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Co-Design of Morphology and Oscillation in Bio-Inspired Tails for Enhanced Robotic Locomotion on Deformable Granular Substrates

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Abstract: Locomotion on deformable granular substrates like sand and mud remains a significant challenge for terrestrial robots, primarily due to complex terradynamic interactions leading to sinkage and slippage. Drawing inspiration from the mudskipper (Periophthalmus barbarus), an amphibious fish that modulates its tail morphology and kinematics to traverse such terrains, this study investigates the synergistic role of tail design and control in a flipper-driven robot. Through systematic robophysical experiments, we evaluated the performance of a mudskipper-inspired robot equipped with interchangeable tails of varying support areas (2 cm² to 24 cm²) under both idle and actively oscillating (5 Hz, 60° amplitude) conditions. Our results demonstrate that tail oscillation significantly enhances locomotion performance, but only when coupled with an appropriate morphological design. Specifically, for tails with a support area ≥ 8 cm², active oscillation increased forward speed by up to 20% and reduced body drag by 46% by locally fluidizing the substrate and reducing shear resistance. Conversely, oscillation with smaller tails increased sinkage and was detrimental to performance. A mechanistic model, validated by penetration and shear force measurements, reveals that the benefits of oscillation-induced fluidization are contingent upon the tail's ability to limit sinkage. This establishes a critical co-design principle: effective mobility on flowable ground requires the simultaneous optimization of tail morphology (large support area) and motion (oscillation). These findings provide a framework for the design of next-generation robots capable of traversing complex natural terrains for applications in planetary exploration, search and rescue, and agricultural robotics.

Keywords: *bio-inspired robotics, granular media, terradynamics, robot locomotion, tail morphology, substrate fluidization, mudskipper, co-design*

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1. Introduction

In recent years, significant progress has been made in the field of legged robotics, allowing robots to navigate both urban settings and rough outdoor landscapes (Lee et al., 2024; Cheng et al., 2024; Yang et al., 2022). Despite these advancements, robots still face major difficulties when traversing soft, deformable surfaces like sand, silt, and mud (Li et al., 2009; Qian et al., 2013; Godon et al., 2022). Such granular materials move around robot limbs during movement, resulting in two main problems: sinkage, where the limbs dig deeply into the ground, causing increased drag and sometimes immobilizing the robot; and **slippage**, where the limbs are unable to generate enough thrust due to the ground's loose nature (Qian et al., 2015; Choi et al., 2023). Addressing these issues is essential for enabling robots to perform in crucial

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scenarios, such as rescue operations in collapsed buildings (Lindqvist et al., 2022), monitoring crops in soft soil (Liu et al., 2023), and exploring extraterrestrial terrains that are typically covered in fine, granular regolith (Arm et al., 2023; Liu et al., 2024a).

One effective way to tackle these complex problems in robot movement is by looking to nature for inspiration. Over time, animals have developed specialized body shapes and behaviors that help them move efficiently across difficult surfaces. For example, sandfish lizards use wave-like body motions to swim through sand with little resistance (Maladen et al., 2009; Sharpe et al., 2013), while sidewinder snakes use a distinctive movement to climb sandy hills without slipping much (Marvi et al., 2014; Astley et al., 2015). Sea turtles, on the other hand, rely on flexible flippers to push themselves forward by firming up the sand in front of them (Mazouchova et al., 2013). These natural strategies have inspired roboticists to design and control robots in similar ways, resulting in better mobility for machines on loose, shifting ground (Maladen et al., 2011; Kolvenbach et al., 2022).

Of all the body parts animals use for movement, the tail stands out as a flexible and relatively under-investigated tool for getting around on soft terrain. In nature, tails help with many tasks, such as stabilizing the body during jumps or flight (Libby et al., 2012; Jusufi et al., 2008), helping animals move over uneven ground by flexing or tapping (Soto et al., 2022; Buckley et al., 2023), and providing momentum for climbing (McInroe et al., 2016). Yet, how tails might help reduce problems like sinking and drag on completely soft ground remains less well understood.

