

Launching engineered prototypes to better understand the factors that influence click beetle jump capacity*

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Abstract—In nature, click-beetles use a unique hinge structure between their prothorax and mesothorax that acts as a latch-mediated spring actuation system to produce a high acceleration that can result in a jump. This mechanism enables them to jump a height of several times their body length without using their legs when the beetle is unconstrained. To study the beetle jump trajectory, we designed simplified beetle-inspired prototypes and a launching platform. The simplified prototypes are fundamentally two masses connected by a spring. The masses simulate the portion of a click beetle's body located anteriorly (M1) and posteriorly (M2) to the clicking mechanism, and the spring simulates the elastic energy storage element. The launcher uses a quick-reaction release mechanism and magnetic actuator to simulate the unlatching process. In trajectory analysis, the parameters that are most important are initial velocity at take-off and the take-off angle since both the click beetles and the prototypes are governed by ballistic motion. We determined that morphological features such as elytra (body) curvature and the ratio of the two body masses affect these two dynamic parameters. Our findings provide further insight into the design and fabrication of legless jumping robotic mechanisms and apply engineering models and experimental tools to answer key biological questions.

I. INTRODUCTION

In click beetles (Coleoptera: Elateridae) (Figure 1) there exists a flexible joint between their prothorax and mesothorax that allows them to perform an extremely fast bending maneuver (i.e. the clicking motion) resulting, when unconstrained, in high acceleration jumps [1] [2] [3] [4] [5]. This joint or hinge, and its associated structures, act as both latch and spring mechanisms.

The hinge is composed of two conformal parts: the peg and the mesosternal lip (Figure 1), which together form a mechanical latch. When the latch is engaged potential energy is stored in a distributed spring which encompasses part of the beetle's cuticle and musculature. When the beetle is on its back the recoil of these spring components results in the clicking motion and jump. The latch geometry and

mechanism, as well as the jump kinematics of various click beetle species have been studied [6] [7]. Before the jump, the head and prothorax (M1) rotate backward, arching the body until it reaches a brace position with the peg latched on the mesosternal lip. At take-off, the latch is released and the center of mass moves upward owing to the flexion of the hinges. When the body has completely left the ground, in the airborne phase, it is mainly governed by the physics of ballistic motion. However, how morphologies such as the shape of the elytra (front wings), the body parts that come in contact with the ground, and spring stiffness affect a beetle's jump is difficult to study because such parameters cannot be altered on actual live click beetles. Engineered prototypes can be designed and modified to mimic a click beetle's jump and explore a larger parameter space.

The overall goal of this paper is to study the morphological parameters that affect the click beetle's jump kinematics, such as the take-off velocity and angle. More specifically, this article presents the design of biologically relevant click beetle prototypes, a special launching platform that would be able to launch the prototypes without adding constraints, and a preliminary analysis of how the prototypes and launcher can be used to study the effects of prototype (beetle) curvature and ratio of body masses on the jump parameters.

II. METHODS

A. Click Beetle Prototypes

A simplified analytical model was used for the computer-aided design (CAD) (SolidWorks, Dassault Systèmes) of the click beetle prototypes (Figure 2). A prototype consists of two masses: M1 (representing the head and prothorax) and M2 (representing the meso-, meta-thorax, and abdomen). Both masses were printed using a Creality Ender 3 V2 3D printer outfitted with a 1.75 mm polylactic acid filament (ComGrow). The latching mechanism has not yet been incorporated into the prototypes (see launcher section below). All prototypes used for the experiments described here have a total length of 6.5 cm and a weight of 6.68 ± 0.06 g. Using CAD files we are able to alter elytra (front wing) curvatures and mass ratios between M1 and M2 (Figure 2A). We used these prototypes to test how these morphological features affected the dynamic parameters involved in the jump.

