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David's Choice: A Sling and Tactical Advantage

A military technology analysis of one of the most famous individual battles in human history

by
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The confrontation between David and Goliath as described in the Bible (1 Samuel 17) was analyzed using modern ballistics and computational methods. The result is confirmation of the detailed descriptions of the battle and its physical results --- a stone sunk into Goliath's forehead.

Although the Bible does not contain many small details of the battle itself, the Bible does contain enough details about the preparations and end result to permit a modern reverse-engineering analysis. Ballistic analysis of the sling, its stone projectile, and the stone's impact against a human skull show that the end result was achievable as described in the Bible. In order to achieve this, David had both to have skill in the sling's use and to employ tactics permitting him to get within its effective range, which also had to be close enough that his opponent would remain practically motionless during the time from launch to impact.

INTRODUCTION

The confrontation between David and Goliath described in the Bible (I Samuel 17) is perhaps the first record of a battle's fate being determined by the result of an individual encounter between two champions. The tactics of such a combat are of interest to today's students of military history, as all the elements thought to be essential to any successful confrontation are present, as well as errors resulting in lost advantage.

When David prepared himself to fight Goliath, he knew that Goliath was protected by the heaviest and most modern armor of that time. He knew as well that Goliath had a heavy sword and spear which were able to penetrate any armor that David could put on himself. David did try the armor belonging to Saul (I Samuel 17:38) but discarded it as being too heavy. Therefore, David chose to wear no armor at all, as he knew that if Goliath managed to come into close range, any blows from his sword or spear would be fatal, regardless of the armor that David could wear. David chose mobility to achieve his goal.

To win, David had to use a weapon that would be effective at a greater range than Goliath's spear and yet allow him to come close to Goliath. One obvious choice would have been the bow and arrow. Why then did he not use a bow and arrow? We do know that the bow was well known to David because Jonathan used one shortly after the battle with Goliath to inform David that his father, Saul was after him. It was probably clear to David that if he carried a bow to the battlefield, Goliath would immediately understand David's intentions and would arm himself with a more powerful bow than David could handle, thus negating the value of David's choice. A more powerful bow would allow Goliath to reach a longer distance and have a greater penetration capability at that range. This would give the attack advantage to Goliath.

וְחֶרֶב אֵין בְּיַד־דָּוִד.

And There Is No Sword in David's Hand

David had to hide his plan of attack and divert Goliath's attention from it. That is why he brought a shepherd's stick with him. Goliath saw it and became contemptuous as he expected a warrior, properly armed and worthy of singular combat. In order to learn the stick's purpose, he asked David: "Am I a dog, that you come to me with a stick?" (I Samuel 17:43) David did not reply immediately and thus Goliath continued the dialog by cursing David and provoking him. Furthermore, David understood Goliath's intention and answered referring to Goliath's weapons by saying: "You come to me with a sword and a spear and I come to you by the name of the Living God, the God of the armies of Israel, which you have cursed..." This answer increased Goliath's confusion. Since David did not appear to have a weapon, Goliath could not understand why he should be wary.

While Goliath was walking toward David in his confused state, David ran up to him in order to deny Goliath the time to regain his full concentration. When the distance separating the two opponents was sufficiently close to discern facial features, according to the Bible 's description, Goliath also felt an instant dislike for David, once he saw that David was very young, red headed and had beautiful eyes (I Samuel 16:12). This dislike and feelings of contempt may have affected Goliath's judgement, overcoming his military training which had begun in his childhood. Thus, it is quite possible that Goliath clung to ideas that David was acting as a clown to aggravate him, and that David was not going to fight but rather to taunt him and run away, as he was not properly dressed for battle. Goliath may also have been offended by not being challenged by a warrior matching his physical strength.

ANALYSES

The Sling --- for a surprise lethal strike

The sling is a small weapon that can be hidden in the fist before being used, and thus David could surprise Goliath with his first shot. It also was important that Goliath would come to a standstill, in order to allow David to aim confidently and achieve a lethal first hit,--- all that he could hope for in such an uneven battle. Moreover, the sling does not allow the opponent to guess the point at which the stone is aimed. This point is known only to the user of the sling, as the point of impact depends on the time at which one of the strings is released by the user's thumb. Thus Goliath had to guess where David was

aiming the stone and he probably did not have time to think about what part of his body he needed to defend. Furthermore, although Goliath's heavy armor would have given him a sense of security, its inertia also slowed down any possible defensive reactions. (Besides, with Goliath not having the benefit of having played American baseball during which 74mm balls are thrown from a distance of 18.4 m at speeds approaching 40 m/s, his ability to predict the projectile (ball) trajectory would not be as well developed as in a modern ball player.)