Mudskippers serve as an excellent example for studying how tails can help with movement. These amphibious fish move themselves across land by using their front fins, while their tail stays very active. Importantly, mudskippers can change the shape of their tail, making it either thin or wide and flat, and they also switch between quickly moving their tail and keeping it still, based on the type of ground they encounter (Naylor & Kawano, 2022). This behavior points to a complex and adaptive approach in which the design and movement of the tail are closely coordinated to reduce sinking and increase forward movement.

Taking inspiration from the mudskipper, this research uses a robophysics method (Aguilar & Goldman, 2016) to thoroughly examine the idea that both the shape of the tail and its oscillating motion need to be designed together to improve movement on loose, granular surfaces. We created a robot modeled after the mudskipper with tails that could be swapped out, then ran tests to see how it moved over granular ground. The main goals of our study were to:

1. Measure both the separate and combined impacts of tail surface area and tail movement on how fast the robot can travel.
2. Assess how tail motion changes the forces from the ground, including penetration resistance and the sideways drag the robot experiences.
3. Create a simple physical model to explain how tail shape and movement work together.
4. Establish a general rule to help choose the best tail movement strategy depending on ground firmness and tail design.

Our results confirm that moving the tail back and forth can lead to major improvements in performance, but only if the tail's shape offers enough support to prevent extra sinking caused by the loosened ground. This research lays out a key principle for designing robot parts that work on soft surfaces, with important consequences for developing bio-inspired robots.

2. Materials and Methods

2.1 Robotic Platform Design and Kinematics

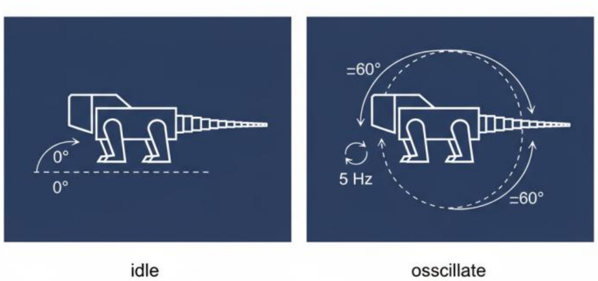
To focus on and analyze how the tail interacts with the ground, we developed a specialized robot inspired by the way mudskippers move (Kawano & Blob, 2013). The robot features a central body containing all electronics, along with two motorized front flippers that mimic the mudskipper's supportive pectoral fins.

The two flippers were 3D-printed from Polylactic Acid (PLA), each with a rectangular profile of 60 mm (length) × 40 mm (width). They were attached to the front of the robot body and actuated synchronously in the sagittal plane by two Dynamixel XL-330 servo motors at a constant angular velocity of ω = 60 RPM for all experiments. This provided a consistent forward thrust mechanism, allowing the effects of the tail to be studied independently.

One important aspect of the robot is its modular tail system. A third Dynamixel XL-330 servo motor was installed at the back of the robot to control the tail movement. This arrangement allowed us to test two different ways of operating the tail (see Figure 2B):

- **Tail-idle mode:** The tail stays fixed in place at a neutral angle (α = 0°), aligned with the length of the robot.
- **Tail-oscillate mode:** The tail is driven to oscillate horizontally (yaw motion) with a fixed amplitude of α = 60° and a frequency of *f* = 5 Hz.

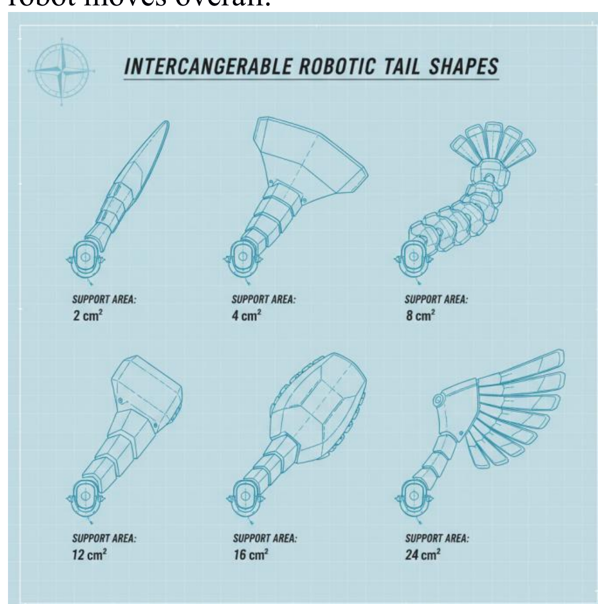
Figure 2B



All motors were controlled by an Arduino Uno microcontroller, which was mounted on the robot.

