THE EFFECT OF ROTATIONAL SPEED ON STICKING PROBABILITY AND IMPACT FORCE IN KNIFE THROWING

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ABSTRACT

The goal of knife throwing is to stick the knife in the center of the target. With the intent of focusing on optimizing the knife's sticking probability, it is important to identify the relationship between the knife's rotational dynamics and its impact with the target. This information serves to aid the performance of knife throwers and athletes in similar sports such as darts or axe throwing. To determine the effects of the knife's velocity on its impact force and sticking probability, a knife was thrown at a force plate for 45 trials. The knife's motion and impact was captured on camera for video analysis to determine the knife's rotational speed, linear velocity, and sticking angle. Data collected suggested an optimal flight angle of around 2.8π and final angle between -40 and 20 degrees.

Keywords: Rotational speed, flight angle, sticking probability, impulse, knife throwing

INTRODUCTION

While a niche sport, knife throwing is practiced around the world. People are drawn to the practice because it serves as both a performance art and combat skill. The sport works by people throwing a knife, usually by the blade, at a target. The goal is to stick the knife in the center of the target, similar to archery or darts. Achieving this requires precise technique to control the knife's rotation and impact, and in order for a knife thrower to better adjust their form after each throw it is essential to understand the mechanics of knife throwing itself.

Knife throwing is governed by the principles of rotational dynamics and projectile motion. The principles of projectile motion explain how the knife travels through the air, influenced by its initial velocity and angle of release. Rotational dynamics, specifically the spin of the knife, is crucial for ensuring stability and accuracy, as the angular momentum affects the knife's trajectory and orientation. Impact forces also come into play when the knife strikes a target, with the depth of penetration and damage determined by the knife's speed and rotation. All these factors can be analyzed together to determine the optimal conditions for knife throwing performance. For example, by understanding the ideal number of rotations a knife should complete before impact, a thrower can adjust their release to control its rotational speed. Similarly, knowing the optimal amount of force needed for the knife to stick in the target helps throwers determine how hard to throw. Lastly, these optimal conditions are also useful in helping athletes in similar sports such as darts or axe throwing.

These optimal conditions were defined by maximizing the knife's sticking probability, or the likelihood that a knife will embed and remain in the target. Future work could explore how to optimize the location on the knife where it sticks, but for this experiment, the set up involved a force plate, camera, and a Perfect Point, model PAK-712-12, throwing knife. The knife was thrown 2.0 meters away from a force plate mounted on the wall with plywood taped over the plate for 45 trials. Each throw was captured on video and then analyzed in Vernier Video Analysis to identify the knife's speeds, revolutions, and impact angle. Using data from the video analysis and the force plate, the knife's optimal conditions were determined. These conditions were expressed as an optimal range of total radians during flight, the impulse of the knife's impact, and the final angle at which it hit the plywood.

BACKGROUND

To begin the investigation on identifying the optimal conditions in knife throwing, prior research on projectiles were looked at. This research is primarily categorized into two areas: the knife's flight, including its linear and rotational velocities, and the impact, including the final angle and impulse.

2.1 ROTATIONAL SPEED OF A PROJECTILE

There has been little experimentation and research on how a knife specifically acts as a projectile. In 2022, a study discovered that there is a direct correlation between rotational speed of an object and depth of projectile penetration [1]. The study digitally simulated a 35mm armor-piercing projectile penetrating an armored steel plate under different rotation speeds [1]. The results suggested that at higher rotational speeds, there was an increase in penetration depth. Similar results were also observed in a study conducted in May 2024. In this experiment, they observed the effects of rotational speed on dropping a ball into granular material [2]. Despite similar outcomes, both experiments look at similar shaped objects with a smooth surface and same axis of rotation. By analyzing the dynamics of knife throwing, it will build on these studies' previous results as a knife is a much more complex structure and it rotates differently than the other projectiles.

