

**PRINCIPLES OF FIN AND FLIPPER LOCOMOTION ON  
GRANULAR MEDIA**

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# PRINCIPLES OF FIN AND FLIPPER LOCOMOTION ON GRANULAR MEDIA

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*To my family*

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## SUMMARY

Locomotion of animals, whether by running, flying, swimming or crawling, is crucial to their survival. The natural environments they encounter are complex containing fluid, solid or yielding substrates. These environments are often uneven and inclined, which can lead to slipping during footsteps presenting great locomotor challenges. Many animals have specialized appendages for locomotion allowing them to adapt to their environmental conditions. Aquatically adapted animals have fins and flippers to swim through the water, however, some species use their paddle-like appendages to walk on yielding terrestrial substrates like the beach. Beach sand, a granular medium, behaves like a solid or a fluid when stress is applied. Principles of legged locomotion on yielding substrates remain poorly understood, largely due to the lack of fundamental understanding of the complex interactions of body/limbs with these substrates on the level of the Navier-Stokes Equations for fluids. Understanding of the limb-ground interactions of aquatic animals that utilize terrestrial environments can be applied to the ecology and conservation of these species, as well as enhance construction of man-made devices.

In this dissertation, we studied the locomotion of hatchling loggerhead sea turtles on granular media integrating biological, robotic, and physics studies to discover principles that govern fin and flipper locomotion on flowing/yielding media. Hatchlings in the field modified their limb use depending on substrate compaction. On soft sand they bent their wrist to utilize the solid features of sand, whereas on hard ground they used a rigid flipper and claw to clasp asperities during forward motion. A sea turtle inspired physical model in the laboratory was used to test detailed kinematics of fin and flipper locomotion on granular media. Coupling of adequate step distance, body lift and thrust generation allowed the robot to move successfully forward avoiding previously disturbed ground. A flat paddle intruder was used to imitate the animal's flipper in physics drag experiments to measure the forces during intrusion and thrust generation.