To mimic the distributed spring mechanism used by click beetles, the two masses were connected to each other by a rectangular strip of 1095 wear-resistant spring steel (McMaster-Carr). For the variable elytra curvature experiments, 10 mm wide 0.203 mm thick spring steel was used,

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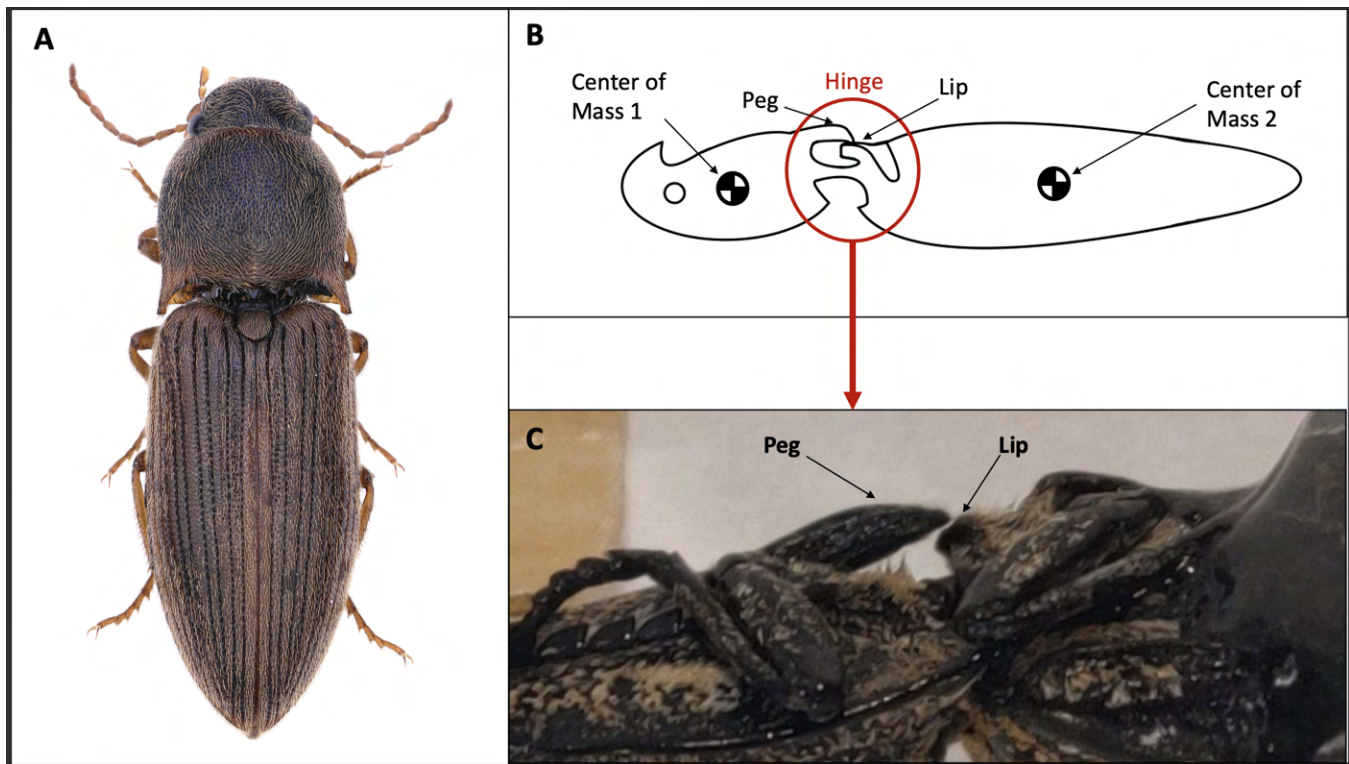


Fig. 1. (A) Dorsal view of *Agriotus mancus* click beetle (photo credit: Julien Saguez). The hinge occurs at the intersection of the prothorax and mesothorax. The prothorax and elytra (in this species appearing striped) make contact with the ground when the beetle is lying on its back. (B) The body of a click beetle can be divided into two subunits (M1 and M2) linked by a hinge which is comprised of a peg and a mesosternal lip. (C) The peg latches mechanically to the lip during the pre-jump stage and slides into a cavity when the latch is released. These schematics are adapted from [5].

and for the variable mass ratio experiments, 8 mm wide 0.203 mm thick spring steel was incorporated into the prototypes.

The radii of the elytra curvature used were 13mm, 19mm, 25mm, and 31mm. A larger radius meant flatter elytra. The M1/M2 mass ratios used were 0.26, 0.46, 0.55, and 0.70. A larger mass ratio value means that M1 is relatively heavier than M2.

