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A Ballistic Evaluation of Arrow Penetration: Kinetic Energy, Momentum, and Mass Dynamics

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Abstract

This paper presents a ballistic evaluation of arrow penetration using principles of classical mechanics. Through controlled testing in various media, we examine the influence of kinetic energy, momentum, and mass on penetration performance. By isolating each variable through matched-energy and matched-momentum conditions, the findings demonstrate that kinetic energy is the primary determinant of terminal arrow performance. This study aims to clarify the physical principles behind arrow behavior, independent of anecdotal or biologically confounded interpretations.

1. Introduction

Ballistics is traditionally divided into internal, external, and terminal phases. While much has been studied in the context of firearms, the same principles apply to arrow dynamics. This paper focuses on the terminal phase penetration by examining how kinetic energy (KE), momentum (p), and arrow mass affect performance. All testing is conducted in controlled media to isolate variables and eliminate biological inconsistencies.

2. Methods

Testing involved arrows of various masses (400–810 grains) launched from compound bows at known velocities. Controlled test media included foam blocks, ballistic gel, and hard composite plates (e.g., PVC). Arrows were evaluated under matched KE or matched momentum conditions to isolate effects. Penetration depth was recorded as the primary outcome. Some tests varied Front-of-Center (FOC) to examine its influence.

All ballistics tests were conducted using field points to eliminate confounding variables such as broadhead sharpness, blade design, or edge retention. This ensured that observed differences in penetration were attributed solely to ballistic properties namely kinetic energy, momentum, and mass and not to cutting efficiency or mechanical deformation.

3. Theoretical Framework

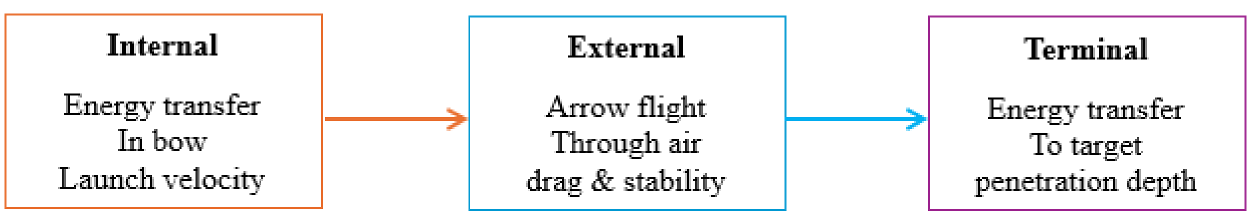
• Kinetic Energy: $KE = \frac{1}{2}mv^2/225218$ (m in grains, v in ft/s, KE in foot-pounds)

• Momentum: $p = mv/225218$ (m in grains, v in ft/s, p in slug-ft/s)

• Work-Energy Theorem: Penetration results from work done by force over distance ($W = F \cdot d$)

• Drag Force: $FD = \frac{1}{2}\rho v^2 CDA$ (ρ = air density, v = velocity, CD = drag coefficient, A = cross-sectional area)

Figure 1: The Three Phases of Arrow Ballistics.
A schematic representation of the three phases of arrow ballistics:
• **Internal** — Energy transfer within the bow during draw and release, determining launch velocity.
• **External** — Arrow flight through the air, governed by drag and stabilization to maintain trajectory.
• **Terminal** — Energy transfer to the target, determining penetration depth and terminal performance.
Arrows between phases illustrate the continuous progression from launch to impact.



3.1 Internal Ballistics

Internal ballistics refers to the mechanics of energy storage and transfer within the bow–arrow system prior to and during launch. In a compound bow, potential energy is stored in the limbs as the string is drawn and is transferred to the arrow upon release. The draw length, draw weight, cam profile, and string elasticity all influence the amount of energy available at release.

Efficiency losses due to limb vibration, string oscillation, and arrow flexing reduce the proportion of stored energy that is converted into kinetic energy. While not the focus of this study, it is important to note that internal ballistic efficiency determines the arrow's launch velocity and initial kinetic energy, which in turn sets the upper limit on penetration potential.

