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Animal and Robotic Locomotion on Wet Granular Media

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Abstract. Most of the terrestrial environments are covered with some type of flowing ground; however, inadequate understanding of moving bodies interacting with complex granular substrates has hindered the development of terrestrial/all-terrain robots. Although there has been recent performance of experimental and computational studies of dry granular media, wet granular media remain largely unexplored. In particular, this encompasses animal locomotion analysis, robotic system performance, and the physics of granular media at different saturation levels. Given that the presence of liquid in granular media alters its properties significantly, it is advantageous to evaluate the locomotion of animals inhabiting semi-aquatic and tropical environments to learn more about effective locomotion strategies on such terrains. Lizards are versatile and highly agile animals. Therefore, this study evaluated the brown basilisk, which is a lizard species from such habitats that are known for their performance on wet granular media. An extensive locomotion study was performed on this species. The animal experiments showed that on higher saturation levels, velocity of the animal was increased due to an increase in the stride length. A basilisk-inspired robot was then developed to further study the locomotion on wet granular media and it was observed that the robot can also achieve higher velocities at increased saturation levels. This work can pave the way for developing robotic systems which can explore complex environments for scientific discovery, planetary exploration, or search-and-rescue missions.

Keywords: Wet granular media · Bipedal/quadrupedal locomotion · Basilisk lizard · Bio-inspired robot

1 Introduction

Robots are poised to enter our everyday lives, transforming how humans interact with the physical world. In the near future, multi-functional robots will advance scientific discovery across disciplines (e.g. archaeology, biology and geology), planetary exploration, aid first responders in search-and-rescue missions and even traverse hazardous environments to mankind [1]. Unfortunately, typical robotic

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systems are still restricted to maneuvering upon hard planar surfaces. Difficulties in improving terrestrial robots arise due to the inadequate understanding of moving bodies interacting with complex natural substrates (i.e., sand, dirt, mud, and rocks) [2–6]. Soft granular media and friable terrains have already seen to pose complications in regards to wheel sinkage, entrapment, and eventual immobilization of NASA Mars rovers, Opportunity [7–9]. Rover wheels have gotten trapped in sand, preventing it from maneuvering out without digging itself deeper into the trap, almost ending the mission [10]. Therefore, robots must have the ability to effectively traverse on complex, diverse, and extreme terrain topographies. Future robots will require legs to reach and operate on such terrains for cross-discipline applications. While legged robots are certainly not the only solution, they have been observed to perform better on granular media compared to wheeled or limbless robots [11,12]. Therefore, such legged robots will need to address granular media interaction.

Interaction of foreign bodies with granular media, like that of sand and mud, introduces a highly nonlinear behavior [3–6,13]. Complications arise when attempting to formulate mathematical models for these interactions. This is due to the fact that individual particles hold an inhomogeneous force distribution, causing the ground reaction forces for interaction to be quite difficult to predict [2,14–16]. Furthermore, it is infeasible to measure the influence of grain inertial forces [14,17,18] upon the moving body as it accelerates over the medium. This factor is of significance when evaluating moving bodies at high speeds. When it comes to the mechanics of locomotion, there have only been few studies on dry granular media [3,6,12,13,19–23], whereas wet granular media is largely unexplored [24–28]. The properties of granular media significantly change in the presence of liquids, due to inter-grain cohesion [29–32].

Few robots, such as Big Dog [24], AmphiHex [26,27], SeaDog [28], and [25] have shown potential to move on wet granular media. However, the mechanics of animal locomotion and physics of the environment have not been adequately explored. Thus, the performance of these robots on wet granular media cannot be compared efficaciously to that of their biological counterparts. There is a need for carefully designed studies on animal species that are highly agile on such terrain to seek potential solutions for robotics locomotion on wet granular media.

In comparison to man-made devices, organisms such as snakes, lizards, and insects can effectively move on nearly all natural environments. Scientists and engineers have sought to systematically ascertain the biological principles of their movement and implement them within robotics [33]. This "bioinspired robotics" approach [34] has proven to be fruitful for designing laboratory robots with advanced capabilities (gaits, morphologies, control schemes) including rapid running [24,33], slithering [35], flying [36], and "swimming" in sand [12]. By using biologically inspired robots as the basis of the organisms' "physical models," scientific insights have revealed the principles governing movement in biological systems and low-dimensional dynamical systems. However, minimal studies have transmitted biological principles into conventional field-ready mobile devices [24, 37], capable of operating and interacting in and with natural terrains.