The conditions of battle allowed David to aim his first shot quickly, quietly and accurately to hit Goliath's weak point, his undefended forehead --- a task requiring coolness, full concentration and very high accuracy. David probably aimed at the center of Goliath's face because David had experience fighting bears and lions in this manner. Why Goliath did not have his helmet on is not known. Perhaps he was not ready for this kind of confrontation, thinking more along the lines of classic combat (in his time) with swords at arms length. Perhaps, he was trying to frighten David by his frown and his angry looking eyebrows, which he may have considered an advantage against a weak enemy, such as he considered David to be.

Our interpretation is not the only one possible as the Bible does not give as many details about the battle as it does in describing David's preparation for the duel. David went to the creek, chose five stones very carefully and put them in his shepherd's bag (I Samuel 17:40). David inspected his ammunition very carefully, because he wanted his warhead (the stone) to fly very accurately and hit the target as he intended. Thus, he chose stones that had the right weight, shape and texture to fly properly. David also had acquired the ability to select stones to defeat wild animals, like lions and bears (I Samuel 17:34), and probably knew that he could bring down any opponent by hitting them on the nose, regardless of their size. The stone's velocity (kinetic energy) had to be sufficient to stun (or to kill) the giant Goliath by impacting the frontal area of his head.

As soon as David began to swing the sling, Goliath would have been aware of the weapon David was using and would have had to prepare to defend himself. We have postulated that Goliath did not have his helmet on and therefore the only vulnerable area on his body, not protected by armor, was his head. In theory, he could have protected himself by raising his shield or lowering his head (or turning around and ducking). Goliath may not have had his shield on his arm, (if he was not quite ready to fight, his shield bearer would still have had it). Dodging the projectile depends on both judgmental reaction and the time determined by Goliath's distance from David and the projectile's velocity, which we will later estimate.[1] Similarly, Goliath probably could not protect his head by tilting it or by turning around, as his judgmental reaction time would be too long. Even if he had managed to lower (tilt) his head, the result would have been to move the impact point from the nose bridge area to the forehead --- another vulnerable point.

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[1] Modern confrontations between police and armed criminals have shown that an officer's reaction time from when a criminal begins to point a gun at the officer, to the time the officer would fire his gun in self defence, is invariably too long due to judgement time. Current data show a criminal can shoot and hit the officer before he can squeeze his gun's trigger, even if his gun is already drawn. Baseball also demonstrates that batters who are expecting a ball to be thrown at them must wear protective helmets because they are not always capable of dodging a "beanball".

Stones Are Effective

The skin covering the skull is thin and has no stopping power, thus the whole kinetic energy of a projectile has to be absorbed by the forehead skull bone. Kinetic energy as low as 20 joules can produce damage either by accelerating the skull backwards, thus shocking the brain into unconsciousness, or by displacing the bone and breaking it. Goliath's tough but brittle forehead bone, being hit almost perpendicular to the forehead surface, probably could not bend more than about 2 millimeters without starting to break.

The Bible tells us indeed that the stone stuck into Goliath's forehead. This means that David's stone probably knocked him unconscious, or instantly killed him. However, David also took into consideration the possibility that hitting Goliath in his face might just knock him out temporarily. This is why he prepared five stones for the battle. The other four would have been used if Goliath was still conscious after the first hit. David also knew that the result of the duel had to be recognized as decisive to achieve the necessary psychological impact on the enemy. Thus seeing Goliath down on his face, David did not stop to check whether Goliath was just knocked out, or that the stone imbedded in his skull had killed him. He took Goliath's sword out of its sheath and beheaded him. This act, which could be clearly seen by both of the observing armies from where they were standing, made it clear to all how the duel ended.

Modern Engineering Calculations Show How a Sling and Stone Can Be Effective

To bring all of the above into focus, we can perform some computations using the most probable elements in David's actions. We must first estimate the size of the stone that he would have to select in order to have sufficient kinetic energy at impact to stun or kill Goliath. Table 1 lists the attributes of stones ranging from 33 to 41 mm in diameter weighing from about 50 to 90 grams considering a typical stone density of 2.5 to 2.7 g/cc. Stone bullets used with sling are known to be in this range from archeological findings and carved figures. Small stones require larger impact velocities (and therefore larger launch velocities) to bring the impact kinetic energy to the level where lethal damage can be expected than larger stones, which have sufficient mass to bring the launch velocity down to the working region for slings. However, the heavier stones require more energy from the human launcher to accelerate them to the working velocity range. Thus, an upper limit also exists where stones are too heavy for a person to effectively sling them to a working velocity.