2.2 Tail Morphology Variations

Taking inspiration from the mudskipper's ability to change its tail shape, we created six different tails that could be swapped in and out, each with a different horizontal support area (see Figure 2C). The support area refers to the surface projected perpendicular to the direction the tail pushes into the ground, and it mainly determines how much resistance the tail encounters when moving through granular material (Li et al., 2013). All tails were kept at the same height (40 mm), but the support area was adjusted from as small as 2 cm² (making the tail narrow and vertical) to as large as 24 cm² (making it wide and flat). This setup let us systematically study how the size of the support surface affects the way the tail interacts with the ground and how well the robot moves overall.



2.3 Granular Substrate and Experimental Trackway

All the experiments took place in a large test track (115 cm by 54 cm by 12 cm) filled with 10 cm of artificial granular material. The track was filled with 6 mm round plastic beads (Matrix Tactical Systems), chosen because they behave similarly to real sand and soil (Maladen et al., 2009; Li et al., 2013). Their uniform shape and size also ensured that we could consistently prepare and test the substrate. Before each experiment, we raked and leveled the bed to achieve an even surface and consistent packing density.

2.4 Locomotion Performance Experiments

We performed three trials for each tail configuration. The robot started at one end of the track, using its flippers to move forward. For every combination of tail shape (*A* = 2, 4, 8, 12, 16, 24 cm²) and tail movement (idle or oscillating), we repeated the test three times.

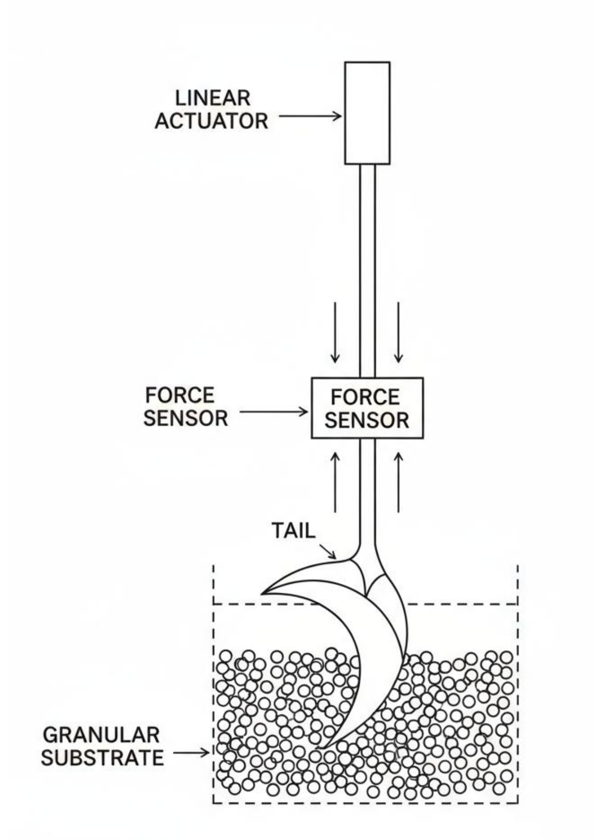
The robot's movement was tracked with an Optitrack Prime 13W motion capture system. Two cameras mounted above the track recorded its position in three dimensions (forward, sideways, and vertical) at a rate of 120 times per second. The main measure of how well the robot moved was its average forward speed, calculated over the middle part of the track to avoid the effects of starting and stopping. A camera placed to the side also captured the robot's tilt and how deeply the tail and body pushed into the granular material, giving both qualitative and quantitative information about how the robot and ground interacted.