The 2022 study analyzed the rotation of a bullet, which has a different axis of rotation than a knife. As depicted in Figure 1, the knife rotates into the page, whereas the axis of rotation of a bullet points in the same direction as its linear velocity along the page. This difference between axes may change how the knife interacts during its trajectory and final impact.

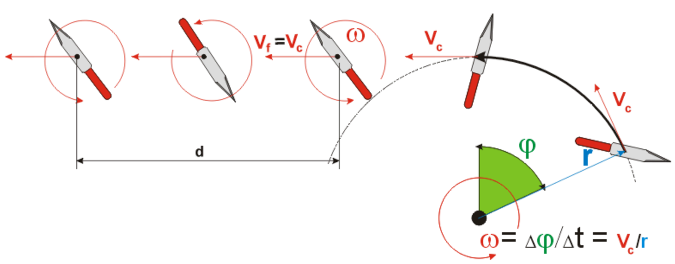

Figure 1. Schematic of a knife throw. In this schematic, the black dot where the angle φ comes from represents the shoulder of the thrower. φ is the angle of release, and r is the radius between the shoulder joint of the thrower and the knife's center of gravity. V_f is the translational velocity of the knife's flight which is equal to the circumferential velocity, V_c, at the moment of release. The key aspect of this figure is to illustrate how the knife's axis of rotation points into the page, and its angular velocity is determined by the angle at which the knife is released [3].

In terms of dictating how the knife impacts into the target, the ratio between the knife's translational and rotational speed may be significant. A study in 2024 found that if a projectile's translational velocity is high and its rotational speed is low, then the projectile will be less effective penetrating a target due to lack of surface contact [4]. Conversely, a high rotational speed, especially relative to translational velocity, may enhance surface contact and improve interaction with the target [4]. However, the precise relationship between these factors and their collective influence on impact dynamics, particularly in terms of force and sticking probability, is not yet fully understood and merits further investigation.

2.2 THE IMPACT OF ENERGY

When a knife hits a target, there is a transfer of energy that occurs according to the law of conservation of energy. The change in energy of the projectile can be calculated by subtracting the residual energy after impact from the initial energy of the projectile.

$$W_T = E_{ip} - E_{rp} \tag{1}$$

Where W_T is the total energy that the target received. E_{ip} is the projectile's initial energy, and E_{rp} is the projectile's residual energy after impact [4]. Additionally, the projectile's residual energy can be broken down further.

$$KE_{rp} = KE_{T,rp} + KE_{R,rp} \tag{2}$$

Where KE_{rp} is the total residual kinetic energy of the projectile. $KE_{T,rp}$ is the projectile's translational kinetic energy after perforation, and $KE_{R,rp}$ is the projectile's rotational energy after perforation [4]. The translational and rotational kinetic energy can be calculated using the projectile's linear and rotational velocity.

$$KE_{Total} = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2 \tag{3}$$

Where I represents the inertia of the projectile, ω is rotational speed, and v is the linear velocity. To derive the rotational kinetic energy for a knife, it can be modeled as a rod that rotates about the center, so the following inertia formula can be used.

$$I = \frac{1}{12}ML^2 \tag{4}$$

Understanding the energy transfer between a spinning projectile and a target is significant in determining the effect of the knife's impact onto the plywood. In 2021, a study concluded that the most significant factor in determining damage to a target was power not momentum [5]. They supported this by demonstrating that, in baseball, the transfer of energy from bat to ball is more crucial than momentum transfer; therefore, using a lighter bat can lead to a longer hit because it allows for a higher swing speed, maximizing energy transfer to the ball [5]. While knives are quite light in mass in comparison to a bat, it is important to understand all the factors that contribute to a knife's impact force and damage onto the target.