# CHAPTER I

## INTRODUCTION

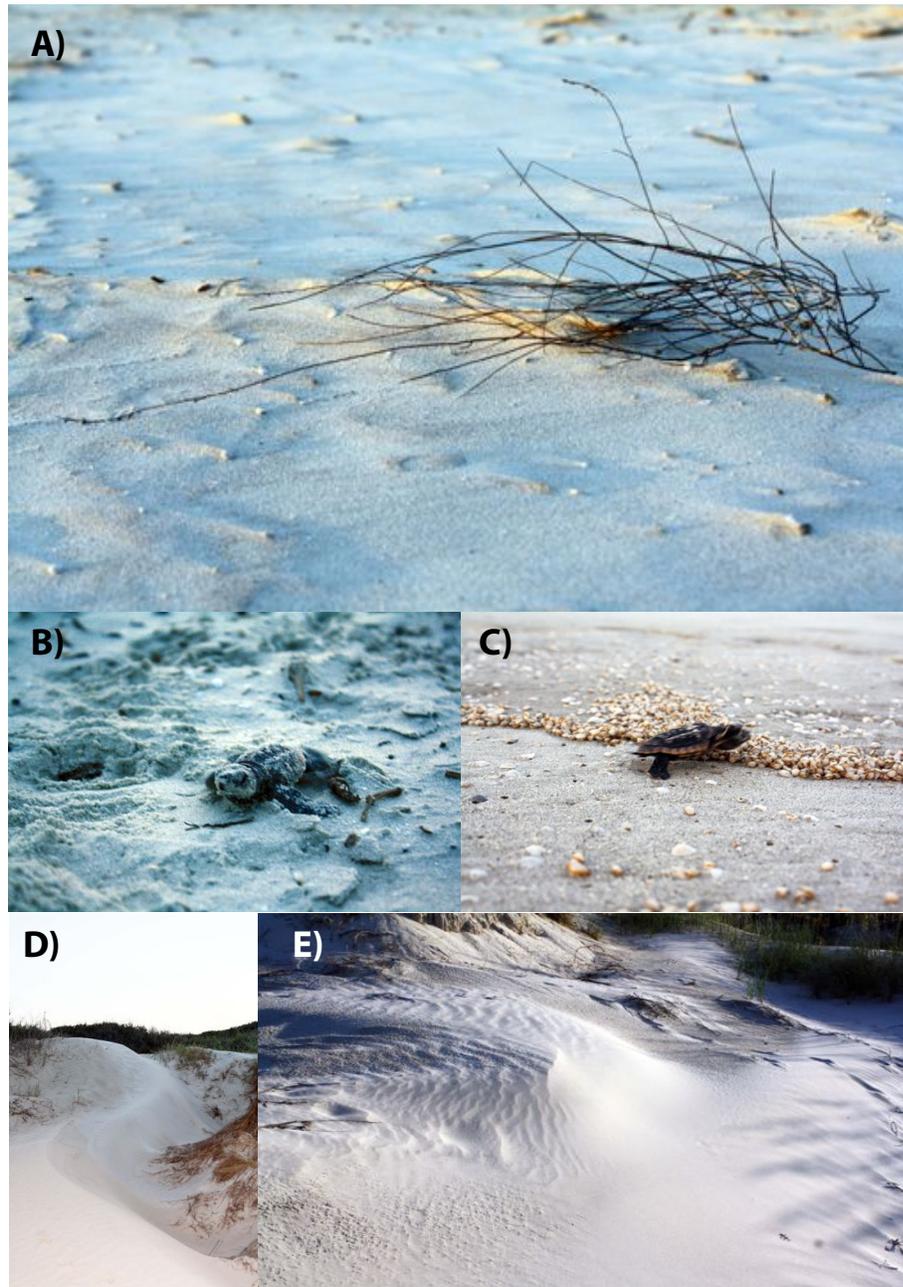
### *1.1 Motivation and Overview*

Locomotion of animals [2], whether by running, flying, swimming or crawling, is crucial to the survival of animals. Natural environments are often highly complicated [2, 14]. They can be fluid [68] such as air or water, as well as solid [2] as found on terrestrial environments. In particular, terrestrial environments are often uneven [11], inclined [49], dispersed [61], and are composed of heterogeneous materials, like dirt, mud, sand, rubble, snow and debris. These materials can yield and flow during footsteps and display both solid- and fluid-like properties [45], and thus present great locomotor challenges.

Tetrapod (four legged) locomotion evolved at the water's edge with the first walkers, such as *Tiktaalik*, adapting to terrestrial environments by using their fins to walk on land [60]. It is to the same environment we look today to understand how animals with aquatically adapted limbs are capable of moving on complex substrates. Various animal classes like fish [63, 33], reptiles [75], and mammals [17, 7] interact at the water-land interface, regularly emerging from the sea onto rocky and sandy environments Figure 2A. They carry out tasks such as feeding, mating, reproduction or resting using limbs that seemingly were adapted for swimming through fluids on a complex, yielding terrain.

While principles of legged locomotion on solid ground have been discovered, the mechanisms by which animals move on yielding/flowing terrestrial surfaces remain poorly understood [2, 14]. Unlike for flight and swimming where complex interaction can in principle be understood by solving Navier-Stokes Equations [68], no fundamental theory yet exists to describe the interactions with yielding substrates.

Most aquatic animals encounter granular media (e.g. sand) when emerging from water. Granular media is defined as collections of discrete particles that interact through dissipative, repulsive contact forces [38]. When forced, granular media remain solid below the yield



**Figure 1:** Pictures taken on Jekyll Island. A) Sand surface is uneven and contains debris. B) Loggerhead sea turtle hatchling shortly after emergence from nest near dune area. C) Hatchling traveling towards the ocean encountering shells. D) Dune area showing complexity and incline angle of natural beach environments. E) Wave lines on sand surface are caused by wind action. Pictures taken by Nicole Mazouchova.

stress, but can act as a fluid when the yield stress is exceeded [50]. Granular media can be controlled by varying the volume fraction (ratio between solid volume of the medium and the volume it occupies) [38] to mimic natural surfaces which animals encounter in nature.

