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Article

Investigating momentum transfer with gall-forming wasps

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SUMMARY

Neuroterus saltatorius **is a gall-forming wasp species endemic to the U.S. During summer, large numbers of galls detach from oak leaves and fall to the ground. They jump several times per minute in random directions earning them the moniker "jumping galls" or "flea seeds". The mechanism behind this unique behavior has not been established, but one hypothesis suggests that encapsulated gall larva forces fluid through its U-shaped body at high speeds. The momentum of this fluid is transferred in such a way that a hopping motion occurs. We believe that understanding momentum transfer is important for applications focused on momentum transfer. Inspired by the jumping gall and to understand momentum transfer, we constructed a model using a mousetrap with attachable weights to demonstrate that a moving mass can cause jumping through momentum transfer. We predicted that adding weight to the arm would increase the jump height because the arm swings at the same speed with increased momentum from the larger mass. Increasing weights to the arm allowed us to identify the optimal mass for the highest jump. This modeling approach provided insights into the physical process underlying the galls' jumping behavior and extended beyond that. An application of the theory is to use momentum transfer when exploring microgravity environments like comets and asteroids because instrument packages cannot be moved by wheeled vehicles on extremely rough surfaces. An alternative is to construct robots capable of moving by momentum transfer.**

INTRODUCTION

Momentum transfer plays a significant role in diverse scientific disciplines, including physics, chemistry and engineering. It is essential for understanding the dynamics of moving objects and their interactions with the local environment. It is crucial for the development of advanced space exploration technology and transportation and energy systems. Because no one has studied momentum transfer in jumping galls before and further exploration may yield additional benefits, we are investigating a natural phenomenon that has the potential to inspire a broader understanding of momentum transfer.

Neuroterus saltatorius, often referred to as jumping gall wasps, go through their life cycle on a variety of oak species, including blue oak (*Quercus douglasii*), valley oak (*Quercus lobata*), and Oregon oak (*Quercus garryana*). Native to the western United States, *Neuroterus saltatorius* produce 1-1.5 mm galls with a unique ability to jump after they fall to the ground during the mid-summer season (1). They jump sporadically several times per minute for many weeks (2). The jumping action enables the gall and its larva to move into the soil and leaf litter where it overwinters, protected from temperature and humidity fluctuations and its parasitoid enemies (3). A previous study established that galls also jump to escape from potentially fatal hot summer temperatures (2).

A previous study proposed that a jumping gall larva uses momentum transfer to propel its jumps despite filling the entire gall (2). The larva forces fluid through its U-shaped body at high velocity, and the momentum of this fluid is transferred to the mass of the gall, thereby causing the hopping motion (2). To better understand the dynamics of momentum transfer, we designed a model system using a mousetrap with weights attached to the bar. With our model system, we aimed to simulate how jumping galls use momentum transfer to jump and study how to achieve a maximum jump height. Because similar studies have not been previously conducted, this research represents a novel exploration. Our hypothesis proposed that the upward swing mechanism of the mousetrap's arm, which caused the trap to jump due to momentum transfer, was the same principle underlying the fluid movement mechanism that causes the gall to jump. We also predicted that adding weight on the arm would result in higher jumps because the arm swung at the same speed but gained more momentum from the added mass. Our experimental findings revealed that as we added more weights on the arm, the jump height initially increased, reached its peak, and then decreased due to the increasing heaviness of the trap. By extending this principle to other disciplines such as space technology, we propose that momentum transfer can be used to propel instrument packages on extremely rough surfaces such as comets and asteroids.

RESULTS

Mousetrap model system

To understand and simulate how the momentum transfer of fluid in galls caused the hopping motion, we designed and built a mousetrap system. This system consisted of a mousetrap with variable numbers of tin fishing weights attached to the trap's swing bar (**Figure 1A**). We used a kitchen scale to measure the weight of the trap, and a vertical measuring stick to measure the jump height. A quarter coin was dropped to trigger the trap and caused it to jump by momentum transfer (**Figure 1B-C**). This simulation modeled the fluid motion within the larva's U-shaped body, demonstrating how momentum transfer caused it to jump.