2.5 Substrate Force Measurement Experiments

To separately and directly measure how the tail affects forces during movement, we set up two extra experiments:

A. Penetration Resistance Force Measurement:

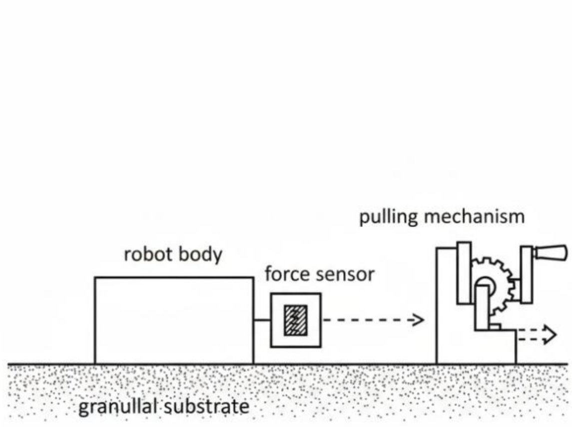
We created a test to measure how much vertical force (f_z) was needed to push each tail shape into the ground at different depths (see Figure 7A). The tail was mounted on a linear actuator and lowered straight down into the granular material at a steady speed. An in-line force sensor (DYMH-103) measured the resistance from the ground. The data collected was used to find the penetration resistance coefficient (k_z) for each tail, showing how resistance changes with depth and surface area.



B. Shear Resistance (Body Drag) Force Measurement:

To measure just the sideways drag on the robot's body (shear force), we placed the body (without flippers) on a horizontal stage and pulled it through the granular material at a steady speed of 2 cm/s and a set depth of 1 cm (see Figure 5A). A force sensor recorded the amount of shear resistance (f_x). This experiment used the tail (A = 16 cm²) attached in a way that avoided force transfer to the sensor. We ran the test with the tail both stationary and moving to directly measure how tail oscillation reduced drag.

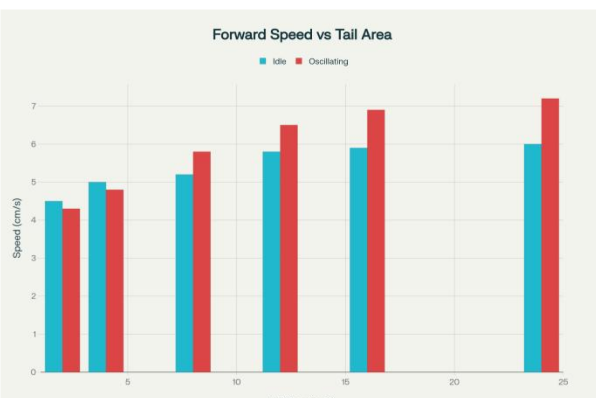
Figure 5A: Line schematic of horizontal sheair resistance test setup



3. Results

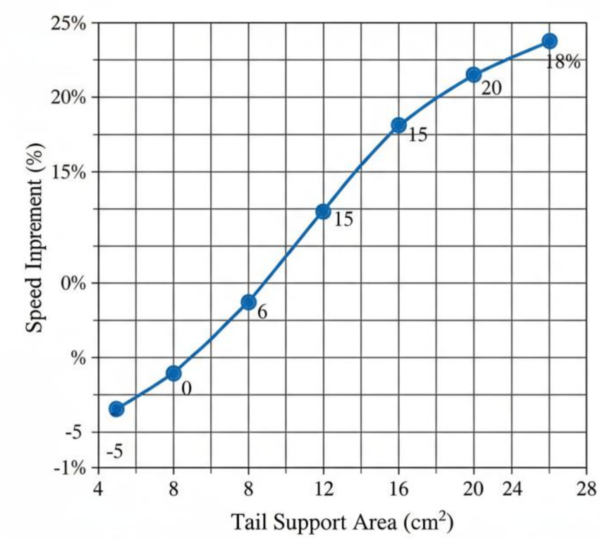
3.1 Tail Oscillation and Morphology Jointly Determine Locomotion Speed

Locomotion tests showed that how the tail moves and its shape both play important roles. For example, with a tail size of 16 cm², actively swinging the tail made a notable difference. The robot's average forward speed rose from 5.9 ± 0.18 cm/s with a stationary tail to 6.9 ± 0.23 cm/s when the tail was oscillating—a 17% improvement (see Figure 3).