Table 1. Attributes of Stone Projectiles

Weight grams	Diameter mm	Area sq. cm	Volume cu. cm
50	33	8.55	18.82
60	35	9.62	22.45
70	37	10.75	26.52
80	39	11.95	31.06
90	41	13.20	36.09

Military slingers from the Roman Empire through the middle ages chose small metallic projectiles (lead, about 80 grams) and probably reached 40 m/s and a kinetic energy of about 64 Joules. Such heavy metal projectiles would lose less energy to aerodynamic drag and would increase the energy density at target impact. A typical short range sling of the

period is shown in Figure 1.

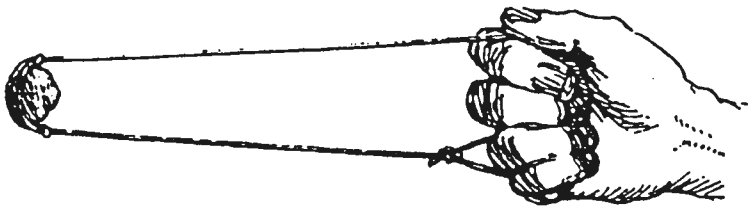

Figure 1. A Typical Short Range Sling

The results of computations for the tangential velocity of typical slings are shown in Table 2, where a fixed sling radius (ranging from .6 to 1. meter) and a given angular velocity produces a circumferential velocity (the launch velocity).

Table 2. Projectile Velocities (m/s) Attainable Using a Sling

Radius m	0.60	0.70	0.80	0.90	1.00
Circumf. m	3.77	4.40	5.03	5.65	6.28
RPS / 6	22.62	26.39	30.16	33.93	37.70
7	26.39	30.79	35.19	39.58	43.98
8	30.16	35.19	40.21	45.24	50.27
9	33.93	39.58	45.24	50.89	56.55
10	37.70	43.98	50.27	56.55	62.83

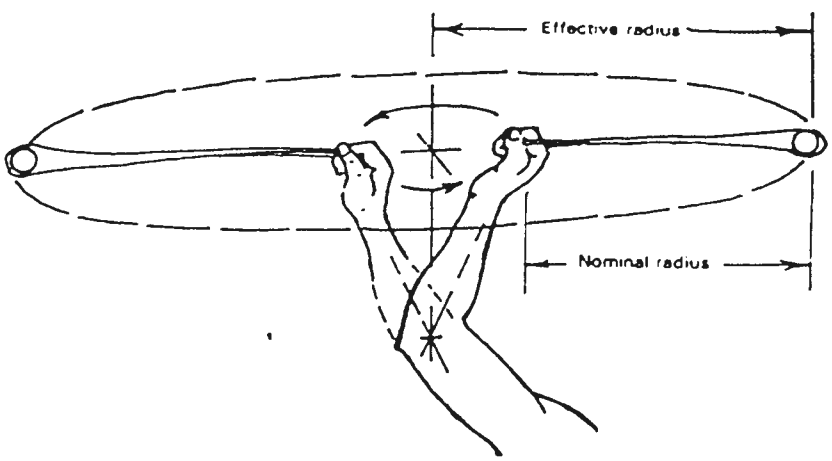

Figure 2. Effective Sling Radius When Using Elbow as Pivot

These geometric computations show that it takes 8 revolutions per second (rps) to produce a tangential velocity of 40 meters per second with a 0.8 m radius sling with a fixed center point. However, Figure 2 shows how by swinging about the wrist, elbow and shoulder (as shown in stone carvings from the ancient city of Niniveh), the effective radius of the sling may be larger than the nominal fixed length of the sling. The same sling used above, when swung on a circle using the pivot of the elbow, produces an effective radius of 1 meter and only a rate of 6 rps is required to reach 38 m/s. The stone accelerates when the arm is pulling on the string. When the arm is being repositioned to pull again, the stone coasts, being affected by aerodynamic forces, gravity, inertia and the properties of the sling and arm as it twists about. The overall action is similar to pumping or ratcheting the system to accumulate projectile kinetic energy. For

an experienced slinger, one or two complete revolutions is all that may be required to reach maximum tangential velocity, the launch velocity.

