description of the cushion has been greatly misinterpreted and that this vertical framework never existed at all.

Marcellinus described the bumper as follows:

> "In front of the arm is placed a great cushion of hair-cloth stuffed with fine chaff, bound on with strong cords, and placed on a heap of turf or a pile of sundried bricks; for a heavy machine of this kind, if placed upon a stone wall, shatters everything beneath it by its violent concussion, rather than by its weight."[14]

It is a common misconception that the onager released its projectile when the arm collided with the bumper. Payne-Gallwey observed that the projectile came away from his "cup" catapult when the arm was at an angle of about 45 degrees even though the bumper was located at about 90 degrees.[15] No exact figures were given for the angle of release when the sling was incorporated into the design. This was really irrelevant because the hook at the end of the arm could be bent to make the sling release at any angle. An analysis of the dynamics of the onager show that the maximum trajectory is obtained when the projectile is released at 45 degrees if wind resistance is neglected.

Since the bumper had no effect on the release of the projectile then the only purpose it served was to stop the forward motion of the arm. Both Schramm and Payne-

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[13] Marsden, pp. 254 - 255
[14] Rolfe, pp. 329
[15] Payne-Gallwey, pp. 282

Gallwey encountered problems with the arm breaking from hitting the bumper too hard.[16] It stands to reason that the further the arm was allowed to travel, the more time it would have to decelerate. I propose that the bag of chaff was actually placed on the beam that spanned the front of the onager. This would have provided several advantages. First, the arm would have time to slow down and therefore hit the bag with less force. Second, the arm could be wound back almost 180 degrees, giving it significantly more power. Finally, without a vertical framework the onager would be much lighter and the main beams would not have to be notched, making the frame stronger.

The next component of the onager that has been subject to debate is the mechanism used to wind the skein and crank down the arm. Payne-Gallwey used a convenient ratchet mechanism in his reconstruction, but it is very doubtful that such a device was originally employed on the onager. It must be kept in mind that the onager became popular because it was simple to use. Although it was less accurate and harder to aim, it could be easily constructed and operated in comparison with other pieces of ancient artillery.

Landels gave an excellent description of a crank mechanism that was similar to the one most likely used on the onager. Metal washers were fitted over the holes bored through both of the onager's main beams. These washers consisted of a part that would fit inside the holes and a wider flange that was wider then the holes. The washers would have a recessed area to receive the pins that the skeins were wrapped around. To prevent the washers from rotating, several holes were drilled and pegs were inserted into the main beams. These holes could have also received a tool that could be used to turn the

[16] Marsden, pp. 262

washers and tighten the skein if the pegs were removed. Tightening the skein was probably a process of repeatedly inserting the tool, removing the pegs, rotating the washer a half-turn, reinserting the pegs, and repositioning the tool. Similar washers would have been used to wind down the arm, with the exception of the recess for the skein pins. See the Figure 1 below for further explanation.

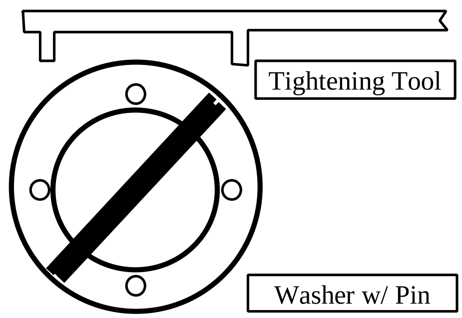

Figure 1 - Washer and Spanning Tool

There is no way to know for sure how the arm of the onager was released to fire the projectile. Marcellinus mentioned a bolt that was struck out with a hammer. Marsden pointed out how dangerous it would have been to stand anywhere near the onager and Marcellinus even relayed a story of how a man had been killed doing just that. I back Marsden in his support of Payne-Gallwey for creating a simple yet effective trigger. He used a metal slip hook that was tied to the cord used to wind down the arm, and linked to the arm through an eyelet in its end. A second cord was tied to a small extension on the hook that would release it when pulled. See the Figure 2 below for further explanation.