Therefore, optimizing bow tuning and arrow spine to minimize energy losses during release is an integral aspect of maximizing ballistic performance.

3.2 External Ballistics

External ballistics encompasses the arrow's flight from release to impact, including the effects of gravity, drag, and stabilization mechanisms. Once launched, the arrow encounters aerodynamic drag proportional to the square of its velocity and the product of its drag coefficient and cross-sectional area.

In this study, heavier arrows demonstrated slower deceleration over distance compared to lighter arrows, consistent with lower sensitivity to drag forces. This is a direct consequence of their greater momentum and lower initial velocity. The drag force acting on the arrow can be expressed as:

$$\mathbf{FD = (1/2)\ \rho v^2\ CDA}$$

where ρ is air density, v is velocity, CD is the drag coefficient, and A is cross-sectional area.

Flight stability, maintained through spin induced by fletching, ensures that the arrow maintains a nose-forward attitude, minimizing yaw and drag-induced deviation. Although these aerodynamic factors do not substantially affect short-range penetration, they significantly influence long-range accuracy, energy retention, and terminal velocity. Optimizing vane configuration and arrow straightness reduces drag and maintains consistent energy delivery at impact.

3.3 Terminal Ballistics

Terminal ballistics describes the interaction of the arrow with the target upon impact, including how its energy is transferred to penetrate through media. This phase is governed by the arrow's kinetic energy at impact, the resistance of the target, and the efficiency with which the arrow delivers force over a distance.

As the arrow enters the target, it decelerates due to opposing forces from tissue, bone, or test media. Penetration depth depends on the amount of work the arrow can perform against this resistance, consistent with the work-energy theorem:

$$W=F\cdot d$$

where W is the work (equal to the arrow's available kinetic energy), F is the resistive force of the medium, and d is the distance the arrow travels into the target.

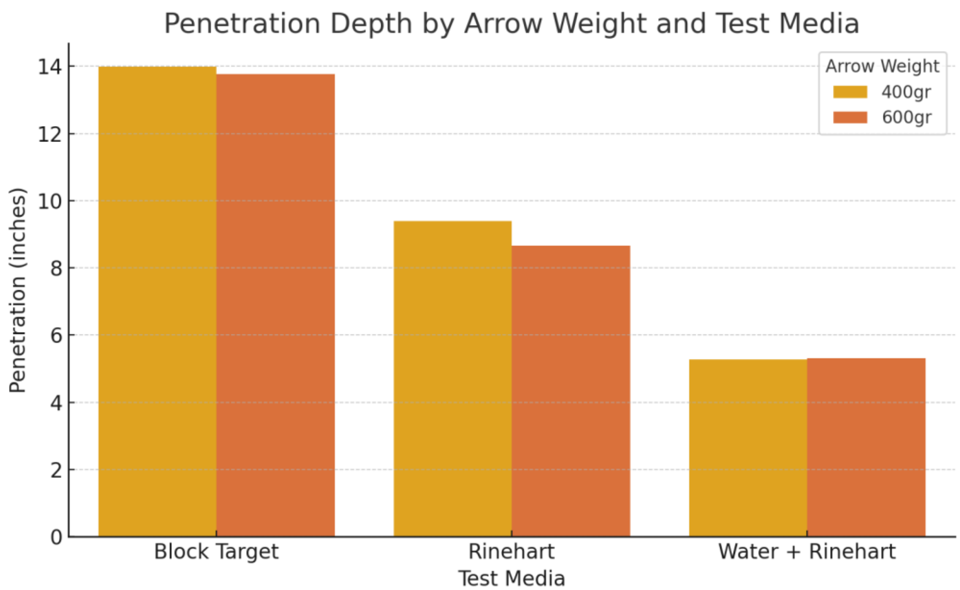
A well-tuned arrow with sufficient kinetic energy and appropriate mass can overcome target resistance and achieve deep or full penetration. The design of the point (field point vs. broadhead), arrow alignment, and impact angle also influence terminal behavior.