Lizards are known to be versatile animals which can walk on all four legs, run on two legs, swim, climb, and burrow in, on, and through diversified terrains [38–42]. Lizard species which live in habitats covered with wet granular media, such as rain-forests, utilize different interfacial structures and locomotion patterns than other terrestrial animals for effective locomotion on muddy terrain. Therefore, our focus is on species which inhabit semiaquatic environments; ones that live along flowing stream beds, use water as a mean of retreat, and interact with vast saturation levels of granular media. During our preliminary studies, one reptile stood out amongst the others-the brown basilisk lizard (*Basiliscus vittatus*). This specimen which has gained recognition for running across water, was observed to leap into bipedal gait when running on granular media. While previous locomotion studies have been performed on basilisk, they have mainly been on water [40, 43, 44] and dry hard surfaces (i.e. sandpaper) [45]. Furthermore, previous studies on bipedal motion of other lizards [46, 47] have focused on the development of mechanical modeling and running in water [41]. While, to the best of our knowledge, no bipedal behavior study has been performed on wet granular media. This research provides an insight to the animal's morphology and locomotion transformation as the medium transition from dry to wet.

This work aims to simplify and optimize elegant designs found in highly agile and versatile animals, such as lizards, toward developing bioinspired robotic systems for diversified terrains. Through our animal studies, our main objective is to identify the optimal morphology and gait parameters for mobility on complex deformable terrain, specifically granular media at different saturation levels. A bioinspired robot has been designed and fabricated that addresses one of the deficiencies existing in "all-terrain" robots, namely the inability to traverse on complex granular terrains. More precisely, transitioning from quadrupedal to bipedal gait (and vice versa) within a few steps and effectively traversing bipedal on granular media at different saturation levels.

2 Methods

2.1 Experimental Setup

A Fluidized Bed sized at $2 \times 1\,\mathrm{m}^2$ was built to perform dry and saturated granular experimentations (Fig. 1a). The setup consists of a porous and honeycomb sheet separating the sand from air-duct system, which is positioned underneath it. The air-duct system controls compactness (volume fraction) of the sand. In the fluidized bed, above a critical air flow rate, the granular material behaves like a fluid. By gradually decreasing the air flow to zero, the media reaches a loosely packed state with a flat surface, removing previous disturbances to the medium. Air fluidization only occurs prior to each test run and not during experiments. After fluidization and once the media has settled, the bed can slowly be inclined to an angle from $0°$ to $45°$. For these series of experiments the bed was kept at an inclination angle of $0°$.

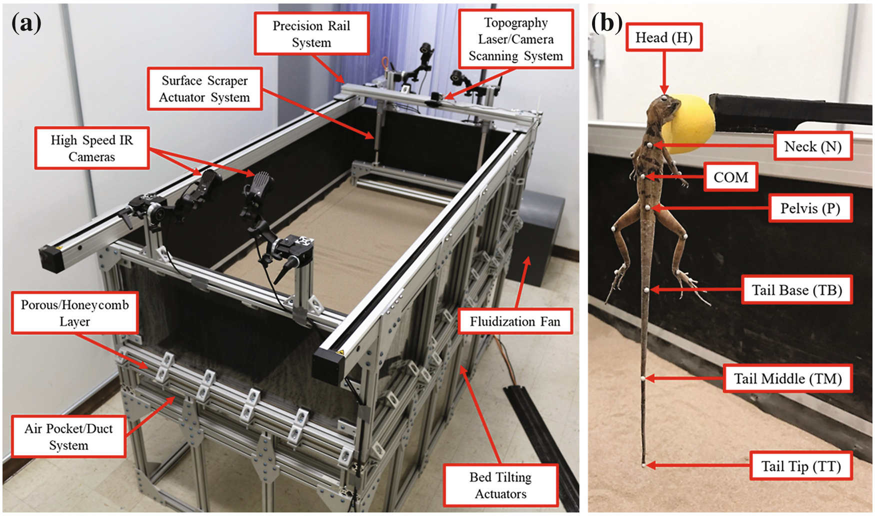

Fig. 1. (a) Air-fluidized bed setup. (b) A basilisk lizard with IR markers.

For saturated granular media experiments, fluidization was infeasible and thus not performed. Instead, saturation was performed manually by evenly pouring water over the bed and mixing the medium thoroughly with an industrial hand mixer. A soil moisture sensor (GS1 manufactured by Decagon Devices) was used to measure the saturation level (i.e., volumetric water content) of the medium prior to experimentation. Nine distributed points throughout the bed were sampled (with the sensor fully embedded under the soil). For saturation level, the average was recorded as the saturation level of the bed. This was performed before and after each experiment to ensure the saturation level remains constant throughout the experiment.