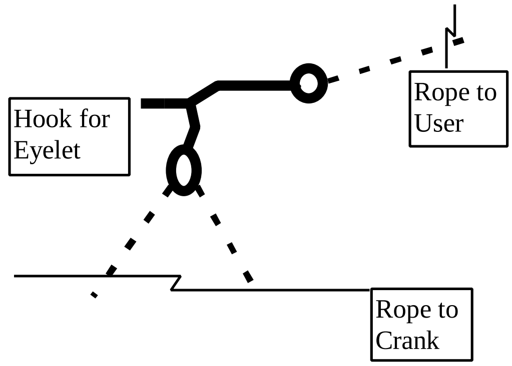

Figure 2 - Slip Hook Trigger

The final major issue to be resolved about the onager is transportation. There has been significant debate as to whether or not the onager had wheels. Most agree that wheels could only be used during transportation and would have to be removed in order to use the onager. The violent firing of the onager would quickly break the axles if wheels were left on. If the axles did survive, the onager would have jumped forward with each use.

Payne-Gallwey's reconstruction of a mid-sized onager weighed over two tons and my own model confirmed this. If wheels were added to move the onager, they would probably have cut into the ground and eventually gotten stuck. Payne-Gallwey, Marsden, and Chevedden all agree that the onager was most likely disassembled for transport. If the vertical framework did not exist, as I have suggested, the onager would have been fairly easy to take apart and reassemble. For long distance travel, the main beams were probably discarded and only the smaller beams, sinew, and smaller mechanisms carried with the army. New main beams could be constructed from trees at the sight of the next siege, and the onager reassembled.

Chapter 4 - Computer Reconstruction and Analysis

Until now, it would have taken a tremendous amount of time and money to build and test a full scale onager. With the limited amount of information available, the process would have required a lot of trial and error. With the advent of powerful computers and simulation software, it is possible to reconstruct the onager based on only the existing sources. Only through extensive testing of all theories, will we ever be able to obtain solid evidence of the onager's appearance, range, and power.

I have created a detailed computer model using the TrueSpace computer modeling and animation software. Using Payne-Gallwey's work as a base, I have reconstructed his largest onager, beam by beam. In order not to confuse the model, I have left out the sling and winding mechanisms. I also used the crank mechanism described by Landels, not the ratchets used by Payne-Gallwey. For aesthetic purposes, I have applied a wooden texture to wooden surfaces, a metal texture to the metal surfaces, and a muscle/tendon texture to the sinew skeins. The grain of each beam also follows its length and the edges of the beams have been chamfered, again for aesthetics. All of the drawings are exactly to scale and are accurate to within one inch.

Figure 3 (below) is shown in grayscale and is followed by Table 1 which contains approximate measurements for the onager. In all cases, I have rounded up to the nearest quarter inch. The goal here was to find the approximate volume of Payne-Gallwey's model and apply the density of oak (48 lb/ft^3) to find the weight of the onager. My calculations gave an approximate weight of 4089 pound - just over two tons as Payne-Gallwey had determined. Figure 4 is a larger, color image that is shown from an angle to

give a true feel for the appearance of the onager. Figure 5 is a color plan (top) view, and Figure 6 is a color side view.