This phase, more than any other, determines the effectiveness of the arrow for hunting or testing purposes, making it critical to evaluate kinetic energy delivery and resistance characteristics of the target medium.

4. Results

4.1 Equal Kinetic Energy Tests

Figure 2: Penetration Depth by Arrow Weight and Test Media This figure compares penetration depth between 400gr and 600gr arrows across three test media: block target, Rinehart target, and water + Rinehart. Kinetic energy was matched in all tests. The results confirm that in uniform media, penetration is nearly identical, whereas fluid resistance introduces minor mass effects.

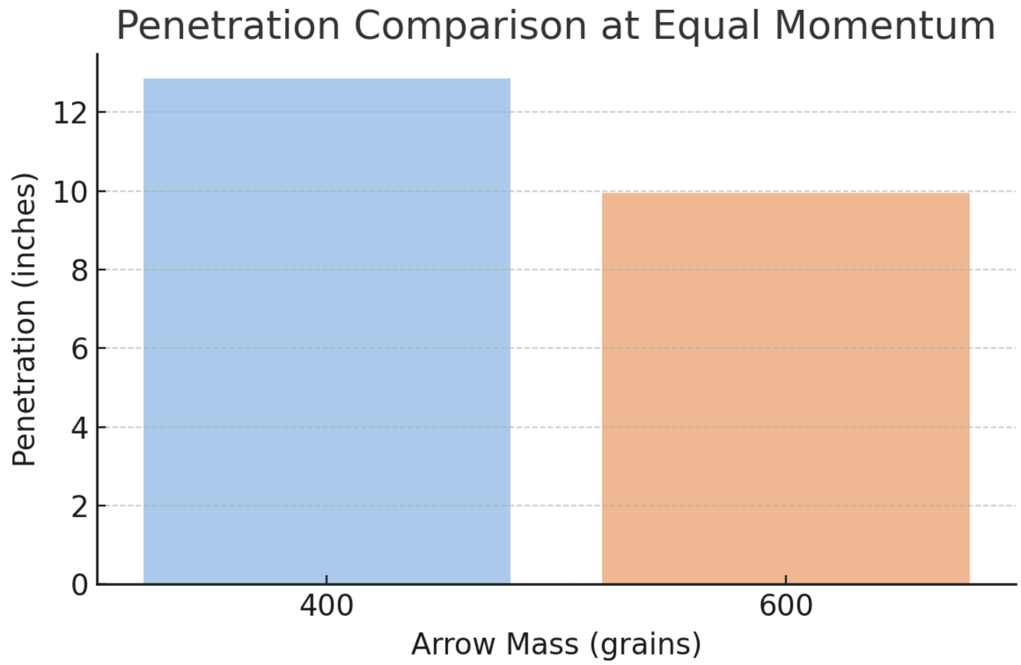


4.2 Equal Momentum Tests

Figure 3: Penetration Comparison at Equal Momentum Arrows of 400gr and 600gr were shot at equal momentum (~0.556 slug·ft/s). The lighter arrow penetrated farther, despite the lower mass. This disproves the claim that higher mass at equal momentum guarantees more penetration, affirming kinetic energy as the more predictive metric.

Figure 3: Penetration Depth under Hard Impact Conditions This figure summarizes four hard-impact tests using foam and PVC targets. When kinetic energy was matched, heavier arrows penetrated slightly deeper. When momentum was matched, lighter arrows outperformed. In some cases, the heavy arrow failed to breach the barrier altogether, confirming kinetic energy as the