But this improvement wasn't seen with every tail design. The increase in speed depended heavily on how big the tail's surface was (see Figure 4). Tails with a support area of 8 cm² or larger saw speed gains of 6% to 20%, with the best results for tail sizes between 12 and 16 cm². In contrast, smaller tails (less than 8 cm²) saw much less benefit, and the smallest tail (2 cm²) actually made performance worse when it was oscillating. This shows that the physical design of the tail determines if swinging it will help or hurt movement—oscillation alone isn't always the answer.

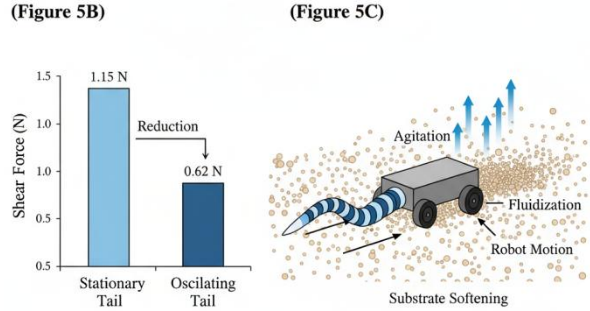
Figure 4: Speed Improvement vs. Tail
Tail Support Area



3.2 Oscillation-Induced Fluidization Reduces Shear Resistance

Tests measuring shear force clarified the reasons behind the speed improvement. When the robot was dragged through loose ground, an oscillating tail consistently reduced the sideways drag acting on the robot. On average, the resistance decreased from 1.15 N with the tail stationary to 0.62 N when the tail was moving back and forth—representing a 46% reduction in body drag (see Figure 5B, C).

(Figure 5B) (Figure 5C)

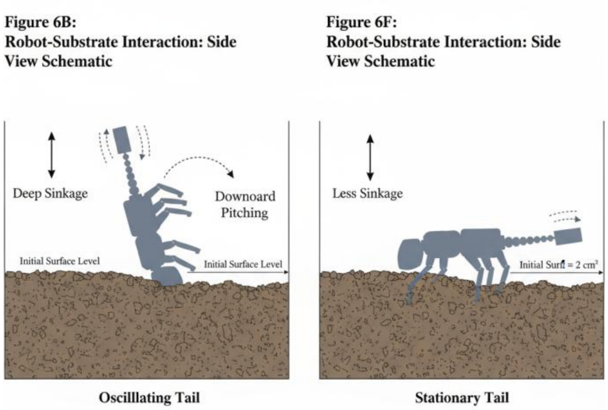


Figures 5B and 5C: Shear force reduction with tail osclation and substrate fluidization

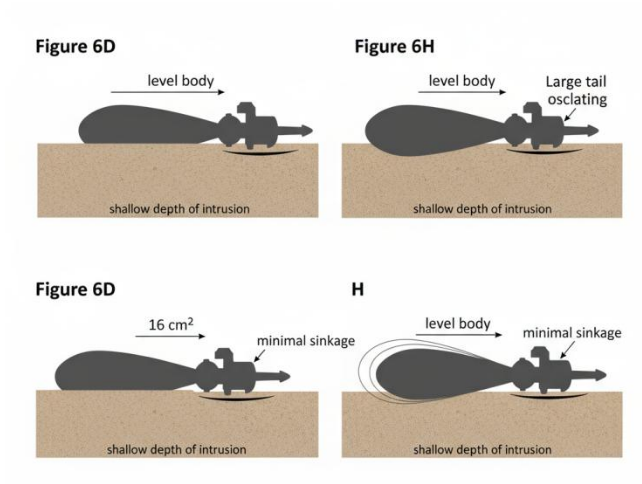
This outcome is consistent with the phenomenon of granular fluidization, in which vibrations or shaking make loose material easier to move through by decreasing its internal strength (Xie et al., 2022; Jiang et al., 2022). By swinging, the tail acts like a mini agitator, disrupting the frictional bonds between the particles behind the robot and creating a local area where the ground becomes softer. As a result, the robot can move with less drag, much like how certain lizards swing their heads to lower resistance while swimming through sand (Sharpe et al., 2015).