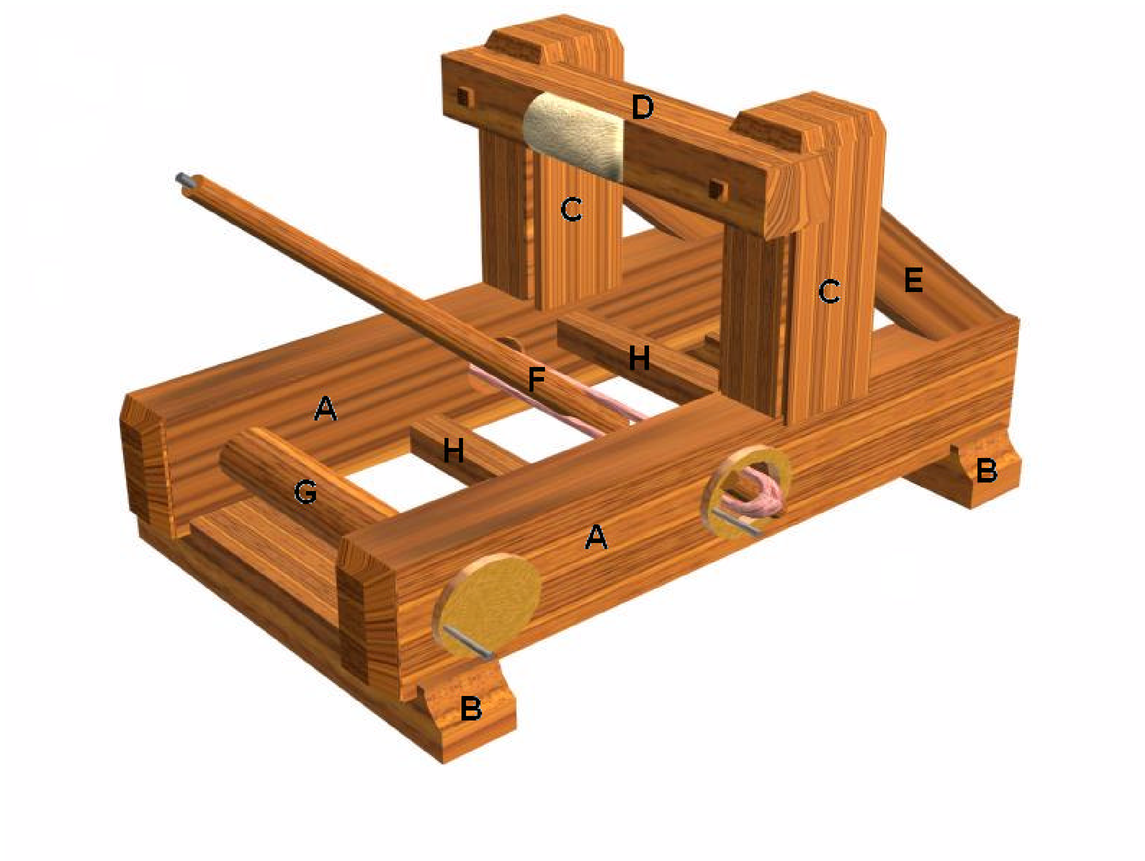

Figure 3 - Greyscale 3-D View

Item	Name	Length (ft)	Height (ft)	Width (ft)	Volume (ft^3)	Quantity	Weight (lb.)
A	Main Beam	11.00	1.75	1.00	19.25	2	1848
B	Cross Beam	1.00	1.00	7.00	7.00	2	672
C	Vertical Post	1.75	4.00	1.25	8.75	2	840
D	Bumper Crosspiece	1.00	0.75	6.25	4.69	1	225
E	Angled Support	3.50	1.00	0.50	1.75	2	168
F	Arm	8.00	0.25	0.25	0.50	1	24
G	Shaft	1.00	1.00	6.00	6.00	1	288
H	Horizontal Support	0.25	0.25	4.00	0.25	2	24
							4089