Three saturation levels were used for experimentation: 0%, 15%, and 30% water content. With the experimental focus being on the change in saturation level, the volume fraction of the medium was not varied and ensured to be compact. To preserve a relatively smooth and compact surface, an actuated scraper was grazed back and forth across the bed. The nine distributed locations throughout the bed were measured for soil height using a pair of digital calipers to obtain the relative height of the soil.

Six infrared (IR) OptiTrack motion capture cameras were mounted on the bed and orientated to obtain the maximum image overlap. With a horizontal field of view of 56° and a frame rate of 120 fps, the cameras recorded the 3D locomotion of the animal and robot through the attached IR reflective markers on the desired locations of analysis. Prior to each experiment, the cameras were calibrated and a reference coordinate system was established. Utilizing the Motive software developed by OptiTrack, post capture analysis of each marker's position with respect to time was evaluated. The speed was calculated as the measured distance traveled of a marker per unit time. Penetration depth was obtained based on the z-displacement of markers. Aside from the IR motion capture cameras, a Canon DLSR (EOS 70D) camera along with a GoPro (Hero5) were used to capture visual observations from the top and side view, respectively.

The sand used for the dry and saturated experiments was commercially available playground sand (washed, sterilized, and dried) that was sieved with a sieve shaker to particle size range of 250–600 µm. A total volume of about 102 L of sand was sieved and displaced into the bed.

2.2 Animal Studies

Three juvenile Brown Basilisk (*Basiliscus vittatus*) were used for the animal experiment, with SVL = 8.37 ± 0.43 cm and mass = 18.6 ± 3.6 g (Fig. 1b).

All of the animal experiments were reviewed and approved by ASU Institutional Animal Care and Use Committee (IACUC) under IACUC Protocol #: 16-1504R. Arizona State University DACT (Department of Animal Care Technologies) were delegated with their housing and care. All personnel handling the animals were approved and trained by ASU IACUC. When the basilisk lizards were brought to the lab for experimentation, they were placed into an incubator at 30 °C between trials to preserve their desired environmental temperature condition and agility.

3 mm hemispherical adhesive backing reflective (facial) markers (0.04 g) were placed at each main joint of the lizard and throughout its body for motion capture analysis. Minute amount of nail polish was applied to the base of the markers for better adhesion. The markers were left on to gradually fall off on their own. A total of 17 markers were placed upon each basilisk lizard (Fig. 1b): 3 were placed on each hind limb (Knee, Ankle, and Foot), 2 were placed on each fore limb (Knee and Foot), 3 were placed from the snout to vent (Head, Neck, COM, Pelvis), and 3 were evenly distributed along the tail (Tail Base, Tail Middle, Tail Tip). Only 7 markers from the snout to the tip of the tail were used for these series of locomotion analysis. More specifically, the following parameters were evaluated: Pelvis velocity, stride frequency, and stride length (measured in coordinates of absolute space).

Each lizard was placed in one end of the Fluidized Bed and its locomotion on closely packed sand at different saturation levels (0%, 15%, 30%) was recorded using the IR motion capturing system. Each trial consisted of observing the lizard running along a straight path without any interruptions. Three trials were completed per basilisk lizard per saturation level. 40 min in the incubator was allocated for their rest between trials. The order of experimentation with the lizards were randomized for each saturation level evaluated.

2.3 Robotic Studies

The dimensions of the 3 basilisk lizards were taken from the Motive software and averaged. In particular, the length of fore limbs (3.05 ± 0.25 cm), hind limbs (6.63 ± 0.44 cm), and tail (17 ± 2.89 cm) were measured. The basilisk-inspired robot, Basiliskbot (Fig. 2) was designed based on the averaged dimensions of

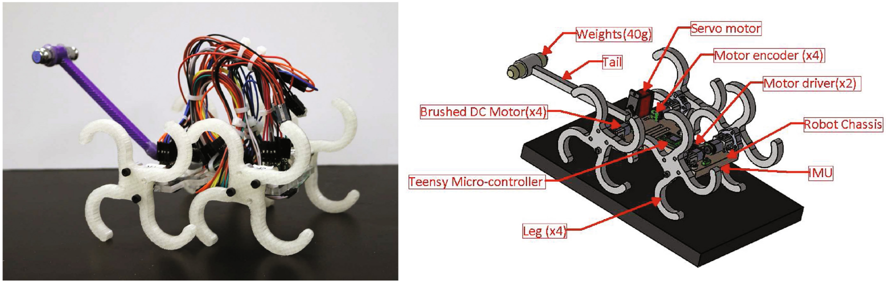

Fig. 2. The Basiliskbot

the animal. The four-spoked legs were 3D printed with Acrylonitrile-Butadiene Styrene (ABS) with a 30% fill and thickness of 8.5 mm, while the body was laser cut using 4.3 mm acrylic. Mass of the robot (without the tail) was 273 g with the following components on board: four 50:1 micro DC geared motors, four magnetic encoders, four aluminum motor mounts, two dual motor drivers, a micro servo, a Teensy 3.2 micro-controller, and an inertial measurement unit (IMU). Total mass of the tail was 45 g (a 40 g mass was attached to the end of a 5 g tail with the length of 12.5 cm).