controlling variable in overcoming resistance



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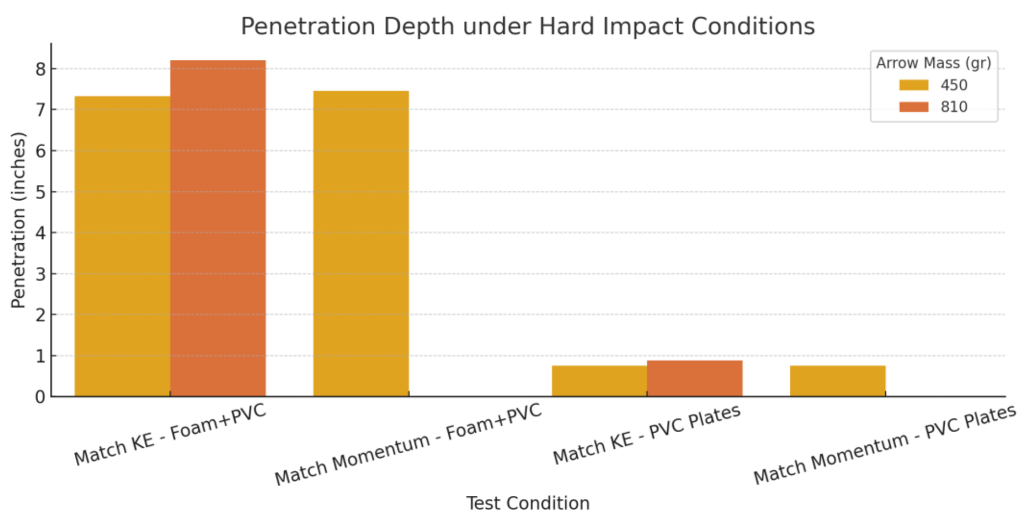


4.3 Velocity Retention and Mass Effect

In ballistic systems, heavier projectiles decelerate more slowly in flight due to lower acceleration under drag. This advantage becomes relevant at longer ranges but does not inherently result in greater penetration. In short-range tests with equal KE and consistent target resistance (e.g., uniform foam blocks), penetration depths are nearly identical across arrow masses. These findings support the conclusion that KE governs penetration in equal-resistance targets.

However, when resistance is no longer uniform such as with the addition of hard media like a 3/8″ PVC plate arrow mass begins to play a secondary role. While KE initiates penetration, the added inertia of a heavier arrow contributes to its ability to continue through the denser medium. This behavior mirrors results observed in bullet ballistics where heavier projectiles, when matched for KE, maintain forward momentum through intermediate barriers.

Thus, the contribution of mass to penetration emerges only when media resistance is high enough to challenge the projectile’s forward motion. Even then, penetration only increases if sufficient KE is present to do the initial work.

Figure 5: Arrow Velocity Loss Over Distance This figure illustrates how lighter arrows (e.g., 361gr) lose velocity more quickly than heavier arrows (e.g., 669gr). The data shows a consistent trend: as arrow mass increases, deceleration over distance decreases, confirming that mass plays a role in aerodynamic drag resistance, though not necessarily in short-range penetration.