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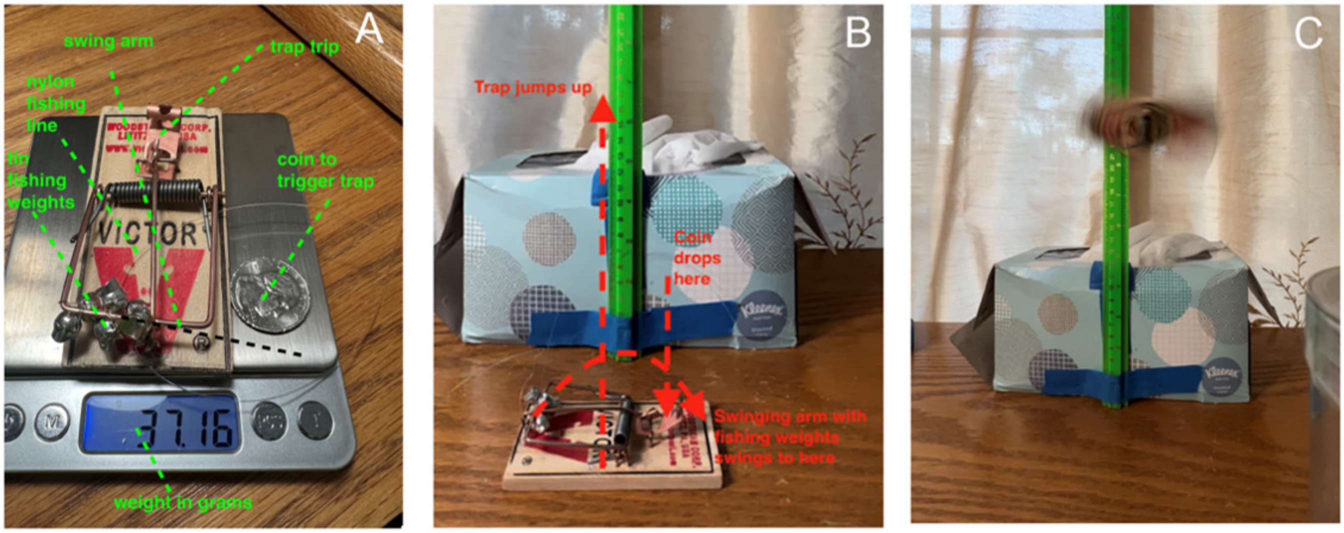

Figure 1: Mousetrap setup, jump mechanism, and midair apex measurement. A) Mousetrap setup is shown with six fishing weights. Each weight averages 1.37 grams. B) When the coin drops on the trip, the swinging arm swings to the right and the mousetrap jumps upward as a result. The height is measured with the ruler. C) The mousetrap jumps up to the midair apex in one of the experiment trials.

We predicted that adding weight to the swing arm of the trap would result in higher jumps due to increased momentum from the larger mass. To test this, we conducted trials where we varied the mass on the arm to identify conditions that produced maximum height. We collected data by recording videos of each jump. By replaying these videos in slow motion several times, we carefully noted the height of each jump using a measuring stick in the background.

Based on the data collected, the recorded average jump heights ranged from 24.72 cm with zero fishing weight or a total weight of 28.96 g to 32.30 cm with four fishing weights or a total of 34.56 g. The trend of increasing jump height with added weight was evident up to the attachment of four weights, after which the jump height started to decrease (**Figure 2**).

Several notable observations emerged from the data. First, the graph of average height by weight exhibited a peak at a total weight of 34.56 g (including the trap and four fishing weights), beyond which additional weight led to decreased jump height. Second, the data could be effectively modeled using a second-degree quadratic polynomial regression equation, confirming the observed trend. Finally, the analysis revealed a relatively high R-squared value of 0.9038. R-squared, also known as the coefficient of determination, measures the proportion of the variance in the dependent variable that is predictable from the independent variables. In our case, an R-squared value of 0.9038 meant that our model accounted for over 90% of the variability in the jump height, indicating a strong fit to the data. This left only about 10% of the variability unexplained by the model.

Calculating biophysical parameters associated with gall jumping

The model and analysis described above successfully simulated the physical principles underlying gall jumping. We then used physical principles to calculate and analyze the energy required by the gall to propel its jumping. The average gall weighed approximately 0.3 milligrams, and each hop was about a centimeter in height (2). Using the principle of conservation of energy, we specifically utilized the potential energy at the height of the jump to calculate the total energy expended in a single hop (**Equation 1**):

$$Total\ Energy = (3x10^{-7}kg)\left(9.8\frac{m}{s^2}\right)(0.01m) = 2.94x10^{-8}\ Joules \quad \text{(Eqn. 1)}$$

We then used conservation of energy to find the speed at which the fluid must be moved in order to provide enough momentum to cause the gall to jump. Since the moving fluid exerted a force on the curved internal surfaces of its U-shaped exoskeleton, this calculation would require integrating all upwards force vectors caused by fluid motion. In order to avoid this, we decided to simplify the problem by using a straightened path that yields an identical result, where the entire momentum was directed upward when the fluid rounded the sharp bend at the top of the gall.