3.3 The Role of Morphology in Mitigating Sinkage

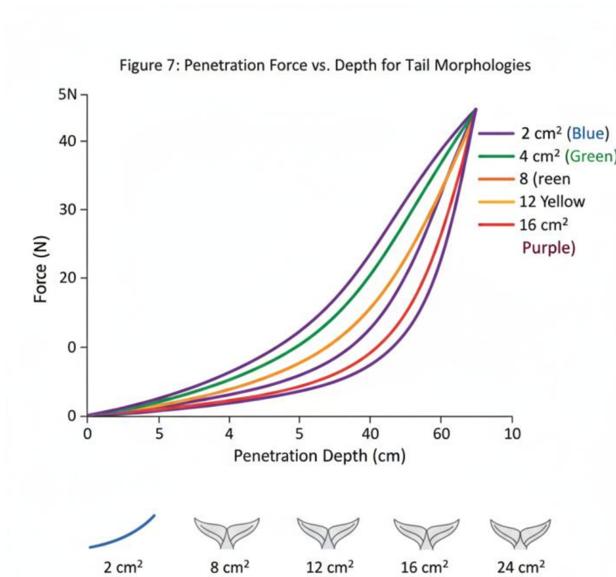
If swinging the tail reduces resistance, why isn't it always good? The problem is that it can also cause the robot to sink more. Video and motion tracking showed that when a small tail (2 cm²) was oscillated, the robot's rear pitched down and sank deeper into the ground (see Figure 6B, F). The small tail just couldn't spread out the weight enough, especially since swinging it made the ground even less able to support the robot.



On the other hand, with a large tail (16 cm²), the robot's body stayed level and didn't sink much whether the tail was moving or not (see Figure 6D, H). The broad tail was able to spread the robot's weight over a wider area, stopping it from sinking, even as the tail's movement softened the ground below.



Penetration force tests made this clear (see Figure 7). The force needed to push the tail down depended on both its size and how deeply it was submerged, with larger tails sinking less under the same weight. The model and experiments showed that while swinging the tail made it easier for all tails to penetrate (meaning the ground was fluidized), the benefit was much greater for larger tails. Since large tails already started at a shallower depth, the extra sinking caused by swinging was small. For small tails, however, the same softening of the ground meant much more sinking and, overall, higher drag—even though the local resistance was reduced.



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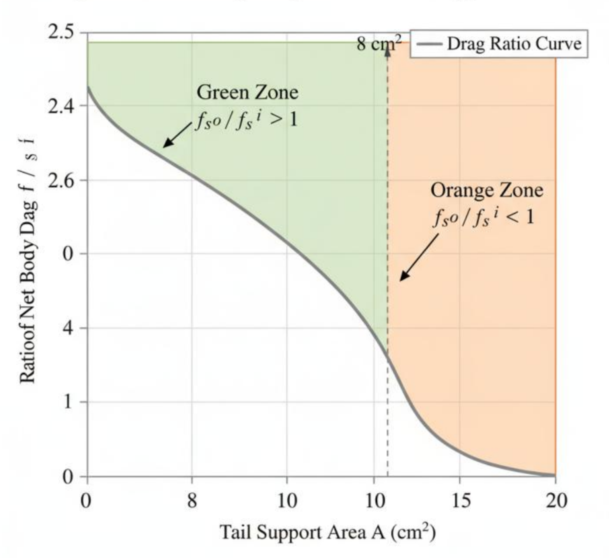
3.4 A Model for Tail Action Selection

Integrating these findings, we developed a model to predict the net effect of tail oscillation on body drag. The total body shear resistance is a function of both the substrate's shear strength (reduced by oscillation) and the intrusion depth of the body (which is often increased by oscillation). The model calculates the ratio of body drag with oscillation to body drag without oscillation (f_s^o / f_s^i).