EXPERIMENTAL DESIGN

In order to measure the flight characteristics of the knife, an iPhone 12 with a 240fps camera was placed on a tripod. A force plate was mounted on a wall, and a knife was thrown from a distance of approximately 2 meters. The iPhone 12 was mounted on the tripod, positioned to capture the entire trajectory of the knife during flight. The camera was aimed at the knife's path to record its motion and impact on the plywood. Two stickers were also placed on the knife to assist with video analysis, one at the center of the knife and the other at the tip of the blade. A photograph of the experimental setup is shown in Figure 2.

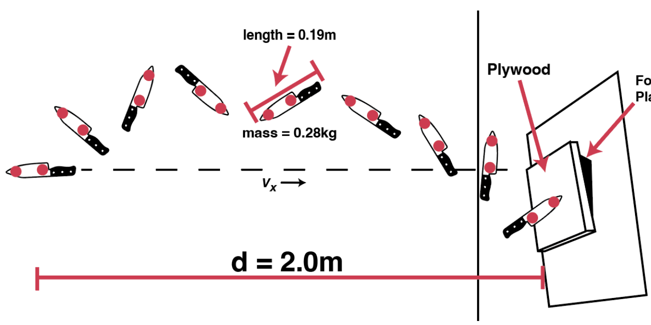

Figure 2. Diagram of the experiment setup. The setup includes an iPhone 12 mounted on a tripod to capture the knife's flight. The knife is approximately 0.19 meters long with a 0.28kg mass. The knife is thrown at a piece of plywood which is attached on top of a force plate that is mounted to the wall.

3.1 MEASUREMENT OF FORCE AND IMPULSE

Each trial produced a graph plotting force against time, as shown in Figure 3. The impact force of the knife was determined by identifying the peak value of the graph represented as F_{impact}.

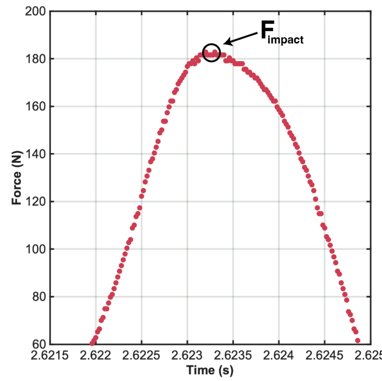

Figure 3. Graph of force as a function of time for one knife throwing trial. This graph is a zoomed in section of the force's peak, and the impact force of the knife is derived from the maximum value of the peak referred to as F_{impact}.

This data was also used to calculate the impulse of the knife, which was determined by integrating the force over the time frame within the peak. Data for calculating the impulse was taken exclusively from the peak of the curve to ensure that the impulse accurately represents the knife's impact, excluding any oscillations from the force plate.

3.2 VIDEO ANALYSIS FOR ROTATIONAL AND LINEAR VELOCITY

Using Vernier Video Analysis, the center and edge point of the knife were tracked and recorded. The angle of the knife was then calculated by taking the arctangent of the knife's tilt.

$$\theta = arctan\left(\frac{y_{center} - y_{edge}}{x_{center} - x_{edge}}\right) \tag{5}$$

The knife's angle was then plotted as a function of time, as shown in Figure 4. The slope of the fitted line across one revolution was used to calculate the rotational speed of the knife in radians per second.

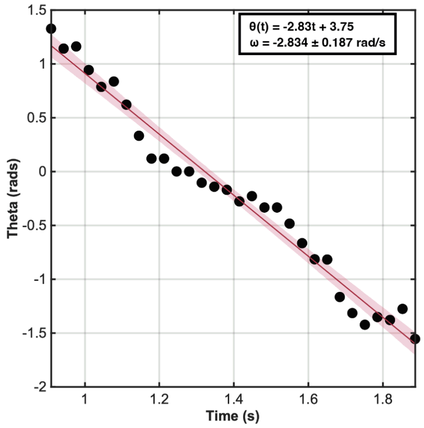

Figure 4. Graph of theta as a function of time for one knife throwing trial. Across one knife revolution a linear model of the form $f(x) = p_1 x + p_2$ was fit. The rotational speed is the slope of this function so in this case p_1= -2.83 ± 0.187 rad/s.