Applying the principle of conservation of energy, the initial kinetic energy of the fluid should equal the final energy when the gall reaches the height of its jump. Based on the assumption that the fluid mass was approximately one third

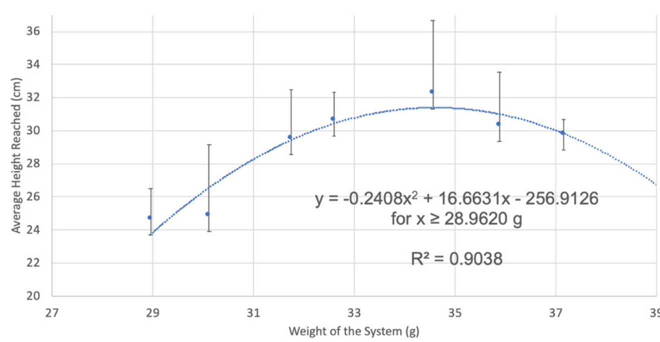

Figure 2: Average height (cm) reached by the mousetrap-weights system. The weight (g) of the system correlates with an increase in height as the weight increases until about 34.5 grams (n = 6 replicates for each weight), where the height begins to decrease. This forms the shape of a downward-opening parabola, shown by the regression equation on the graph. The type of error or variability measure used for the error bars is standard error.

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of the total gall mass and using the previously calculated potential energy during the jump, we derived **Equation 2**:

$$Total\ Energy = \frac{1}{2}\left(\left(\frac{1}{3}\right)(3x10^{-7}kg)\right)v^2 = 2.94x10^{-8}Joules \quad \text{(Eqn. 2)}$$

We then solved for the fluid velocity and determined it to be approximately 0.77 m/s. This indicated that the gall's muscles contract with sufficient force to propel the fluid at 77 cm/s in order to jump 1.0 cm in height. Upon microscopic examination of thin sections of the gall larva, a fluid-filled cavity was evident as well as surrounding muscle fibers lining the cavity.

DISCUSSION

Our original question was how to explain the hopping motion of jumping galls. Our hypothesis was that a moving mass could cause jumping due to momentum transfer. We tested this hypothesis by building the mousetrap model system, which jumped due to momentum transfer from the swinging arm and achieved a maximum jump height from added fishing weights on the arm.

We assumed that the contraction of the gall muscle fibers moved the fluid, contributing to the mechanism of gall jumping. Momentum transfer between the fluid moving inside the gall and the weights attached to the spring arm of the mousetrap exhibited similarities (**Figure 3**). Our calculations demonstrated the conditions under which momentum transfer became a viable explanation.

Additionally, our experiment demonstrated that increasing the weights on the swinging arm increased jump height until the arm was unable to swing at the same speed. Since mass, force, and momentum were universal physical principles governing both jumping galls and jumping traps, which were physical processes, we could infer that the mass of the gall has a comparable effect on jump height to the mass of the trap on its jump height. An optimal mass for galls might exist to achieve the highest jump height. Galls that were too heavy or too light might not jump highest.

Further analysis supported the assumptions made in our experiment and calculations. Our data fitted a quadratic regression model that relates the total weight of a jumping trap (x) to its jump height (y). We assumed that the minimum weight (x) was equivalent to the trap weight without fishing weights. Since no data points were collected for (x) values less than the minimum weight (the trap weight without fishing weights), we did not expect negative regression values.

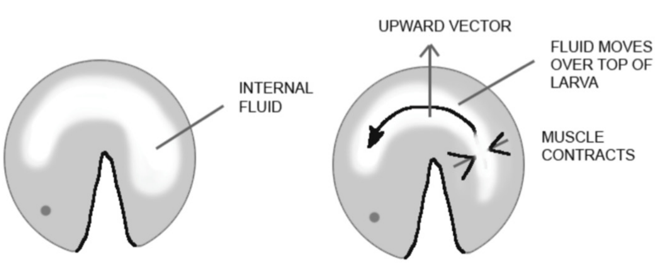

Figure 3: Diagram of the visualization of the jumping process of a gall. The U-shape of the larvae is highlighted. The left image shows a diagram of the gall and the right image shows the process of completing a jump by generating an upward vector from the fluid forced to move over the top of the gall larva by internal muscle contractions. The upward momentum is transferred to the entire gall.