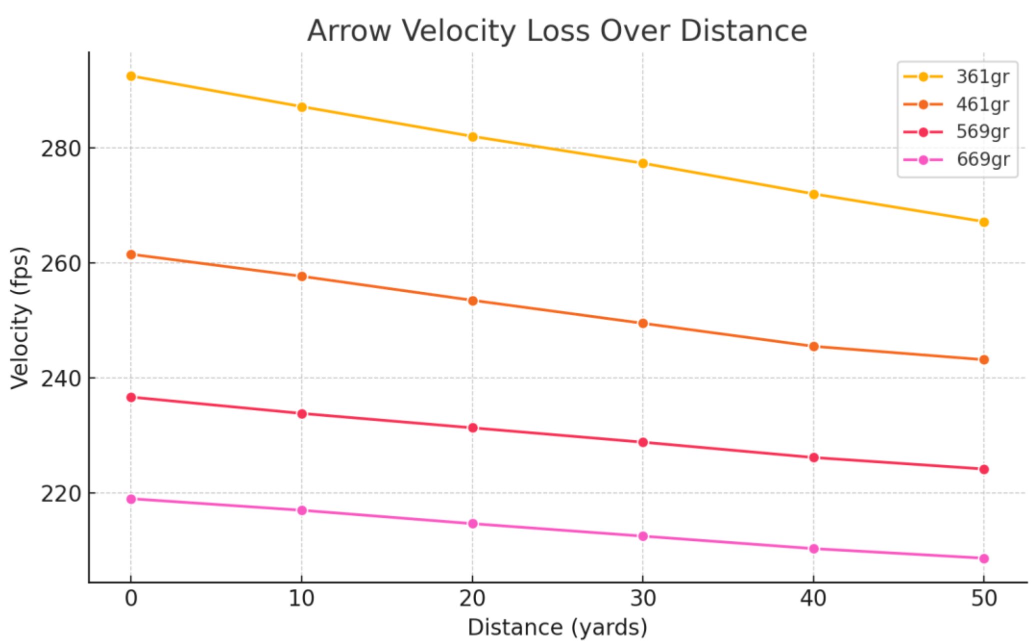


Figure 6: Kinetic Energy Loss Over Distance This chart shows the decay of kinetic energy from 0 to 50 yards. Heavier arrows retain more of their energy, with the 669gr arrow losing only 9.21% of its KE, while the 361gr arrow loses 16.57%. This confirms the KE preservation benefit of heavier arrows, especially in long-range performance.