B. Launcher Design

To simplify our experiments, we did not include latch or muscle elements in our prototypes described in Section II-A. Instead, we incorporated an external latch and actuator in the form of a launcher. To perform the desired task, the launcher must be able to first load the prototype by storing potential energy in the hinge, and then, with limited energy loss due to friction, convert the potential energy into kinetic energy almost instantaneously. Additionally, it is required that the launcher perform this launching sequence repeatedly and accommodate beetle prototypes of various shapes and scales.

The design requirements of the launcher are summarized as follows:

- Restrain prototypes of various shapes and scales in the braced/loaded position.
- Remove the restraint with enough speed such that the restraint's influence on the initial acceleration of the prototype is limited.

- Repeat the restraint and release process over many cycles for differing beetle prototypes

The final launcher design (Figure 3) satisfies these requirements and is described below. To restrain the prototype, the launcher uses two lever arms that press on the anterior and posterior tips of the prototype (Figure 2B). The lower part of the lever arms are loaded by compression springs which are held in place by their respective latches in the form of hooks. The latches are secured by electromagnets that balance the force from the loaded extension springs (Figure 3A).

To understand the release process, let us examine the right side of the launcher (Figure 3B). Once the electromagnet is switched off, the right latch rapidly rotates counterclockwise due to the now unbalanced force relationship between the extension spring and electromagnet. The compression spring extends rapidly, causing the right lever arm to rotate in the clockwise direction thus quickly avoiding the airborne click-beetle prototype. Additionally, the latch system is balanced such that the force exerted on the tip of the latch is aligned with the force from the hinge, which allows for maximized release speed.

The final launcher design also enabled repeatable jumps since the lever arms are consistently pressed down to the same height as the prototype was restrained. All other components of the launcher, including the latches, were fixed in the same configuration for all of the trials. The final design utilized cast acrylic, 3D-printed PLA, and metal springs,

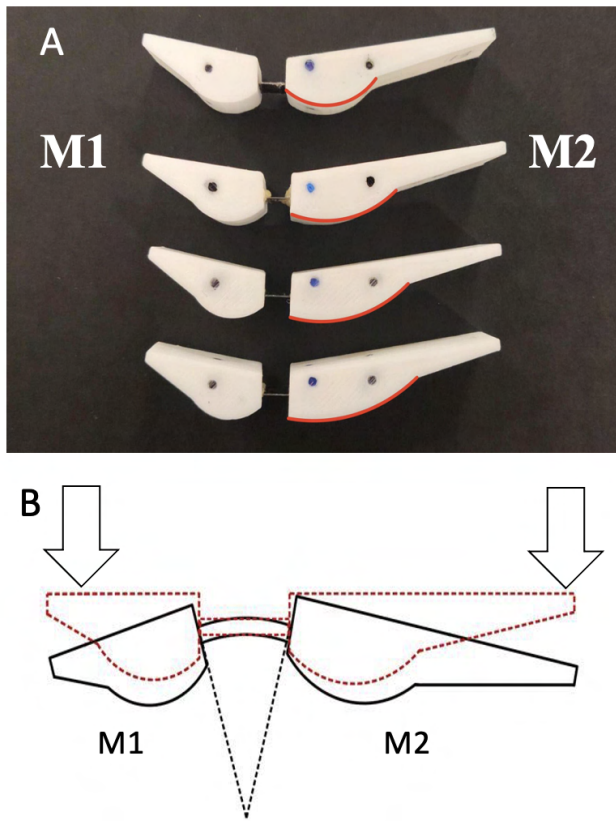


Fig. 2. (A) 3D printed prototypes mimicking click beetles. M1 represents the head and prothorax segments of a click beetle, and M2 represents the meso-, meta-thorax, and abdomen. The two masses are connected to each other with 1095 wear-resistant spring steel. The 4 prototypes shown in A were printed with varying elytra curvatures (in red). (B) By applying an external force to the two masses, deformation of the spring occurs and elastic energy is stored in the spring steel. This energy will be converted to kinetic energy when the masses are released (i.e., the spring recoils), resulting in the prototype jumping vertically with high acceleration.

shafts, flange bearings, nuts, and bolts. These materials did not fatigue significantly throughout our trials and did not introduce vibration which could have altered the energy released as the prototype was launched.