Variations in total trap weight were best represented by the regression analysis. Specifically, the relationship between the total weight (x) and the jump height (y) was well-approximated by a quadratic function (**Figure 2**).

While additional analysis provided valuable details, it was beneficial to also examine a potential source of experimental errors. Potential errors might arise from visually approximating mousetrap jump height against the measuring stick in the video. To increase visual precision, we could consider obtaining a higher resolution professional camera to record the jumps in the future. A camera with a higher frame rate could record the video, enabling calculation of the time the mousetrap spends in the air based on the number of frames and frame rate. We could use the free fall equation ($d = 1/2\ g\ t^2$) to calculate the height.

In summary, our data fitted a quadratic regression model that related the total weight of a jumping trap (x) to its jump height (y). This regression model yielded a relatively high R-squared value, which reinforced our conclusion and indicated a more successful regression model. R-squared represented the percentage of data variance explained by the mousetrap model. With an R-squared value of 0.9038, our model accounted for over 90% of the variability in the dependent variable, leaving only 10% unexplained.

Moreover, our study unveiled a novel concept in gall motility. Previous research studied Mexican jumping beans, which relied on larval wiggling movement in a web attached to the interior wall of the bean rather than fluid motion inside the body of the larva (5). Our investigation into gall motility represents a unique exploration. Since gall motility has not been studied before, there is no published literature available for comparison. Our proposal that momentum transfer can propel gall motility is therefore a novel concept.

Comets and asteroids represent important targets in space exploration. However, conventional wheeled landers and rovers designed for planetary surfaces like Mars face challenges on the rough terrains and low-gravity environments of comets and asteroids. Leaf litter on forest floors presents similarly rugged conditions, yet jumping galls navigate this terrain despite their random directional motion. Could the concept of momentum transfer, inspired by the hopping motion of galls, provide a viable solution?

The principle of momentum transfer as a solution has in fact been explored by Professor Marco Pavone and his graduate student Ben Hockman at Stanford University. Nicknamed the "Hedgehog Project," they have created a cube-shaped robot as a solution to exploring smaller bodies such as asteroids and comets. This robot utilizes internal flywheels to achieve mobility in such low-gravity environments (6). While gall larvae gain upward momentum by moving a fluid over their U-shaped body, the Hedgehog transfers angular momentum from spinning flywheels, converting it to linear momentum that causes it to jump in a defined direction. This system is expected to allow the Hedgehog to navigate hostile terrains, even enabling it to perform a spin maneuver that dislodges the robot if stuck. Researchers have been able to test the Hedgehog in microgravity conditions to much success. The ultimate goal for the Hedgehog is full autonomy on a celestial body, where it will explore freely without requiring human control.

In this paper, we have demonstrated that a moving mass can induce jumping through momentum transfer, as shown

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in our experiments using a mousetrap and weights. We also predicted that the optimal mass could be identified by progressively increasing the weights. For future research, we suggest that this theory of momentum transfer could be applied in microgravity environments, such as comets and asteroids, where wheeled vehicles are unable to move packages over extremely rough surfaces.

MATERIALS AND METHODS

We selected the Victor wooden mousetrap and used Bullet Weights Ultra Tin Split Shot Skillet, size 4, for the fishing weights. The weights were attached using nylon fishing line (Fishing Wire 8.0#). We opted for a single metal pedal wood mousetrap for its convenience in attaching the tin fishing weights to the swinging bar.

Prior to conducting the experiment, we used a kitchen scale to measure the mass of the mousetrap for each trial, ranging from zero to six fishing weights. During the experiment, a quarter coin was used to trigger the mousetrap in each trial, and we monitored the jump height using a measuring stick positioned behind the trap. We used an iPhone 13 to record each jump and subsequently replayed and magnified the videos in slow motion to accurately determine the height, measured from the lowest point of the mousetrap in each trial. Six trials were conducted for each number of weights, and the outcomes were averaged to improve accuracy. The recordings were reviewed multiple times, with specific sections magnified, to ensure accurate measurement of the achieved height in each trial.