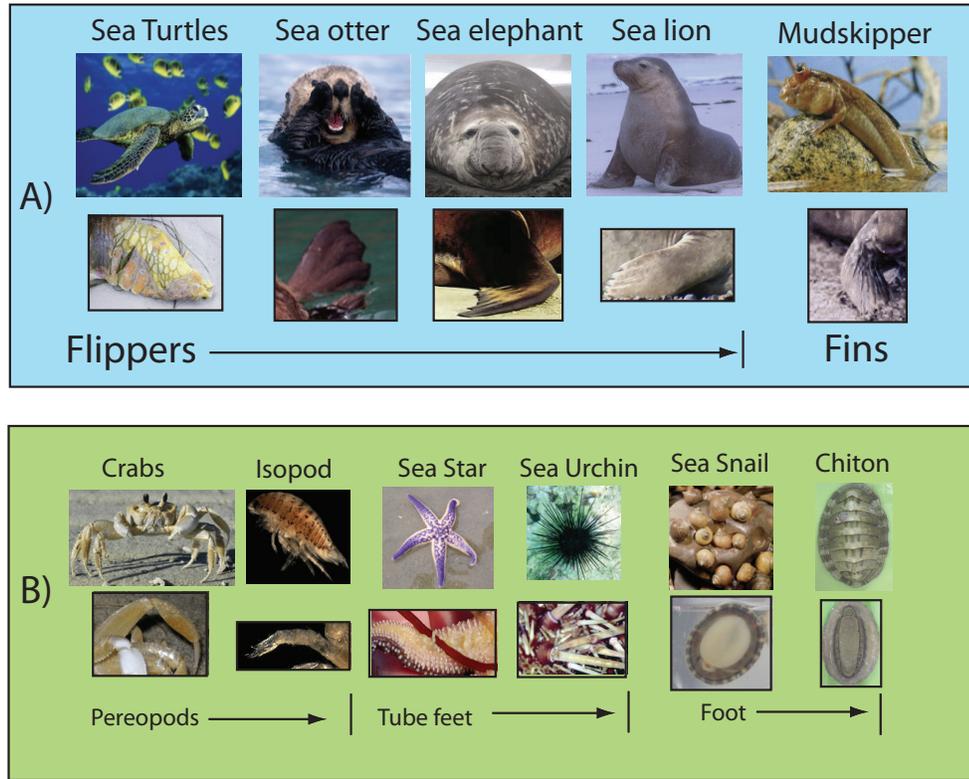
In this dissertation, we use hatchling sea turtles, and a sea-turtle inspired physical model on yielding substrates, and integrate biological and physics studies to discover principles of fin and flipper locomotion on granular media, Figure 1. We conduct field studies with hatchling sea turtles, studying the limb-ground interactions of aquatically adapted limbs with yielding substrates. A specialized laboratory device is used for controlling granular media. In the field we use high speed video to record the animals running on the laboratory devices. We create a bio-inspired physical model with flippers to test physical principles in a controlled laboratory setting. These studies result in an understanding of fin and flipper use on terrestrial media. Such understanding is leading us towards fundamental models of limb interactions with natural surfaces that can yield and flow.

Within this framework, Chapters II-IV are categorized into:

- Biological studies: **Chapter II and IV.**
- Robotic studies: **Chapter III.**
- Physics studies: **Chapter II and III.**

In the following sections of this Chapter, we review previous work and describe experimental techniques that provide the scientific and technical basis of this dissertation.