C. Trajectory Analysis

To capture the prototype trajectory after launch we used a Photron Fastcam SA-Z and PFV4 software (Visualization Lab, Beckman Institute, University of Illinois at Urbana-Champaign). We recorded 10 jumps for each parameter at 500 frames per second (fps). Analysis of the videos was done using Tracker, an open-source video analysis and modeling tool. Each prototype was marked at the center-of-mass (COM) of M1, M2, and the whole prototype by a colored dot. The markings were located on each frame by Tracker automatically, or manually by the researchers. By providing distance calibrations the Tracker software was able to determine the x and y locations of the COMs, thus providing the maximum height achieved by the prototype and the velocity at each point of the trajectory through the air (including initial/maximum velocity). The take-off angle

was calculated manually by fitting a linear function to the positions of the whole prototype's COM from two selected frames. One was taken to be the frame where the two lever arms first lose contact with the prototype while the other was 3-5 frames later. The slope of this linear function provided the take-off angle of the prototype.

The jump trajectory parameters (i.e, take-off angle and velocity) captured from Tracker were then used as input to a mathematical model used to simulate the prototypes' trajectories (Figure 4). We then compared the simulated jumps to each other and to published live beetle trajectories [3] [5]. The model is an ordinary differential equation with initial conditions calculated from the recorded takeoff trajectories. The variable is the special location of the overall center of mass. The following assumptions were made while developing the model:

- The prototype and click beetle perform as a rigid body after take-off.
- Air friction is negligible. The model only experiences gravity force after takeoff.
- The airborne phase is ballistic around the center of mass at a constant angular velocity.

We implemented the model by using the Forward Euler method with equal time intervals of 0.004s. The initial velocity is 2 m/s and the takeoff angle is 76.5 degrees. Other model parameters such as mass and length are measured from real prototypes. The model's center of mass follows a free-fall trajectory. With the assumption that the airborne phase is ballistic around the prototype's COM, the special location of the COM of M1 and M2 can be calculated.

III. RESULTS

The model generated predicted trajectories with different initial conditions such as initial velocity and take-off angle. The predicted trajectories compared to the live beetle jumps recorded previously [5] and are within 5% relative error. Comparing the predicted trajectories with the prototype jumps showed that the trajectories are very similar. The model predicted maximum height and horizontal distance between take-off and landing location with less than 5.5% relative error. (Figure 4). The prototype trajectories showed that angular velocity is constant, as was assumed for the simulation. These results validated the launcher design. Additionally, the prototypes are biologically relevant and can be used to study the effect of elytra curvature and ratio of body masses on the dynamic parameters.

The take-off angle of the prototype did not vary significantly with elytra curvature (Figure 5A). However, the take-off angle did vary depending on the mass ratio of the two masses of the prototype, with the more extreme ratios tested (0.26 and 0.70) resulting in smaller take-off angles than the intermediate ratios (0.46 and 0.55) (Figure 5B).

Initial velocity at take-off increased as the elytra curvature radius increased, especially at the higher curvature values. The initial take-off velocity decreased as the M1/M2 mass ratio decreased (as the mass of the posterior end increased relative to the anterior end of the prototypes).