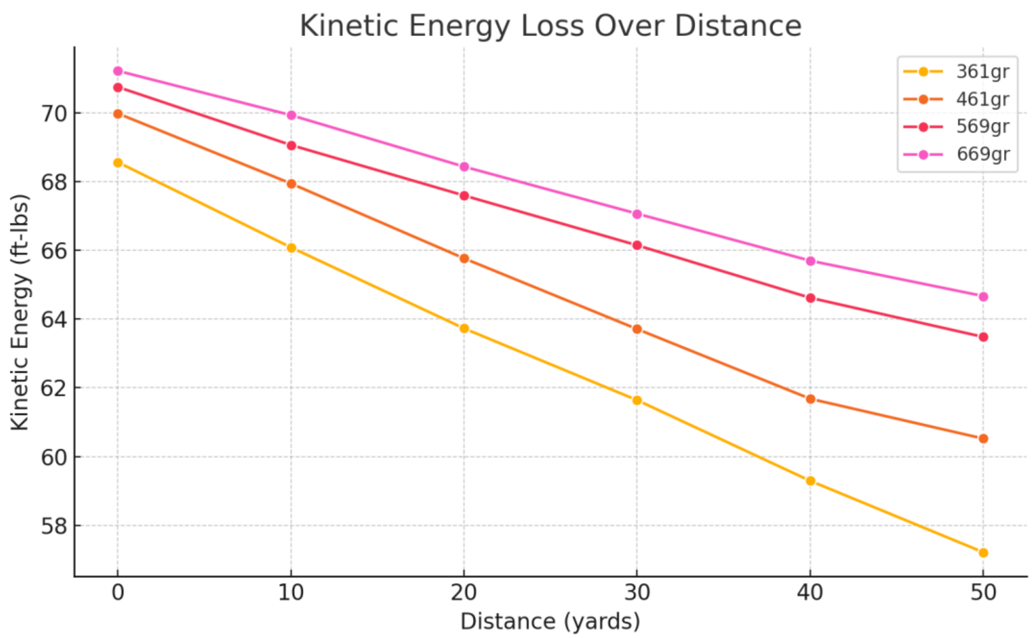
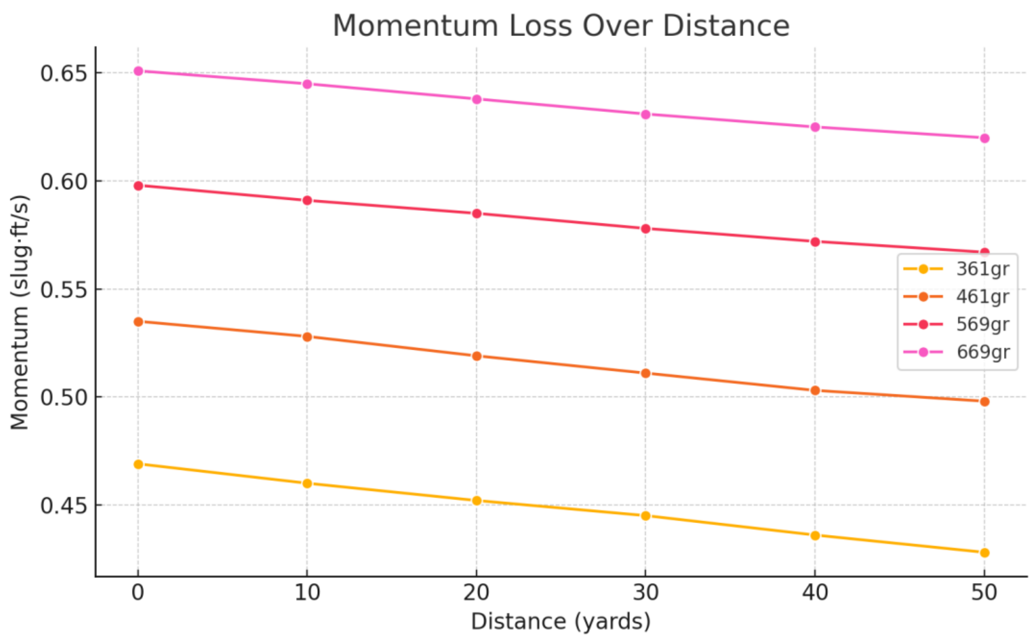
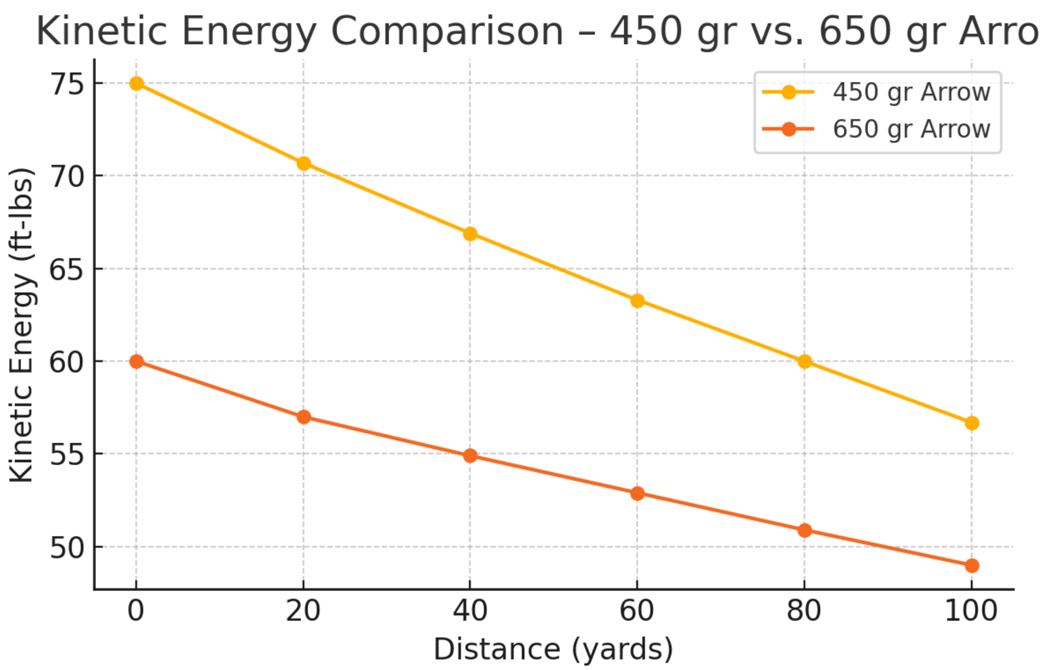


Figure 7: Momentum Loss Over Distance Momentum follows a similar trend to kinetic energy but is less affected by velocity loss. Although heavier arrows retain momentum better, these results reinforce the conclusion that momentum alone does not ensure penetration, kinetic energy remains the governing variable.