## 1.2 *Fin and Flipper locomotion: aquatic*

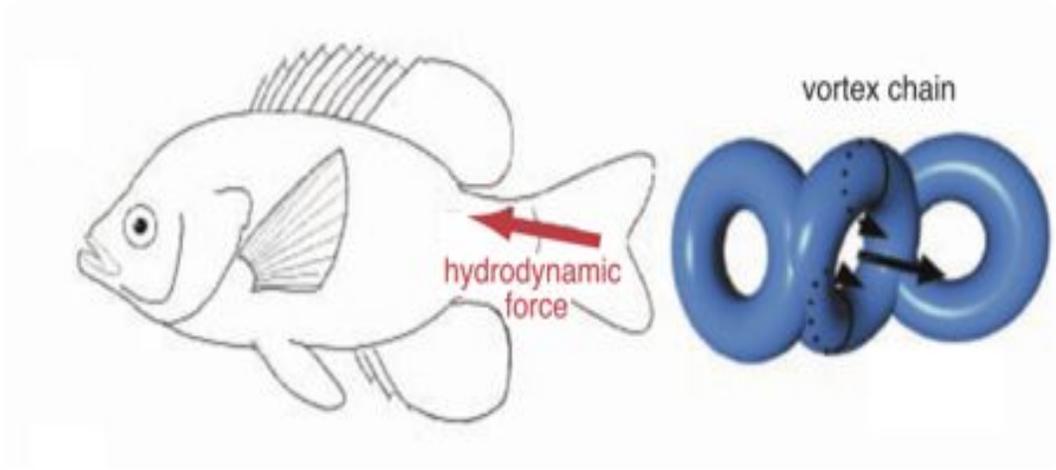


**Figure 2:** A) In the blue box are examples of aquatic animals, which use fins and flippers to swim through water and to varying degrees 'walk' on land. Sea turtles, sea otters, sea elephants and sea lions utilize flippers to swim and walk, whereas mudskippers have fins adapted for both environments (Picture of animal with its pectoral appendage below). B) In the green box are examples of limbs used by animals in the intertidal zone. Crabs and isopods have pereopods for locomotion, sea stars and urchins utilize tube feet, whereas sea snails and chitons have a single foot for locomotion. Image courtesy of A) archive.org, wikipedia.org, B) wikipedia.org, National geographic.

Swimming is the result of transfer of momentum produced by a part of the animal, the propulsor, to the environment [69, 2]. Animals that swim use their appendages and body to push against fluids, propelling themselves forward [14, 12], Figure 3.

Aquatic animals swim through fluid media using different patterns of movement, gaits [68, 18]), utilizing a variety of aquatically adapted limbs [68], such as flippers, fins, tentacles, pereopods and pleopods, Figure 2. Two main propulsion methods have been identified to be used by aquatic animals in fluids: drag-based and lift-based thrust production using paired, flattened, elongated appendages [68]. During drag-based propulsion the appendages

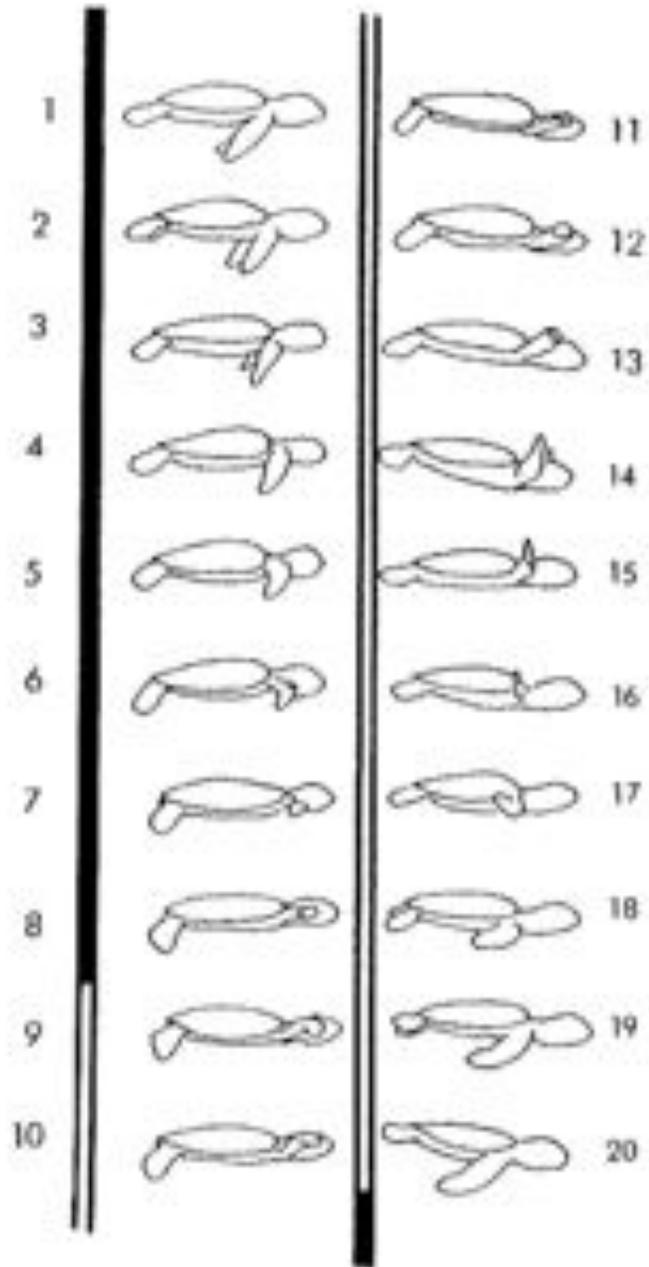
are oriented broadside to fluid flow resulting in main thrust production, and parallel to flow during a forward recovery stroke [68]. Lift-based propulsion is generated continuously, by adjusting the angle of attack of the appendages to maximize the lift-to-drag ratio [68].