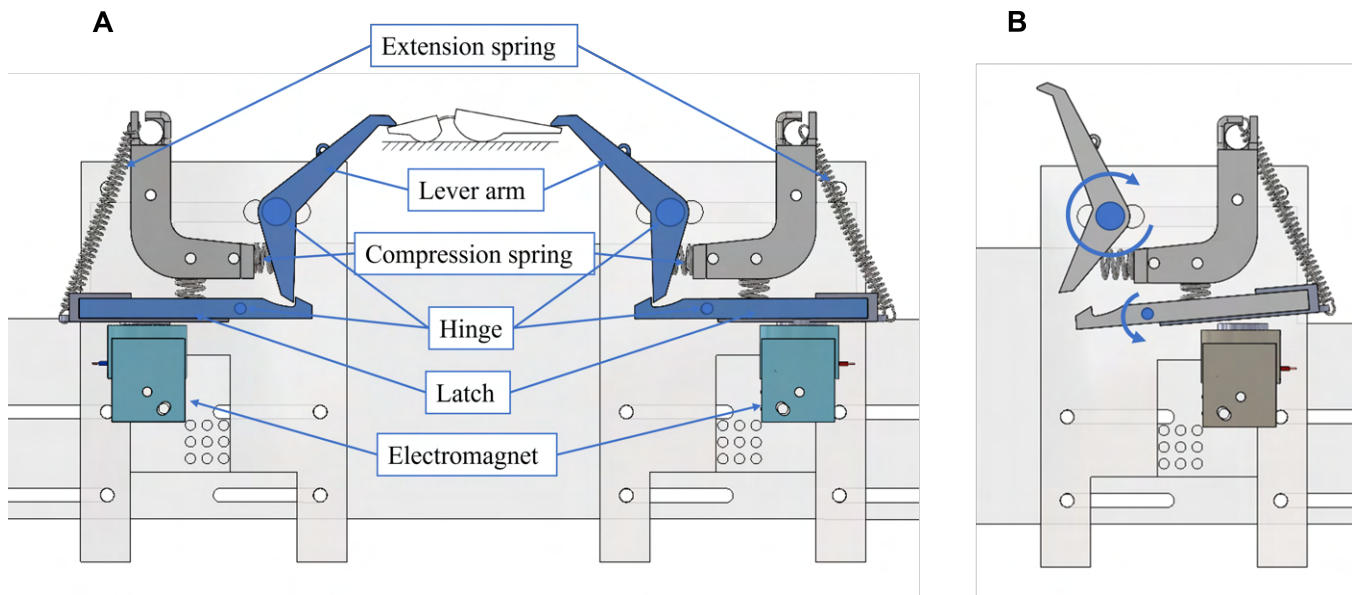


Fig. 3. Launcher design. (A) Position of the lever arms when the prototype is loaded. (B) Position of the level arms once the prototype is released. Further details explained in the text. (Launcher and prototype not to scale.)