The linear velocity was calculated by analyzing how the knife's center x and y coordinates changed over time. Each coordinate was plotted as a function of time, and a linear model was fitted to the data. The respective velocities of the coordinates were then determined by calculating the slopes of the fitted lines, as shown in Figure 5.

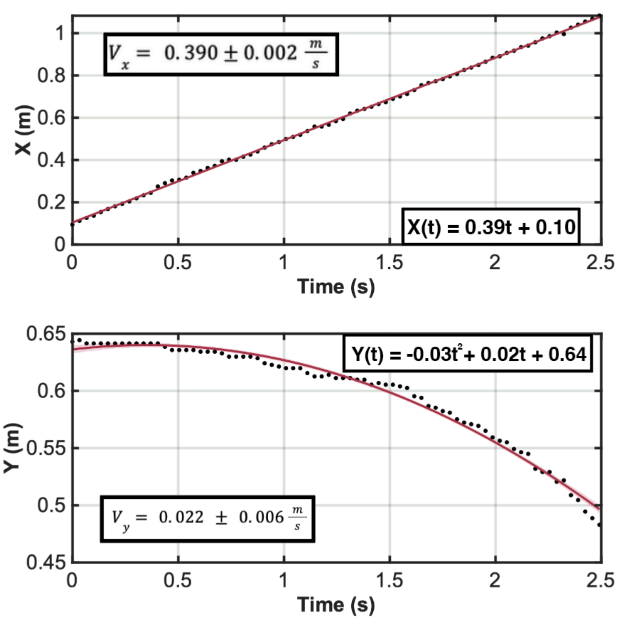

Figure 4. Graph of the knife's center X and Y coordinate as a function of time for one knife throwing trial. To calculate the linear velocity in the x-direction, V_x, a linear fit of the form $f(x) = p_1 x + p_2$ was applied where p_1 or V_x = 0.39 ± 0.0020 m/s. For V_y the fitted model was of the quadratic form $f(x) = ax^2 + bx + c$, where V_y was approximately equal to the b term at 0.022 ± 0.0060 m/s. The total linear velocity was then calculated using $V_{Total} = \sqrt{V_x^2 + V_y^2}$.

3.3 FINAL ANGLE

At the first moment the knife hits the target, that frame was captured on Vernier Video Analysis to calculate the knife's final angle. The location of the angle is shown in Figure 6.

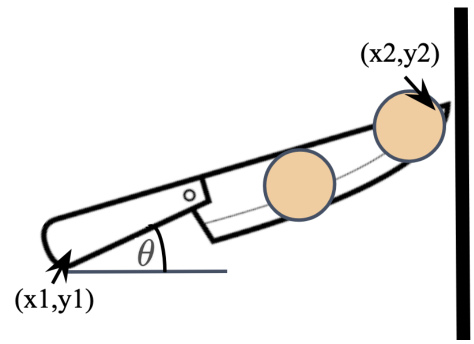

Figure 6. Schematic of the knife stuck in the plywood. The final angle is indicated by theta.

Similar to the angle during flight, theta was calculated using the arctangent of the difference between the points at the tip of the blade and handle.

$$\theta = arctan(\frac{y_2 - y_1}{x_1 - x_2}) \tag{6}$$

RESULTS AND DISCUSSION

To determine the optimal conditions for knife throwing, data was collected using the testing procedure described above, and the results are discussed here. Figure 7 indicates a relationship between momentum and energy by plotting impulse as a function of total kinetic energy.