4.4 Clarifying Mass-Based Misconceptions

Figure 8: Kinetic Energy Comparison – 450gr vs. 650gr Arrow
This chart illustrates two real-world arrow configurations: a 450-grain arrow launched at 75 ft-lbs. of kinetic energy, and a 650-grain arrow launched at 60 ft-lbs. Although the 650-grain arrow retains energy more efficiently due to greater mass, it never catches up to the lighter arrow's energy at any distance out to 100 yards. This confirms that mass cannot compensate for low initial energy; kinetic energy must be sufficient at launch.



Observation: This chart shows KE values over distance for two arrows of different mass. Despite slower KE loss, the 650-gr arrow never exceeds the KE of the lighter, faster arrow launched at higher energy.

Implication for Penetration:
A common belief in some bowhunting communities is that a 650-grain arrow represents a universal "bone-breaking threshold," regardless of how much kinetic energy it carries. This idea ignores basic physics: a 650-grain arrow launched with less kinetic energy will always have less energy than a lighter arrow launched with more kinetic energy. Mass alone cannot overcome a lack of energy. While heavier arrows may retain velocity better over long distances due to inertia, they still require sufficient initial energy to perform work such as penetrating bone or dense tissue. It is a misconception to assume that mass by itself creates penetration; the arrow must deliver energy to do work, and that energy is defined by both mass and velocity. Therefore, penetration potential should be evaluated based on both kinetic energy and mass not on arbitrary mass alone.

5. Discussion

Limitations and Correlation with Real-World Data
While controlled test media do not perfectly replicate the anatomical complexity of live animals, they serve a crucial role in isolating variables like kinetic energy and momentum without the biological inconsistencies of bone, tissue density, and shot angle. It is true that test media outcomes do not directly predict penetration depth in animals. However, the trends observed particularly the dominance of kinetic energy in penetration performance are consistently mirrored in real-world data. As shown by field results from Joel Maxfield, Andy Maxfield, and Dave Holt, the core physical principles observed in controlled tests do translate into consistent terminal outcomes in hunting situations.

5.1 Real-World Field Validation

5.1.1 Joel Maxfield – Asian Water Buffalo

Industry veteran Joel Maxfield provided direct field validation by harvesting a massive Asian water buffalo estimated at over 2,500 pounds. Using a compound bow set at 82 pounds draw weight, he launched a 571-grain arrow at 288 fps, yielding 105.1 ft-lbs. of kinetic energy at the bow.

Three shots were recorded:

At 58 yards, the arrow tipped with an Iron Will fixed-blade broadhead achieved a complete pass-through. Trajectory-based KE estimations show ~92.4 ft-lbs. of energy remained at impact.

At 92 yards, he used a G5 T2 mechanical broadhead, and the arrow buried deeply into the buffalo, stopping only 3 inches from the fletching. Estimated impact energy at this range was ~85.9 ft-lbs.

A third shot, at 32 yards with the G5 T2 mechanical broadhead, resulted in a clean pass-through. While noteworthy, this closer shot falls within the expected performance envelope and is not highlighted further here, as the 58- and 92-yard shots better demonstrate the effects of retained kinetic energy at extended distances.

These results strongly support the conclusion that sufficient kinetic energy not momentum or extreme arrow mass is the governing variable for successful penetration, even on extraordinarily large animals. The second shot, despite using a mechanical broadhead at a long range, still achieved near-complete penetration due to retained energy, highlighting that high-performance projectiles with good energy retention can be effective beyond conventional bowhunting distances.

Joel teaches that optimal arrow mass should fall within the range of 6.2 to 7.2 grains per pound of draw weight, a standard he developed from decades of bowhunting and equipment testing. He emphasizes that while arrow mass is important, it must be accompanied by sufficient kinetic energy to meet the penetration demands of the animal being pursued. His philosophy aligns directly with the conclusions of this study: mass contributes to energy retention, but energy delivery is what determines penetration success.