Table 1 - Data for Payne-Gallwey's Onager

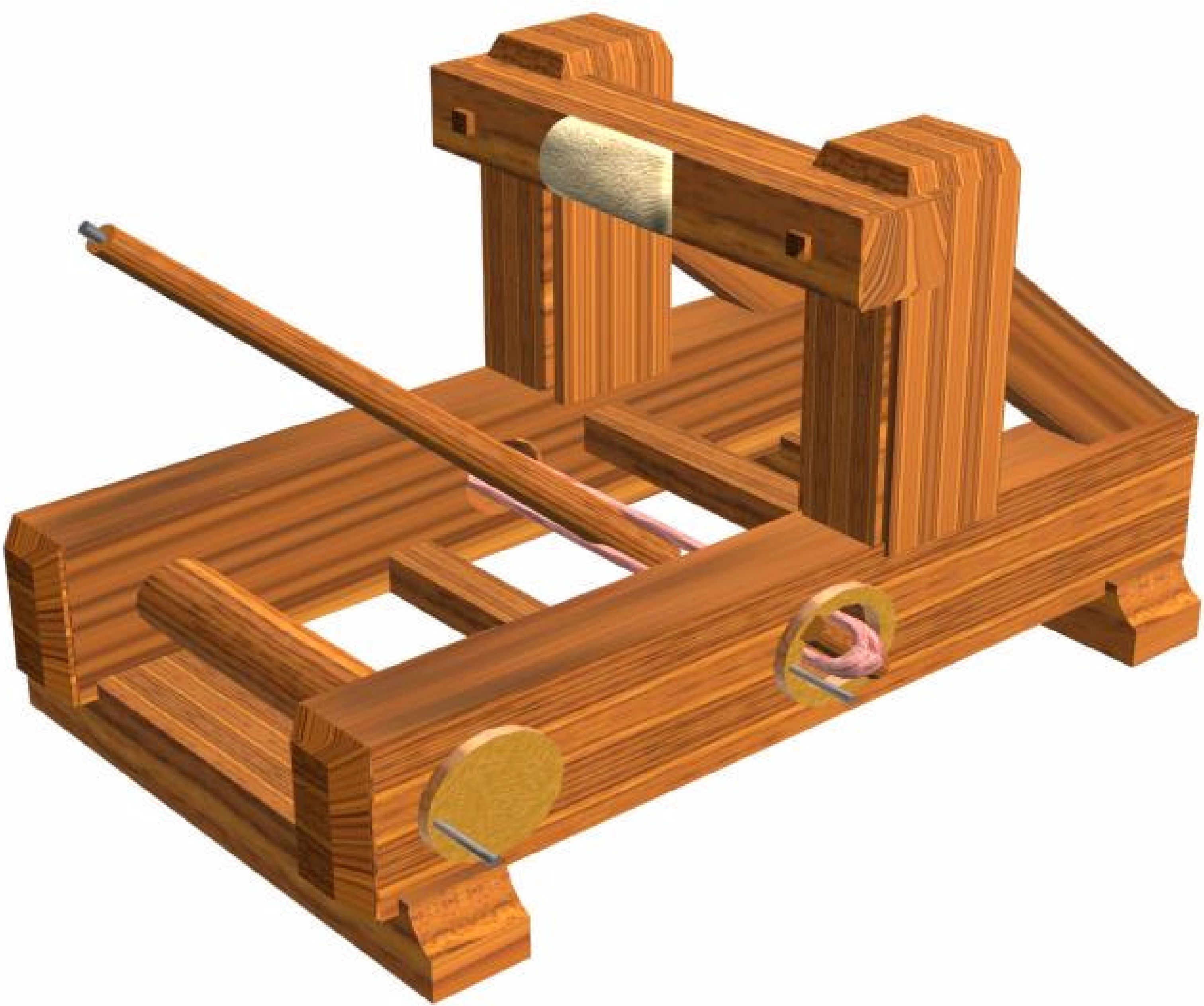

Figure 4 - TrueSpace Computer Model of