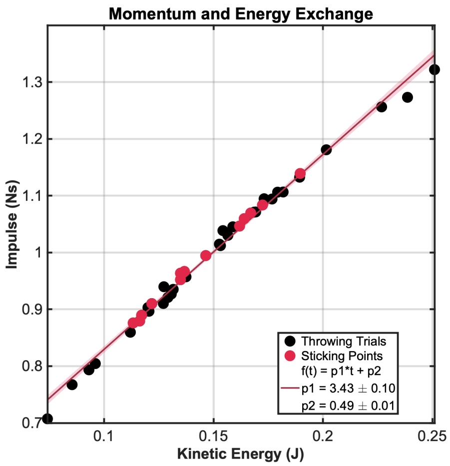

Figure 7. Graph of impulse versus total kinetic energy of each throw. The linear fitted model was of the form $f(x) = p_1 x + p_2$, where p_1= 3.4 ± 0.10 Ns*J and p_2= 0.49 ± 0.01 Ns.

Figure 7 does not present any significant new findings, as the observation that a larger kinetic energy corresponds to a larger impulse is consistent with the principles of kinematics. However, this graph serves as a good confirmation of the experimental setup's accuracy. Although there is a bit of a range of kinetic energy where the probability of the knife sticking seems to increase. Figure 8 provides a more practical analysis by identifying a more prominent optimal range by breaking down each throwing trial based on whether the knife is stuck in the plywood and its corresponding flight angle.

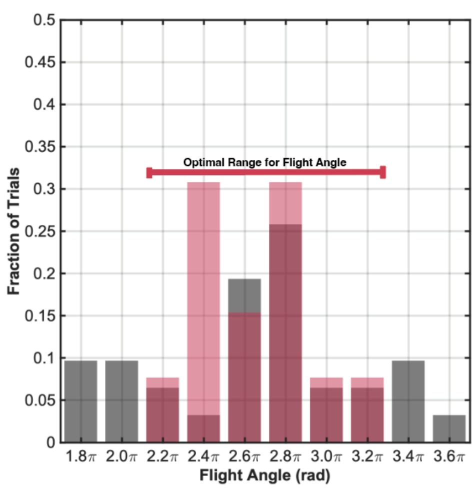

Figure 8. Histogram of the percentage of throws that stuck in the plywood and its corresponding flight angle. The trials that stuck in the target are indicated by the red histogram which overlays the histogram of trials that did not stick. Between 2.2π and 3.2π the probability of the knife sticking increases especially between 2.4π and 2.8π.

Knife throwers commonly throw the knife by the blade, which is how the knife was thrown in this experiment. These results indicate that with a starting angle of pi, the knife should undergo almost 3π or 1.5 revolutions. This makes sense intuitively since the knife would line up hitting the target on the blade. According to Figure 8, the ideal flight angle is more closely situated around 2.8π than 3π. This is likely due to the thrower not consistently releasing the knife at an initial angle of π. Since this experiment was conducted with only one distance, 0.20 meters, away from the target, it makes sense that there is only one ideal flight angle range. Future work could apply this study to multiple distances and see if bands of optimal flight angles arise such as around 3π then 5π then 7π and so on.

The flight angle was originally calculated by finding the time of flight through comparing the distance and translational velocity.

$$T_f = \frac{D}{V_x} \tag{7}$$

Then the flight angle was derived from multiplying the time of flight and rotational speed. However this method elicited fairly infeasible data, so instead of using Equation 7 to calculate time of flight, it was manually recorded based on the lengths of each trial video. This produced much more feasible data. The issue that arose with Equation 7 is likely due to the uncertainty in the distance being too high, since it is very hard to ensure the thrower sticks to the exact distance marker each time and does not lean too far forward or backward. Future work could explore how a thrower's upper body positioning specifically influences the outcome of the knife throw. Despite the original difficulties, the flight angle is a useful calculation and in Figure 9, it helps identify an optimal impulse range by plotting impulse against flight angle.