Both bipedal and quadrupedal gaits were implemented for the robot and tested on closely packed dry and wet sand (0%, 15%, and 30% saturation levels). In addition, a PID controller was used to control the tail angle during the bipedal gait and ensure body stability. Thus, the robot was able to push off the ground and stand up on its hind limbs in a couple of steps and then to perform a stable bipedal gait.

Body velocity was evaluated at five different motor frequencies per saturation level, where three trials were performed per frequency, giving a total of 45 test runs for each gait. Only successful runs were considered, in which the robot was observed to move on a relatively straight path. The experimental setup, procedure, and method were kept the same as that of animal experiments. The DSLR Canon and GoPro cameras were used for top and side view observations, respectively.

3 Results and Discussion

3.1 Animal Experiments

Here we report our experimental results for basilisk lizards and a basiliskbot moving on dry and wet sand. In particular, we look at the effect of saturation level on stride length and stride frequency, and thus the body velocity. The animal's pelvis velocity was averaged between the trials and evaluated per saturation level (Fig. 3a, b). A significant difference ($P < 0.05$ and $P < 0.01$, respectively) in pelvis velocity was observed when the saturation increased from 0% to 15%

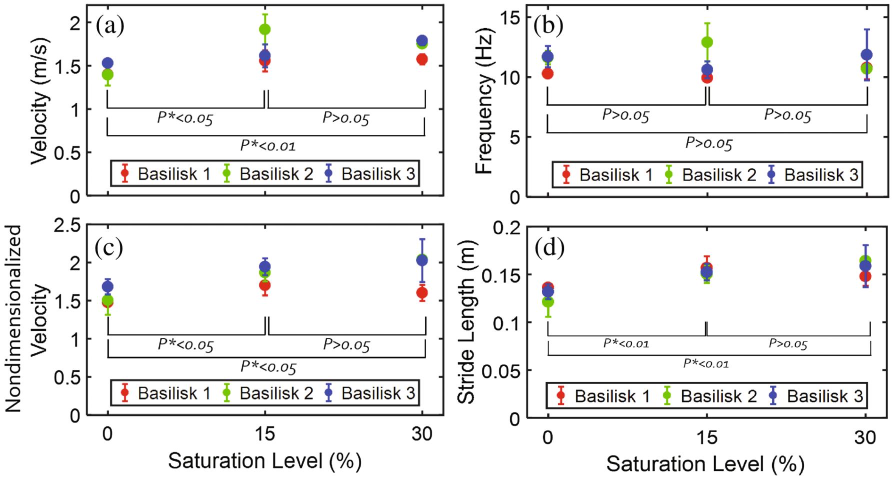

Fig. 3. (a), (b) Pelvis velocity, (c) stride frequency, and (d) stride length of the basilisk lizards performing bipedal running at different saturation levels of sand. SPSS (ANOVA and T-Test) was used with $P* < 0.05$ and $P* < 0.01$ indicating statistically and statistically highly significance. Sample size: n = 3

saturation and from 0% to 30%, but minimal difference was observed from 15% to 30% saturation.

The animal's body velocity increased as the saturation increased. However, no significant difference was observed when evaluating the stride frequency (Hz) from 0% to 15%, 15% to 30%, or 0% to 30% (Fig. 3c). Therefore, the average stride length (about the Pelvis marker) was naturally the next point of evaluation. Significant difference ($P < 0.01$) was observed in stride length when the saturation was increased from 0% to 15% and from 0% to 30%, but minimal change when going from 15% to 30% (Fig. 3d).

This indicates that the significant change in the animal's body velocity was due to the change in stride length at different levels of saturation. As the saturation level increased, the animal's ability to make longer stride lengths increased and thus increased its body velocity. The animal was anecdotally observed to struggle with sinkage when running across dry sand and thus took shorter strides to stay afloat and stabilize. However, saturated sand decreased sinkage and gave the animal confidence to take wider strides of motion. Stride length increased as saturation increased from 0% to 30% with an average stride length of 13.18 ± 1.83 cm to 15.68 ± 2.20 cm. Velocity increased as saturation increased from 0% to 30% with average absolute velocity of 1.44 ± 0.14 m/s to 1.70 ± 0.13 m/s. Interestingly enough, it has been cited [41] that basilisk lizards on water experience an average velocity of 1.3 ± 0.1 m/s, regardless of their size, which is not too far from its performance on 0% saturation.