Payne-Gallwey's Onager

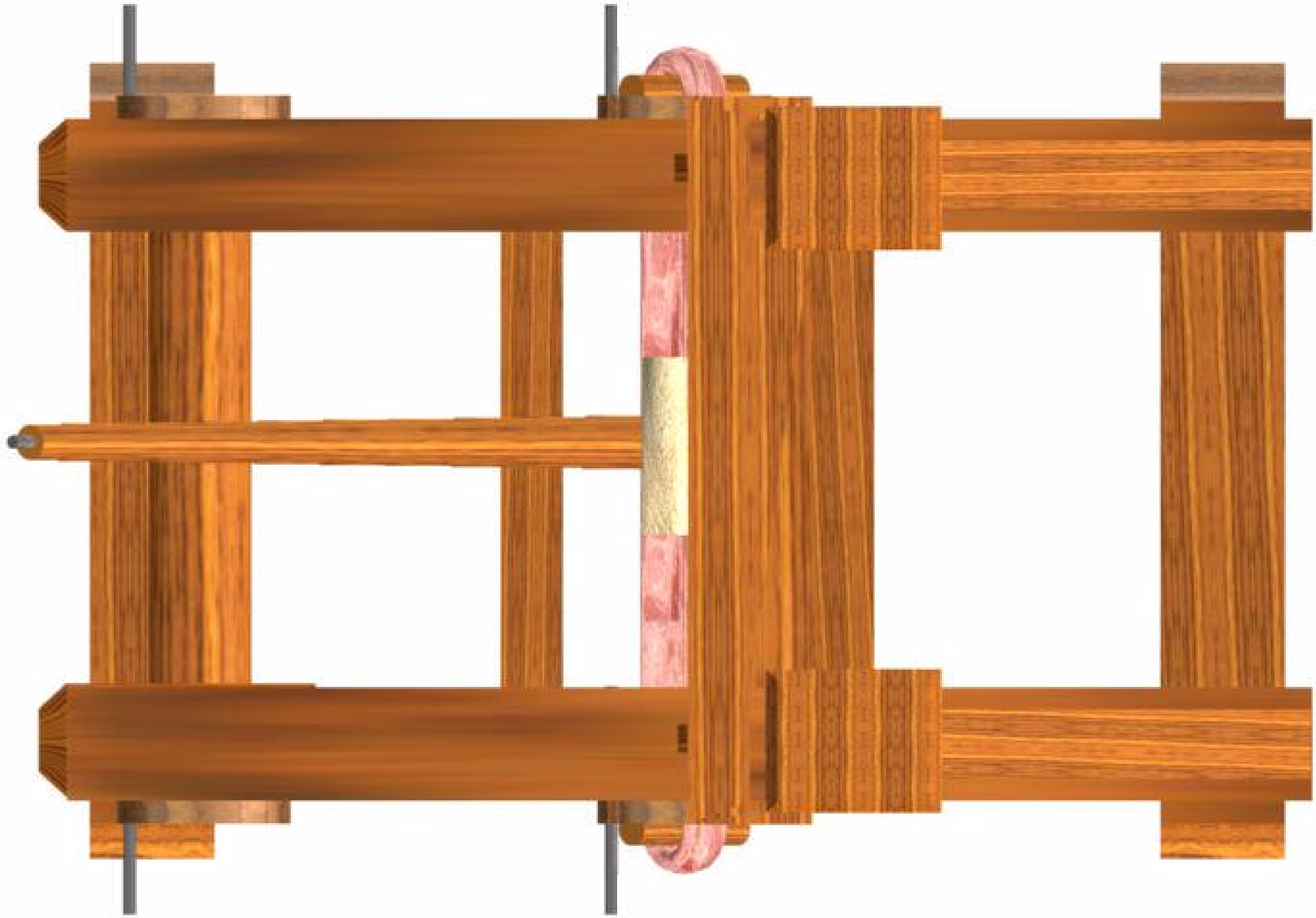

Figure 5 - Computer Model of Payne-Gallwey's Onager (Plan View)