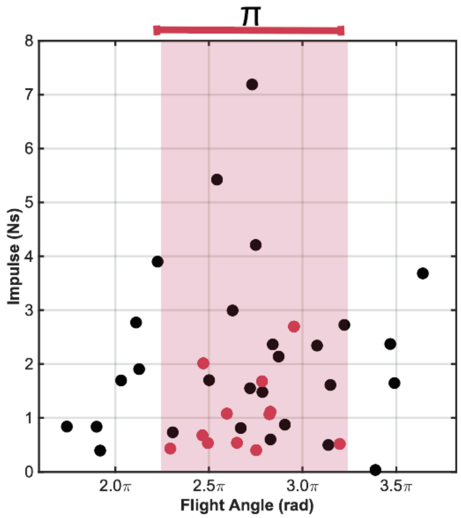

Figure 9. Graph of impulse as a function of flight angle. The sticking points within the optimal flight angle range tend towards smaller impulses between 0.5 and 2.5 Ns.

The uncertainty of the impulse is the resolution of the force plate, which is 0.3N, multiplied with the time at which the force is applied. Assuming the uncertainty is the same for all trials, 0.3N is multiplied by the time frame of the force peak for one trial which was approximately 0.0035 for an uncertainty of 0.0011 Ns. An optimal impulse range offers throwers valuable guidance by indicating the required force for effective knife throws. Training within this range can help athletes condition their muscles for consistent performance. At a broader level, the data suggests that throwing with excessive force does not improve performance and likely hinders it. It is also useful for throwers to understand the range of angles that the knife sticks in the target which is depicted in Figure 10.

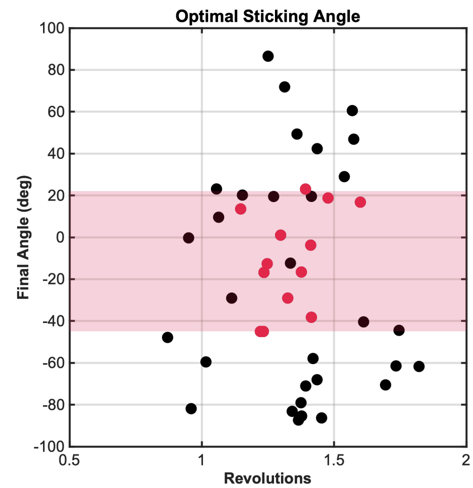

Figure 10. Graph of final angle plotted against total revolutions of the knife. As seen in the prior two figures, the optimal range of revolutions is around 1.5 revolutions which is equivalent to 3π. The red zone highlights the range of final angle that increases sticking probability. This range is between 20 and -40 degrees, so the angle tends negative, likely due to the gravitational force pushing the knife downward.

As discussed in the testing procedure, the final angle is calculated using Vernier Video analysis. To identify the uncertainty in these angle calculations, a different angle was calculated from the same impact frame and the difference between the recorded final angle and other angle is the uncertainty. This process was done for one trial under the assumption the uncertainty is the same for all trials. As a result, the uncertainty of that final angle is 1.8 degrees, which is fairly marginal.

CONCLUSIONS

The ideal conditions to increase the sticking probability for knife throwing were identified by an optimal range for flight angle, impulse, and final angle. The flight angle was between 2.2π to 3.2π which is around 1.1 to 1.6 revolutions of the knife across the entire 0.2 meter distance to the target. This knowledge is valuable for throwers as it helps them understand the relationship between the knife's rotations and its sticking probability, allowing them to effectively adjust the knife's rotational speed during their throw. Throwers also can better control their force with the knife by knowing the ideal range of impulse to increase the sticking probability, which lies between 0.5 and 2.5 Ns with an uncertainty of 0.0011 Ns. Lastly, an optimal range in final angle was determined to be 20 to -40 degrees. There is a slight tendency for a negative angle, and this is likely due to the gravitational force against the knife, since a negative angle would be pointing downward to the ground. This information helps throwers better understand the relationship between the knife's impact and the target. By knowing the optimal angle range, they can more effectively adjust their throws, using previous throws to assess how far their angle deviated and make corrections accordingly. All these relationships could be useful in helping not only train current athletes in knife throwing, but also help those learn the sport for the first time.

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