5.1.2 Andy Maxfield – Asian Water Buffalo

Andy Maxfield, using a nearly identical setup, replicated these outcomes with remarkable consistency. Shooting a Mathews Lift RS at 84 pounds draw weight, he launched the same 571-grain Gold Tip Airstrike arrow at 290 fps, generating 106.6 ft-lbs. of KE at the bow.

Two shots were recorded:

At 54 yards, with a G5 T2 mechanical broadhead, Andy achieved a full pass-through, retaining an estimated ~95.4 ft-lbs. of KE at impact.

At 65 yards, the arrow fully penetrated through the animal, stopping with the fletching hanging up inside the offside functionally a complete pass-through. Estimated KE at impact was ~92.3 ft-lbs.

These results mirror Joel's and demonstrate that the proper balance of arrow weight and retained energy enables consistent terminal performance, even when mechanical broadheads are used. Andy's consistency across long distances reinforces the argument that kinetic energy, not just arrow mass or design, is the controlling factor for deep penetration and successful outcomes in extreme hunting situations.

5.1.3 Dave Holt – Africa Hunt Reports.

The findings from this study are further reinforced by the extensive fieldwork of veteran bowhunter Dave Holt, who has harvested over 2,600 animals globally, including more than 90 African game animals documented over three years of detailed record keeping. In both his 2022–2024 Africa hunts, Holt used arrows weighing 448–474 grains with kinetic energies ranging from 58 to 65 foot-pounds.

Across this data, Holt consistently demonstrated that kinetic energy not raw arrow mass or momentum was the key predictor of penetration, even on large animals such as kudu, zebra, eland, and oryx. Notably, Holt routinely achieved pass-throughs or deep penetration with arrows under 500 grains, provided that sufficient KE was present. In several cases, arrows penetrated deeply or passed through the game weighing over 1,000 pounds.

These results align with the conclusion that arrow penetration is governed by energy transfer, not solely by momentum or mass. Holt's extensive data shows that even with quartering shots or larger animals, penetration remained effective when KE exceeded 58 ft-lbs. and broadhead choice was appropriate. This evidence supports the recommendation to prioritize energy-based metrics over mass-based.

The Dave Holt Reports can be viewed at www.pnltesters.com

6. Conclusion

This ballistic evaluation demonstrates that kinetic energy is the dominant predictor of arrow penetration, both in controlled media and real-world hunting scenarios. Across tests using equal momentum and equal kinetic energy conditions, only kinetic energy consistently correlated with penetration depth across foam, ballistic gel, and hard composite barriers. Lighter arrows at equal momentum often outperformed heavier arrows, disproving the assumption that momentum alone governs penetration.

Additionally, field data from Joel Maxfield, Andy Maxfield, and Dave Holt reinforce these findings. Maxfield's successful penetration on an Asian water buffalo with a 570-grain arrow, and Holt's extensive pass-through records using sub-500 grain arrows, both confirm that adequate kinetic energy not simply high mass or momentum is the critical factor in achieving lethal arrow performance.

In totality, this study supports a shift in emphasis toward energy-based arrow selection and evaluation, especially when comparing performance claims based solely on mass or momentum. While arrow weight and drag affect velocity retention over distance, it is the energy delivered on impact and the work that energy performs that dictates success in terminal ballistics.

Penetration success is best predicted by the arrow's mass and the energy it delivers not by mass or momentum alone.

Acknowledgments.

Special thanks to Joel Maxfield for his critical role in collecting and contributing controlled ballistic test data used throughout this study. His collaboration, equipment support, and extensive knowledge of arrow systems were instrumental in verifying core ballistic principles under consistent test conditions.

Additional thanks to Joel Maxfield, Andy Maxfield, and Dave Holt for sharing field data from successful hunts. Their real-world results under extreme conditions provided meaningful validation of the paper's findings and demonstrated how energy-based penetration principles apply beyond the test range.

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