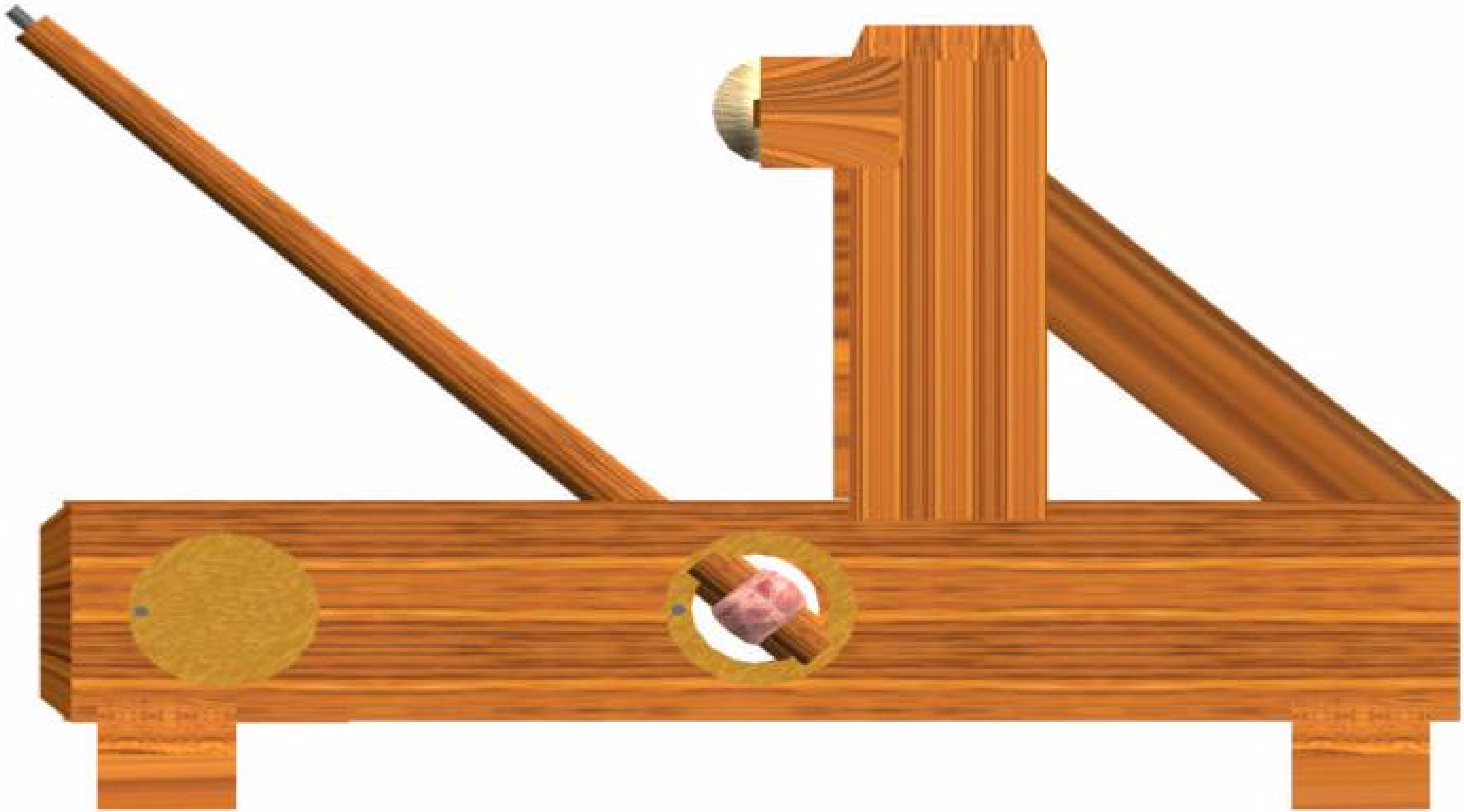

Figure 6 - Computer Model of Payne-Gallwey's Onager (Side View)

The next step in reconstructing the onager was to do a dynamic analysis of Payne-Gallwey's "cup" onager to determine the initial velocity of the projectile. Working backwards, the torsion force applied to the arm of the onager could be approximated. Since Payne-Gallwey's results were obtained with a skein of horsehair, the torsion force determined could be slightly increased to simulate sinew. The formulas are as follows:

Initial Velocity of Projectile:

$R = (V_i^2 \sin 2\theta) / g$
$V_i^2 = (Rg) / (\sin 2\theta)$

(R = Range; V_i = Initial Velocity; θ = Launch Angle; g = Gravitational Constant)

based on Payne-Gallwey's "cup" catapult results…

$V_i^2 = (1050' * 32.1'/s^2) / (\sin 2*(45))$
$V_i = 183.6'/s$

Initial Angular Velocity of Projectile

$V^2/r = w^2 r$
(V = Velocity; r = Radius; ω = Angular Velocity)
$\omega^2 = V^2/r^2$

based on above results…

$\omega^2 = (183.6'/s)^2 / (7')^2$
$\omega = 26.2$ rad/s (radians per second)