During our experiment, videos were captured for each jump and later replayed and magnified in slow motion to precisely determine the height, consistently using the bottom of the mousetrap as the reference point for measurement in each trial. Six trials were conducted for each number of weights, and the results were averaged to minimize experimental error. The video footage was replayed multiple times with different sections magnified to ensure precise measurement of the height achieved in each trial.

Identifying potential experimental errors not only prompted us to verify our procedures but also highlighted the necessity of making adjustments in our experiment to improve accuracy and reliability. Several adjustments were made during the experiment. Initially, we purchased seven identical mouse traps, each designated for a specific number of weights. However, after considering potential errors related to construction variations, such as slight differences in weight and spring tension, we transitioned to using a single trap consistently throughout our experiment.

Furthermore, we addressed specific issues encountered during the experiment. Initially, fishing weights were directly clamped to the metal bar, but they often flew off during the jump. Introducing fishing line allowed the weights to securely attach, preventing them from being lost midair. Additionally, to trigger the mousetrap, we used a fishing weight at first and later small coins, but they yielded inconsistent results. A larger coin was substituted for a more reliable trigger mechanism.

To understand our assumption of using a straightened path in calculating the fluid velocity, imagine a tube in the shape of a half circle (**Figure 4**). A ball bearing could be blown through the tube by a puff of air, and its momentum would produce an upward force vector. However, complications arose due to the bearing's circular motion around a curved trajectory, which produced a force on the sides of the tube. To simplify this calculation, we straightened the circular tube and assumed one sharp 180 degree turn in the middle. By doing so, when the bearing moved through the tube and rounded the sharp bend at the top, its entire momentum was directed upward.

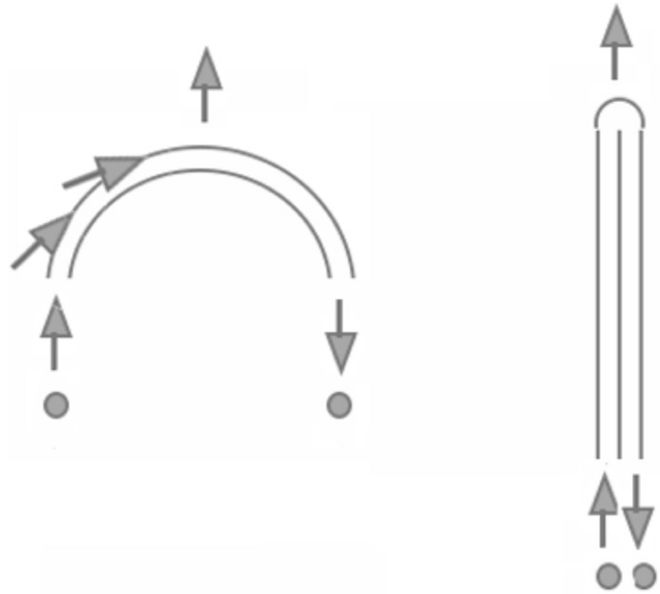

Figure 4: Calculation of speed illustration. We use this thought experiment to simplify our calculation of the speed at which the fluid must be moved in order to provide enough momentum to cause the gall to jump.

Another assumption involved estimating the fluid mass within the gall. The measured average mass of a gall is 0.316 mg and a typical jump was estimated to be 1 cm in height (2). If the gall container was approximately 0.1 mg or a third of total weight, that leaves 0.2 mg for the larva. Typically, the water content of an insect is 45%-90% (4). If water comprised 50% of the larva, it would be approximately 0.1 mg or one third of the total weight. This estimation was based on logical reasoning since no prior research has explored this area.

Equation 3 assumes work by external forces/energy lost is minimal,

$$\Delta E \approx 0 \quad \text{(Eqn. 3)}$$

Equation 4 calculates energy of the gall at the height of the jump,

$$E_f = U_g = m_1 g h \quad \text{(Eqn. 4)}$$

Equation 5 calculates the initial kinetic energy of the fluid in the gall,

$$E_i = \frac{1}{2} m_2 v^2 \quad \text{(Eqn. 5)}$$

Equation 6 equates the initial kinetic energy of the fluid to the final potential energy when the gall is at the height of its hop by conservation of energy,

$$\frac{1}{2} m_2 v^2 = m_1 g h \quad \text{(Eqn. 6)}$$

Where the above symbols represent mass of the gall (m_1),

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mass of the fluid (m_2), gravitational acceleration constant (g, 9.8 m/s^2), and initial velocity of the fluid (v).

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