**Figure 3:** Reconstruction of vortex wake behind a swimming fish. As the tail sweeps back and forth, it creates a series of alternating vortices, aiding in forward motion during swimming. Reproduced from [14].

Sea turtles have a unique body shape compared to fish (use body and limbs to swim through water), with a hard carapace and plastron surrounding a majority of their body, limiting axial movement [28, 75]. This rigid, but streamlined, body plan dictates the appendages to be the main propulsion mechanism. The pectoral flippers are modified into wing-like structures, whereas the hind flippers are used as paddle-like structures [75].

Previous research on hatchling sea turtles has shown that they alternate between three dominant swimming patterns: power stroking, a lift-based mechanism of thrust generation, which moves the animals most rapidly, dog-paddling, a drag-based mechanism that produces slower progress, and the drag-based rear flipper kick, which consists of only the back flippers paddling or rowing while the front flippers are flexed and folded back over the carapace



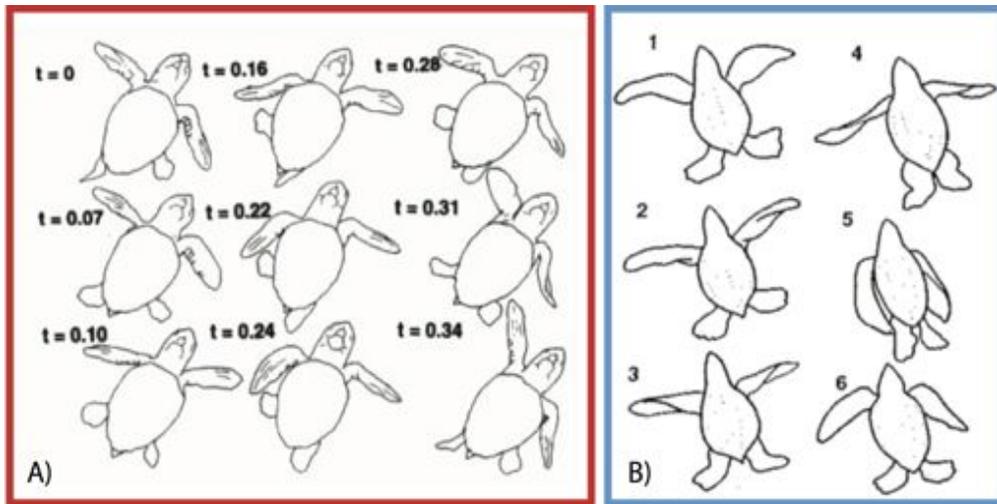
**Figure 4:** Powerstroking by a *Chelonia mydas* hatchling. Simultaneous protraction by forelimbs indicated by dark vertical bars to the left of the tracing. Simultaneous retraction by forelimbs indicated by open vertical bars to the left of the tracing. Redrawn from [74].

[75]. The major propulsion mechanism for both hatchlings and adults is the powerstroke, preferred by all species [75] Figure 4.

Sea turtles are known to regularly emerge onto terrestrial environments to access their nesting habitat, however, little is understood in regards to how they use their aquatically adapted flippers on terrestrial substrates.

### 1.3 Fin and Flipper locomotion: terrestrial

Locomotion with fins and flippers most commonly occurs in water, however, a wide variety of animals utilize their aquatically adapted limbs on terrestrial environments [76]. Transitioning from water to land imposes new challenges such as gravity and increased frictional forces between the body and the terrestrial media [60]. Aquatic animals have evolved an array of adaptations to overcome these challenges on terrestrial substrates. Some species of killifish [21], mudskippers [63, 53] and blennies [33] are known to emerge onto land regularly, displaying varying terrestrial locomotion strategies like leaping, walking and jumping. For