The key to a projectile's ability to stun or kill an opponent is the kinetic energy available at the engagement range; and the kinetic energy depends upon the projectile velocity. We can compute the aerodynamic slowdown of stone projectiles to the different ranges using their launch velocities. Table 3 presents the results of computations based on the attributes (mass, area, drag coefficient and standard atmospheric conditions) of 50, 70 and 90 gram granite projectiles. (1) If the projectile's impact velocity is deemed to be insufficient to cause the required damage, then a higher launch velocity must be imparted by the slinger.

Experiments with cadavers and hybrid simulation models indicate that an impact energy of 72 joules (c. 53 ft-lbs) is sufficient to perforate (but not exit) a cranium when it is impacted on the parietal portion of the skull with a 6.35 mm diameter steel projectile at 370 m/s. (2) A projectile does not have to perforate the skull, but just crush a part of the frontal bone to produce a depressed skull fracture, (at best), or a stunning blow to render a person unconscious. Such an impact produces strain in the blood vessels and brain tissues upon impact to the front of a skull, as depicted in Figure 3, because the motion of the brain lags the motion of the skull.[2] (3) The impact energy required to achieve these two effects are much lower, on the order of 40 to 20 joules, respectively.

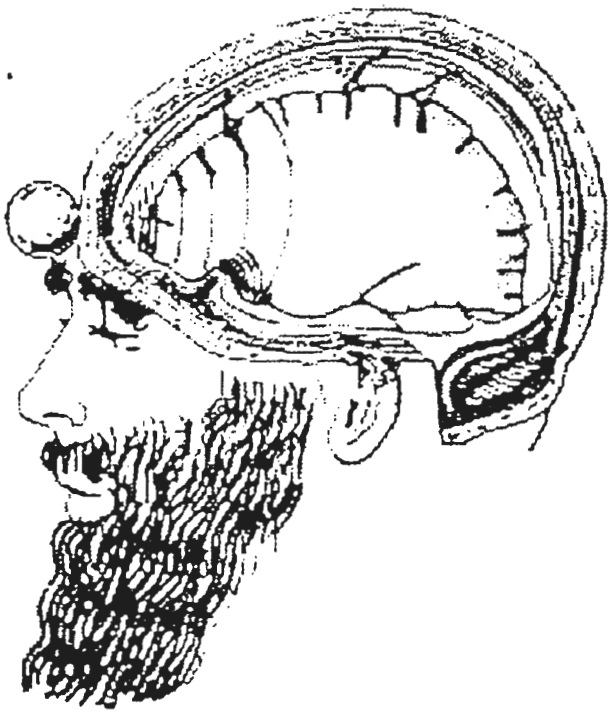

Figure 3. Effects of a Stone's Impact[2]

David's stone may be interpreted in the Bible as having sunk into Goliath's forehead as if a stone sank into mud or into deep water. Computer simulations using Autodyne[3] to describe the impact of 70 gram stones as shown in Figures 4 & 5 have shown that an impact velocity of 30 m/s (32 joules) is necessary for penetration and embedment. At a velocity of 26 m/s (24 joules) the bone was not broken and at 28 m/s (27 joules) no penetration was achieved (as shown in Figure 6.), while at a velocity of 35 m/s the penetration effect was similar to that at 30 m/s.

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[2] Figure 3 has been reproduced from Reference 3 with the kind permission of the author.

[3] Autodyne is a 2-Dimensional Non-linear Dynamic Analysis Code Developed by Century Dynamics, Inc.