3.2 Robotic Experiments

This study focused on the bipedal and quadrupedal locomotion of the Basiliskbot at different leg frequencies on both dry and wet sand. Although stride length cannot be changed with the current design, leg frequency can be modified to study its impact on body forward velocity at different saturation levels. The velocity of the robot as a function of leg frequency for bipedal and quadrupedal locomotion on sand at different saturation levels is plotted in Fig. 4.

As shown in this figure, the higher the saturation level, the higher the robot forward velocity at each leg frequency. This is mainly due to the lack of slip and deep penetration on wet sand compared to dry. Furthermore, the cohesive nature of wet granular media provides the substrate greater reaction forces and thus the (animal and) robot the ability to transverse on saturated mediums at a faster rate as compared to dry sand. However, it is not anticipated to see a continued increase in velocity with increasing saturation level beyond the full saturation (where sand cannot absorb any more water). It is hypothesized that the additional water on the surface would decrease the ground reaction force and decrease the drag force and thus could slow down the robot.

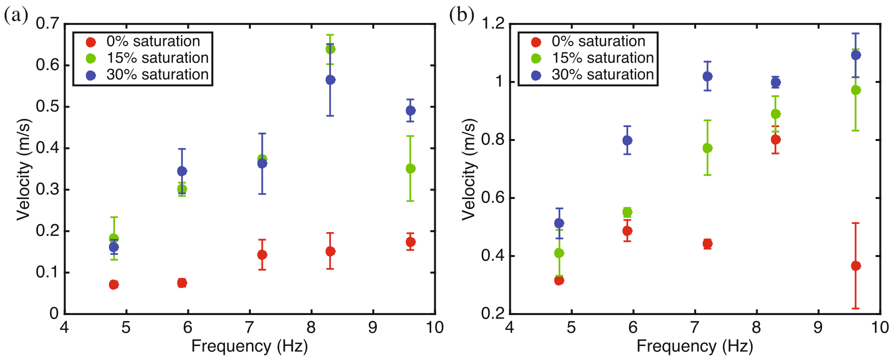

Fig. 4. Velocity of the basiliskbot versus leg frequency for (a) bipedal and (b) quadrupedal locomotion at different saturation levels of sand.

In addition, it is observed that bipedal velocities are smaller than those of quadrupedal. This can perhaps be attributed to multiple factors. First, in bipedal mode hind legs exert a higher normal pressure to the sand and thus penetrate further. As a result, they need to spend more energy and time to come out of sand. This is observed more on the dry sand. Moreover, the controller was sometimes forcing the tail to touch the ground to ensure stability of bipedal gait. This would reduce the bipedal velocity by introducing additional drag force. The tail was also removed from the robot when performing quadrupedal gait to avoid pitch instability due to the presence of a passive tail. This would correspond to 14% reduction in the total mass of the robot.

Finally, it was observed that high frequencies can sometimes result in decreased forward velocities. Reduced velocity at high frequency quadrupedal locomotion on dry sand has been reported by Li *et al.* [19]. In this study, the above mentioned phenomena was also observed for bipedal locomotion on wet sand which needs to be further explored.

4 Conclusion

An experimental study of animal and robot locomotion on wet and dry granular media is presented in this paper. In particular, the effect of sand saturation level on stride length, stride frequency, and body velocity of a basilisk lizard performing bipedal locomotion has been explored. It was found that the animal velocity increased at higher saturation levels due to an increase in stride length (the change in stride frequency at different saturation levels was not statistically significant). Next, the Basiliskbot was developed to explore maximal speeds on dry and wet granular media. In particular, the effect of stride frequency on body velocity at different saturation levels of sand was studied for both quadrupedal and bipedal gaits. It was found that increased saturation level will result in increased body speed at each leg frequency for both bipedal and quadrupedal gaits. In addition, the robot was able to achieve higher speeds using quadrupedal gait, although the effect of tail mass and touching the ground needs to be further explored. Finally, increased leg frequency may sometimes result in decreased forward velocity depending on the gait and the saturation level. Through the series of performed animal and robotic experiments, we have addressed significant contributing factors (e.g. morphology, gait, and adaptation) to legged locomotion on granular media and possible optimal solutions for traversing complex deformable terrain. Using the Basiliskbot, we would like to further study optimal locomotion patterns on complex unstructured environments and develop effective robotic systems for locomotion on such terrains.

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