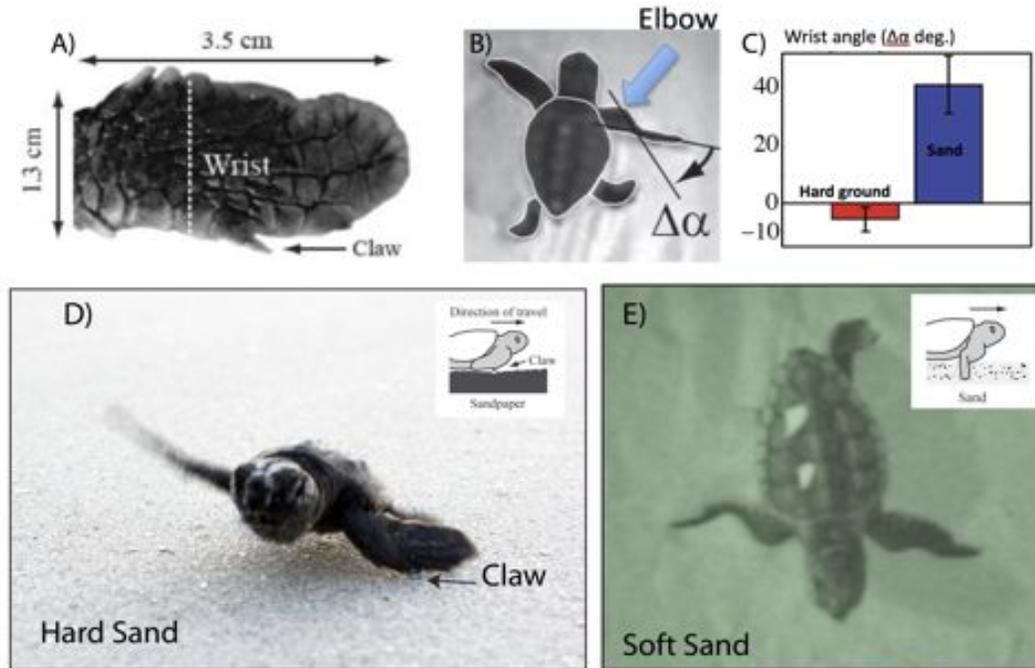


**Figure 5:** A) Illustration of sea turtle hatchling alternating gait on terrestrial media, with time measured in seconds. Diagonal limbs are used synchronously during forward motion. B) Symmetrical gait on terrestrial media. Both the two front flippers and both hind flippers push the body forward. Redrawn from [75].

example, the Mudskipper spends up to 50% of its life on land, foraging for food, creating burrows and laying eggs [63, 37]. Terrestrial Pacific blennies are observed to utilize a jumping response using mostly their caudal fin to propel themselves across land [33]. Sea otters, sea elephants and sea lions utilize the terrestrial environment for 10% to 20% of their life, mostly for basking in the sun and rearing their young [7, 17, 22].

As a contrast, sea turtles only spend less than 1% of their life on land, and predominantly for reproductive purposes [31]. However studies show that this is one of the most important segments of their life cycle for the survival of the species [29]. In the case of sea turtles,

the animals are not capable of producing undulations to propel themselves forward; their carapace and plastron create a hard box around their body with only their appendages capable of producing thrust [54, 28].



**Figure 6:** A) Picture of hatchling sea turtle front flipper illustrating the claw and location of wrist. B) Outline of hatchling moving on soft sand illustrating bending of the wrist and the angle  $\alpha$  measured during motion. C) Graph depicts wrist angle on the two treatments (soft sand and hard ground). There is a statistical significant difference in wrist angle between soft sand and hard ground. D) Picture of hatchling on natural beach demonstrating the use of the claw and a rigid wrist during forward motion on hard ground. E) Picture from video data taken on the experimental setup, showing the bending of the wrist as the hatchling traverse on soft sand.

Sea turtles employ two modes of locomotion on terrestrial media, the symmetrical and the asymmetrical gait (Figure 5), these modes of locomotion vary by age and species, Table 1.