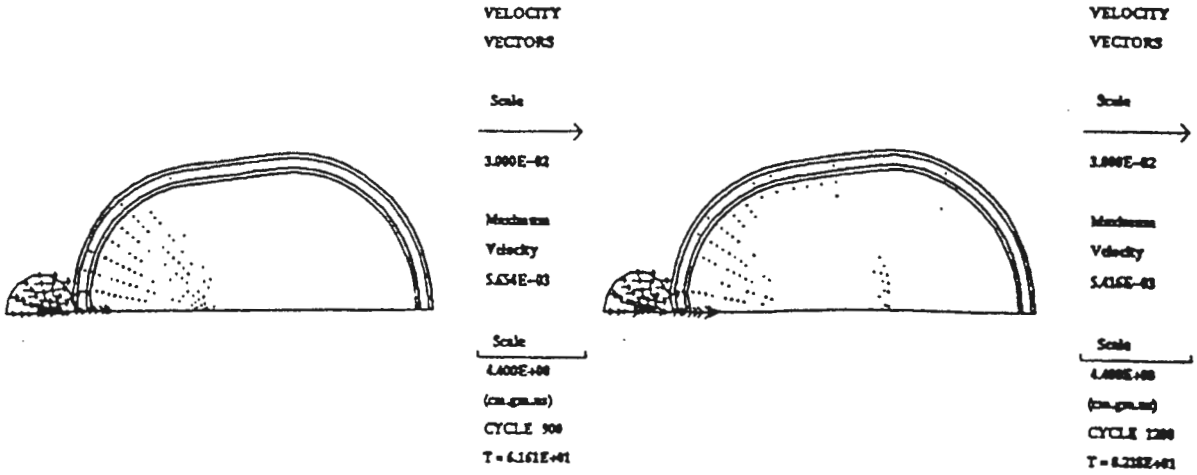

Figure 4. Impact of a 30 m/s 70 gram Stone Against a Simulated Head Showing Bone Breaking and Shockwave Focusing in the Brain

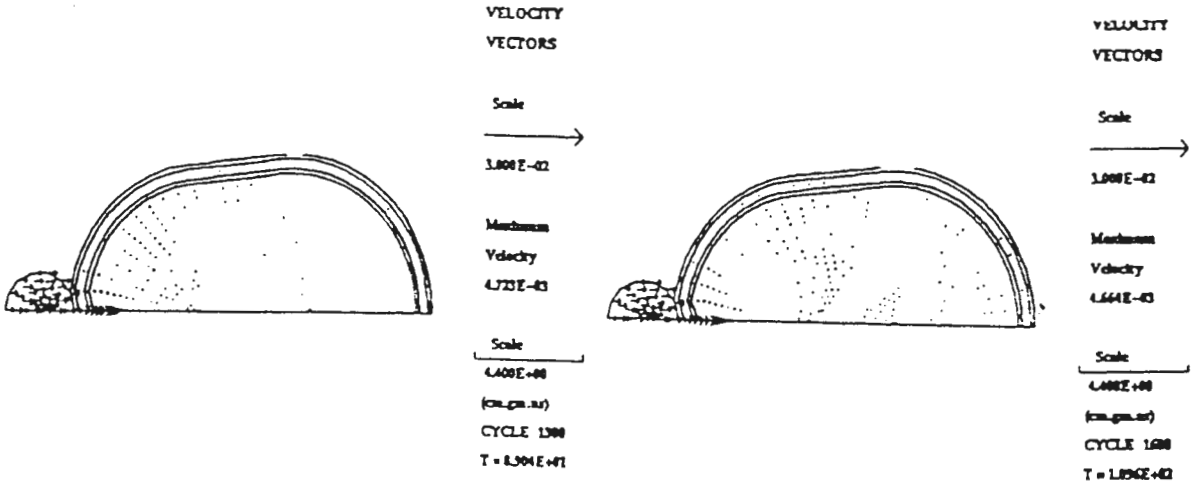

Figure 5. Penetration of a 30 m/s 70 gram Stone Into a Simulated Head

The strength limit of the bone is about 1 kbar; and the simulations show that a 30 m/s impact produces a pressure above 1.2 kbar. It also was important to model the forehead in 3 layers --- a sandwich of fluid-filled porous bone between 2 solid layers, as it really is. The effect of the fluid filling was found to make the bone less compressible and this affects the breaking of the inner bone. Although modeling of the brain within the skull is imperfect, the simulations do show that the brain motion lags the skull causing the shock waves to converge as described by the motion vectors. This effect could possibly have rendered Goliath unconscious at the impact velocity of 26 m/s; but it is highly unreliable as it depends greatly on the physiology of the individual being hit.