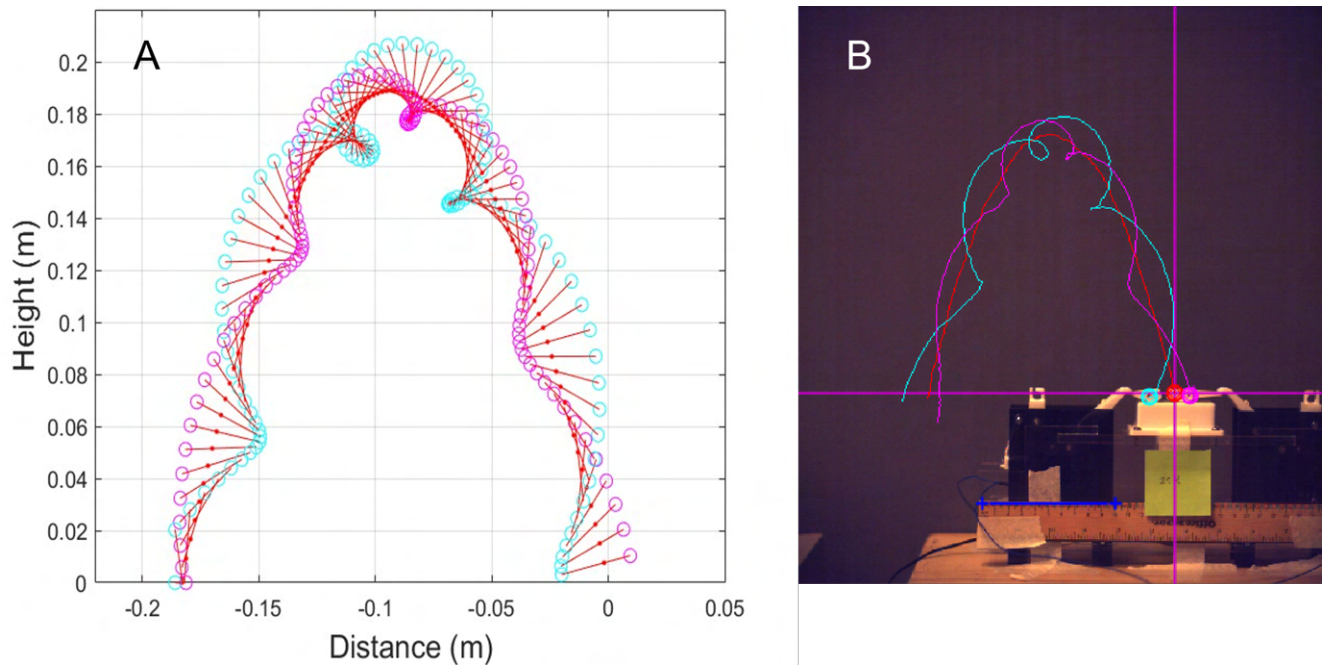


Fig. 4. (A) Predicted trajectory for a take-off velocity of 2 m/s and a take-off angle of -76.5° . (B) Trajectory of the prototype. Teal = M1 COM, Pink = M2 COM, Red = whole prototype COM.

IV. DISCUSSION

Since click-beetle prototype jump trajectories were similar to those of live click beetles, we successfully created prototypes that are biologically relevant representations. However, the simplification of these prototypes as being two masses connected by a spring meant that a latch system outside of

the model was required. Designing a launcher that included the latch system to repeatedly launch prototypes proved to be a greater challenge than expected. The launcher needed to be able to exert force onto the prototype to load the spring, it then had to be able to release this force almost instantaneously and simultaneously (since two lever arms