Average Angular Acceleration of Arm

$\omega_f^2 = \omega_i^2 + 2\alpha\theta$
$\alpha = (\omega_f^2 - \omega_i^2) / 2\theta$
(α = Angular Acceleration; ω = Angular Velocity; θ = Angle Traveled)

based on above results…

$\alpha = (26.2 \text{ rad/s})^2 / 2*(.78525\text{rad})$
$\alpha = 437 \text{ rad/s}^2$

Torque Exerted by Skein

$T_{tot} = T_\alpha + T_g$
$T_{tot} = m_{stone}*r^2*\alpha + m_{arm}*(r/2)^2*\alpha + (m_{stone}*r + m_{arm}*r/2)*g$

(T = Torque; m = Mass; r = Radius; g = Gravitational Constant; α = Angular Acceleration)

based on above results (and converting to metric)…

$T_{tot} = 3.62\text{kg}*(2.44\text{m})^2*437\text{rad/s}^2 + 10.86\text{kg}*(1.22\text{m})^2*437\text{rad/s}^2 +$
$(3.62\text{kg}*(2.44\text{m}) + 10.86\text{kg}*(1.22\text{m}))*9.81\text{m/s}^2$

$T_{tot} \approx 16{,}700 \text{ kg-m}^2/\text{s}^2$

This value is the approximate torque exerted by the skein in Payne-Gallwey's "cup" catapult. Since the skein was not changed between, the "cup" and sling models, the torque should be about the same. The longer, thinner arm used in the sling model would about balance the shorter, thicker arm in used in the "cup" mode. With additional software, this torque value can be assigned to the computer model and realistic simulations can be done on the model onager. The effects of sling length, arm length, and projectile weight can be studied. Also, the cubic formula used to relate skein diameter and projectile weight can be modified to obtain appropriate torque values for larger skeins based on the torque value calculated above.

Chapter 5 - Further Research

I have only begun to lay the groundwork for further research on the onager. A full dynamic simulation remains to be done. By studying previous work, I have created a solid computer model that can be used in these simulations. Although I can presently animate my model, I require additional software to factor in gravity, wind resistance, and the effects of torsion from the skeins. This analysis is an ongoing research project. Results obtained from my simulations will be the topic of a future paper. If my results are favorable, we may finally have a good picture of the onager and its capabilities. These capabilities may give an indication of how widespread use of the onager was. This may also provide a good methodology for the study and simulation of other ancient and medieval artillery.

Chapter 6 - Conclusion

This paper has taken a technical approach to uncovering the history of the onager. By critically reviewing all available sources, I have summarized all primary works and subsequent research. I have addressed all aspects of the onager's design that have ever been the subject of dispute, and challenged several of the traditional views on onager reconstruction, especially the vertical framework.

Through computer modeling and traditional engineering analysis I have laid the groundwork for future research on the onager. I have created an accurate model of Payne-Gallwey's onager and applied realistic texturing to help those unfamiliar with the onager to visualize it. This would otherwise be impossible without actually building an onager. My calculations have resulted in a new formula for relating onager skein diameter to projectile weight, along with a numerical value for the torsion created by Payne-Gallwey's onagers.

This paper has made no attempt to determine how widely the onager was used, but only set its approximate period to 300 AD through 600 AD. Until simulations are done, we can not determine the accuracy or power limits of the onager. It is apparent from the sources that the onager gained popularity due to its simplicity in structure and design, but it was less powerful than the two-armed catapult. While technology was on the decline in the Later Roman Empire, the complicated ballistas were still in use. It may have been that onagers were mass produced and made their impact through quantity and not quality. Although the exact date is questionable, it is widely accepted that all torsion stone-throwers were replaced by the simpler, and more powerful trebuchet after its arrival from the east.

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