Table 3 presents estimates of the aerodynamic slowdown for 50, 70, and 90 gram smooth projectiles launched to have impact velocities above 30 m/s and impact energies above 30 joules at a range of about 30 m. From Table 3, the empirical data, and our computer simulations, it appears possible that David could have used a stone weighing about 70 grams at a range of 25 to 30 m and a typical sling having a working length of 0.6 m while using arm motion to launch the stone about 40 m/s. (The tables also show it to be

Table 3. Aerodynamic Slowdown of Granite Spheres Assuming C_d=0.47

	50 grams		70 grams				90 grams	
R	V	KE	V	KE	V	KE	V	KE
m	m/s	joules	m/s	joules	m/s	joules	m/s	joules
0	39.58	39.21	39.58	55.26	35.19	43.68	35.19	56.02
5	38.64	37.36	38.74	52.93	34.44	41.84	34.5	53.84
10	37.71	35.59	37.91	50.70	33.71	40.07	33.82	51.75
15	36.81	33.91	37.10	48.56	32.99	38.38	33.16	49.74
20	35.93	32.31	36.31	46.51	32.28	36.76	32.51	47.80
25	35.08	30.79	35.54	44.55	31.60	35.21	31.87	45.94
30	34.24	29.34	34.78	42.67	30.92	33.73	31.24	44.16
35	33.42	27.95	34.04	40.87	30.26	32.30	30.63	42.44

possible to achieve similar performance with a 90 gram stone launched near 35 m/s.) If two revolutions at 7 to 8 rev/s were used then we find that David could have slung and hit Goliath in little more than 1 second --- a time so brief that Goliath would not have been able to protect himself and during which he would be stationary for all practical purposes.

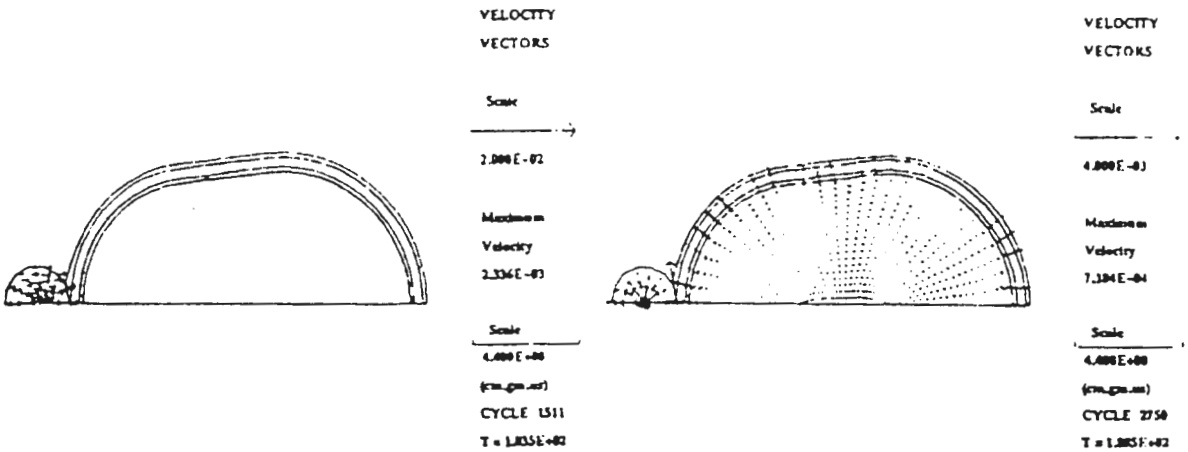

Figure 6. Impact and Rebound of a 28 m/s 70 gram Stone on a Simulated Head

SUMMARY

We find in the confrontation between David and Goliath many classic elements of warfare: deception, disinformation, surprise attack, and weapon choice to provide a tactical advantage over the enemy. We can be very sure that David did not perform calculations and modeling such as described in this paper. However, his actions agree well with these calculations. To the people of his time, David's actions and the result of the battle with Goliath were probably well understood and heroic. David was a very brave and skillful opponent in battle.

ACKNOWLEDGEMENTS

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Goliath challenges the Israelites, 1 Samuel 17
David, saved from lions :34
picks five stones :40
am I a dog? :43
cuts head off :51

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Bullets were cast lead with a weight between 20 and 30 grams, and were capable of penetrating unprotected flesh at 100 meters

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Sling in different lengths, for different ranges: short, medium and long. Smooth rocks, clay balls, and later lead pellets, such as found at Pompeii.

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Complete description of slings and projectiles: bullets of cast lead about 32 mm long by 13 mm high, Stone bullets about 36 mm long by 19 mm high. (Oblate spheroid volume computations using these dimensions yield weights of 80 grams and 50 grams, respectively.) A complete sling is scaled to be about 1.2 m long and 60 cm when folded for use.

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Effectiveness of slings.

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Stone relief from Niniveh showing Assyrian slingers --- elbow and wrist are bent; the stone size seems to be about 15 to 20 % of the figure's hand.