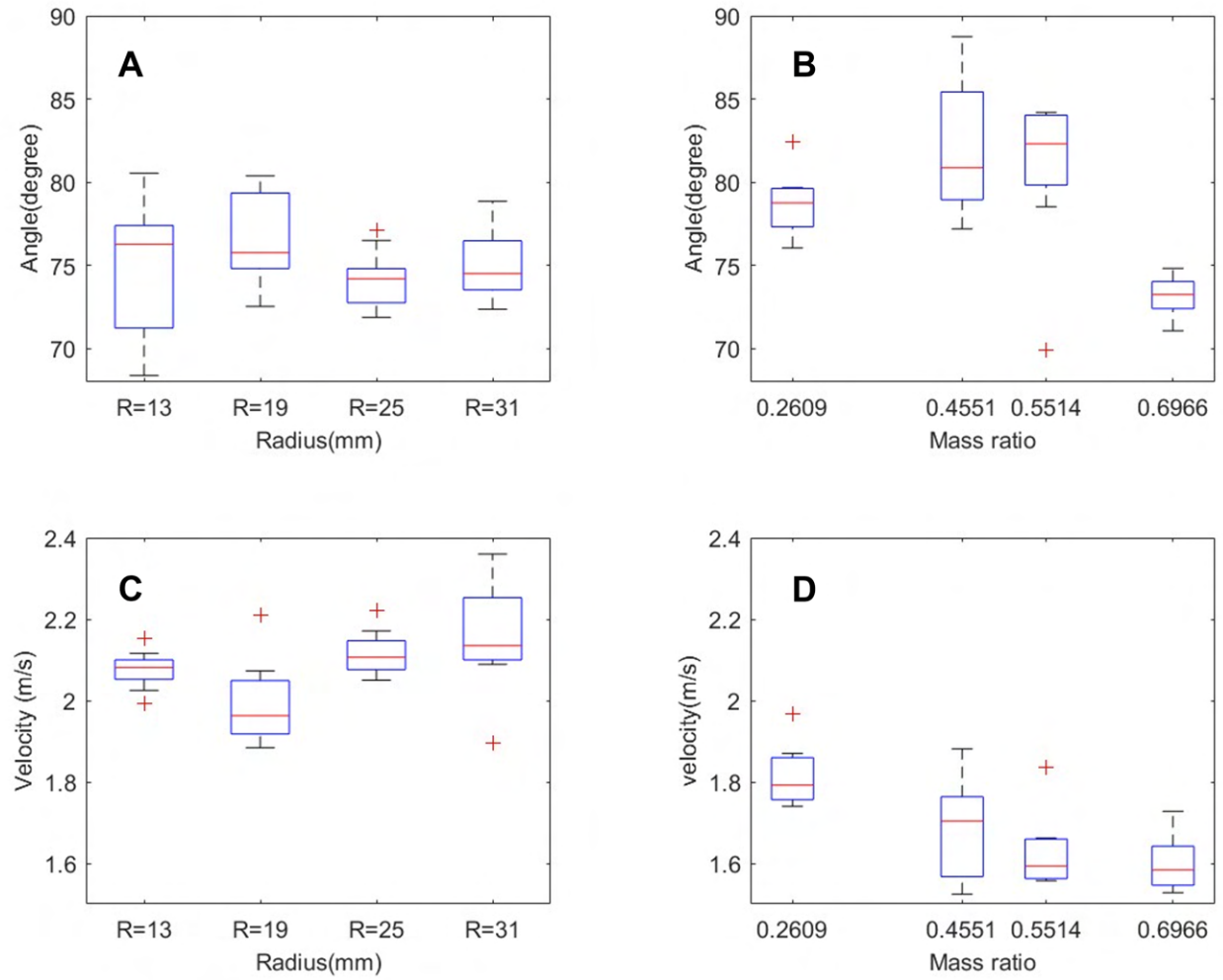


Fig. 5. (A) Take-off angle of prototypes with varying elytra curvatures. (B) Take-off angle of prototypes with varying M1/M2 mass ratios. (C) The initial velocity of prototypes with varying elytra curvatures. (D) Initial velocity of prototypes with varying M1/M2 mass ratios. Each set of data represents 10 jumps.

were involved in the final design), and the prototype should not experience excessive frictional forces as it escaped the lever arms. These requirements were all addressed in the final design of the launcher (see Section II).

However, the launching platform introduces novel constraints not observed in click beetles, such as bending angles of the anterior and posterior portions of the prototype relative to each other. By the nature of our final design, the bending constraint is the height of the lever arm instead of an applied force. Prototypes were pressed into the same height regardless of the geometric configuration. Even though the launcher incorporates an extension spring to help increase the reaction speed, there still exists a short time delay between the discharging of the electromagnet and the release of two lever arms, and the release might not be perfectly

synchronous between the two arms. This may introduce some interference of the lever arms to the initial take-off of the prototype.

A previous study showed that in live click beetles there exists a logarithmic relationship between the take-off angle and the radius of the elytra curvature [3]. As the curvature radius increased, the take-off angle increased. We did not find such a clear relationship in our data. Over the elytra radii range we tested (13 -31mm), the take-off angles Kaschek observed (81-84°) were higher than those we observed (75-79°). It may be that the launcher constraints discussed above influenced the take-off angles somewhat. It is commonly observed that click beetles that end up on their dorsal side, jump at an almost vertical take-off angle (90°). Our prototypes were launched at shallower take-off angles since

their take-off was influenced somewhat by the delay in the two lever arms releasing.

In live beetles, the animal is often rolling during the pre-jump stage [5] [6]. This means that the contact point changes along with the contact curvature and often the head and prothorax (M1) are not making contact with the substrate. Using our prototype and launcher mechanism we cannot vary the contact curvature since the prototype is constrained between the lever arms and cannot roll. In addition, both M1 and M2 always make contact with the substrate since the lever arms always bring the prototype to the same prone position. This limitation may also affect the dynamic parameters we measured.

The simple prototype (two masses connected by a spring) used in this study allowed us to expand the parameter space of click beetle jump trajectories to include biologically-relevant qualities representative of the click beetle. Additionally, it let us explore a larger parameter space beyond biology, i.e. varying the mass ratio and elytra radius of curvature. Using our designed launcher we were able to perform repeatable jump trials that closely compared to live beetle jump trajectories on varying parameter prototypes without incorporating an internal latch. However, the absence of an internal latch not only limits the biological-relevance of our prototype but also our understanding of how the click beetle performs this unique clicking maneuver repeatedly, using a latch-mediated spring actuated mechanism, with little to no damage to their body.

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