The results, plotted in Figure 8B, reveal a clear design principle:

- **For small tails (A < 8 cm², Green Zone):** The detrimental effect of increased sinkage dominates. Oscillation increases net body drag ($f_s^o / f_s^i > 1$). The optimal strategy is to keep the tail **idle** to minimize intrusion.
- **For large tails (A > 8 cm², Orange Zone):** The benefit of reduced shear strength dominates while sinkage remains nearly constant. Oscillation significantly reduces net body drag ($f_s^o / f_s^i < 1$). The optimal strategy is to **oscillate** the tail to fluidize the substrate.

Figure 8B: Net Body Drag Ratio vs Tail Support Area



This model successfully explains the experimental velocity data and provides a quantitative framework for selecting tail action based on tail morphology.

4. Discussion

This study demonstrates that effective locomotion on deformable granular substrates requires the **co-design of appendage morphology and motion**. Our bio-inspired approach, motivated by the mudskipper, reveals that an oscillatory tail action is not universally beneficial. Its efficacy is critically dependent on the tail's morphological capacity to provide support and limit sinkage.

4.1 The Mechanism of Fluidization and Support

The central mechanistic insight is that tail oscillation functions through granular fluidization, a well-documented phenomenon in physics and geotechnics (Albert et al., 1999; Xie et al., 2022). However, applying this principle to a mobile robot introduces a trade-off: fluidization reduces shear resistance but also reduces the substrate's ability to support weight, potentially leading to catastrophic sinkage. Our work shows that a large tail support area resolves this trade-off. It acts as a "snowshoe," providing sufficient bearing capacity to prevent sinkage, thereby allowing the robot to harness the full drag-reducing benefits of the fluidized zone created by oscillation. This explains the mudskipper's behavior of flattening its tail on soft ground; it is morphing to access the oscillation strategy.

4.2 Implications for Bio-Inspired Robotics and Biology

This research provides a concrete design principle for roboticists: on deformable terrain, appendages must be designed with both **support** and **action** in mind. Simply adding a vibrating appendage to an existing robot may worsen performance if its morphology is incorrect. This principle likely extends beyond tails to other appendages, such as legs and flippers. For biologists, our model provides a potential explanation for the observed tail-morphing behaviors in animals such as mudskippers. The ability to dynamically adjust morphology may allow animals to maintain the optimal point on the morphology-action curve as substrate conditions change, seamlessly switching between an "idle" strategy on weak substrates (using a broad morphology for support) and an "oscillate" strategy on stronger substrates (using a different morphology to fluidize).

4.3 Limitations and Future Work

This study focused on a horizontal oscillation in a single type of granular material. Future work should explore:

- **Multi-Degree-of-Freedom Kinematics:** Investigating oscillatory motions in other planes (e.g., pitching) or more complex patterns could yield further improvements.
- **Adaptive Control:** Developing real-time controllers that can adjust oscillation parameters (frequency, amplitude) or even tail shape in response to perceived sinkage or drag.
- **Different Substrates:** Testing the principle across a wider range of substrates, including cohesive soils, muds, and wet granular media, to generalize the findings.
- **Integration with Gait:** Exploring the interplay between tail oscillation and the gait cycle of the primary locomotor appendages (e.g., flippers or legs).

5. Conclusion

In conclusion, we have demonstrated through integrated robotic experimentation and modeling that the performance of a robot on deformable granular terrain is determined by the synergistic interaction between tail morphology and oscillatory motion. We identified that tail oscillation locally fluidizes the substrate, reducing shear resistance by 46%. However, this strategy is only effective if the tail has a sufficient support area ($A \geq 8$ cm^2) to prevent increased sinkage, leading to a net 20% increase in speed. For smaller tails, oscillation is detrimental. This leads to a clear co-design principle: to enhance mobility on flowable ground, tail morphology must be designed to provide support, thereby enabling the beneficial use of oscillation for drag reduction. This reframes the tail design from a problem of separate mechanical and control domains into an integrated system challenge. The insights from this work pave the way for developing more capable and adaptive robots that can traverse the complex, deformable terrains found on Earth and other planets.

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