**Table 1:** Terrestrial gaits grouped by sea turtle species and age

Species	Hatchling gait	Adult gait
Loggerhead ( <i>Caretta caretta</i> )	Alternating	Alternating
Green ( <i>Chelonia mydas</i> )	Alternating	Symmetrical
Hawksbill ( <i>Eretmochelys imbricata</i> )	Alternating	Alternating
Olive Ridley ( <i>Lepidochelys olivacea</i> )	Alternating	Alternating
Kemps Ridley ( <i>Lepidochelys kempii</i> )	Alternating	Alternating
Leatherback ( <i>Dermochelys coriacea</i> )	Symmetrical	Symmetrical
Flatback ( <i>Natator depresses</i> )	Alternating	Symmetrical

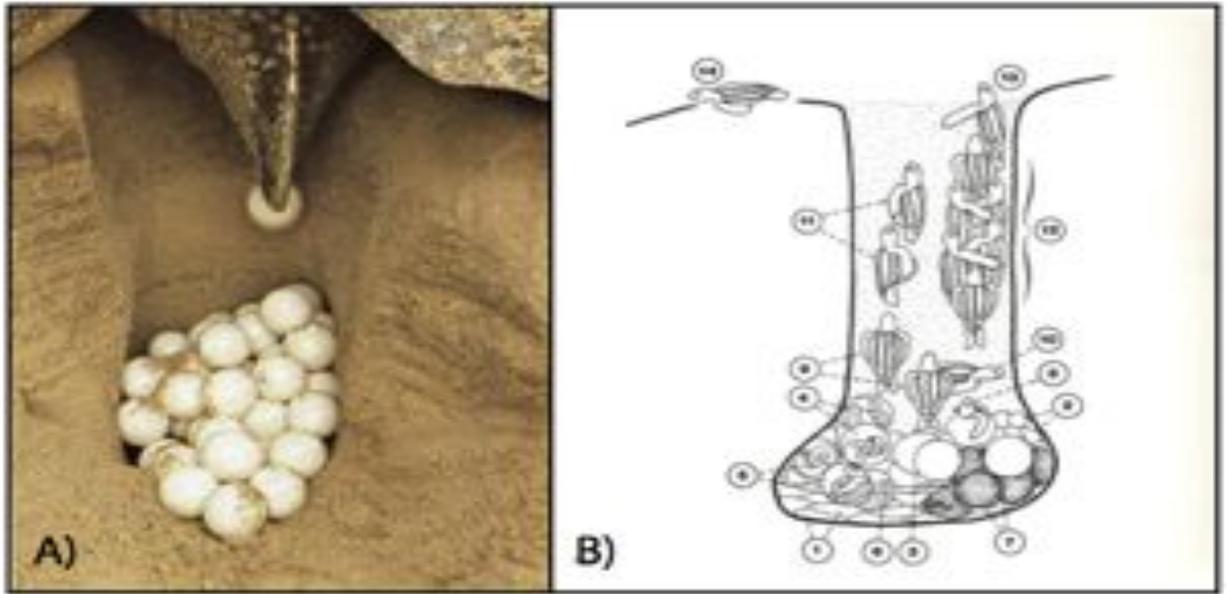
#### 1.4 Study organism: Loggerhead sea turtle (*Caretta caretta*)

There are seven sea turtle species in the world [4] of which we choose the loggerhead sea turtle as our study organism, Figure 7. They range from the Atlantic ocean through the Mediterranean Sea into the Pacific ocean, swimming on migratory routes several hundred of kilometers every year, searching for food and returning regularly to their native rookeries [24]. Some of the major rookeries for loggerhead sea turtles are located along the eastern seaboard of the United States in Florida and Georgia [32]. Due to their evolutionarily restrictive reproduction strategy, sea turtles, belonging to the class reptile, must lay their eggs outside the water, to ensure an adequate incubation environment [47]. Adult females mate in the shallow off-shore waters before approaching the beach at night [24]. They emerge on sandy, ocean-facing beaches, dig nest cavities, and depending on species, deposit anywhere from 50 to 130 eggs per nest [67, 25, 57]. After two month incubation period, the hatchlings break through their shell, resting up to several days below the sand, waiting for a majority of their siblings to hatch before emerging to the surface [47].

After several animals have hatched, they initiate movement within the nest which will cue other hatchlings to start moving as a group, beginning a process to dig themselves out of their nest [72]. This process is called social facilitation and is hypothesized to aid hatchling emergence as a group response to conserve the energy of individuals [72, 6] Figure 8B. In comparison to the time spent by sea turtles in the ocean, their time on the beach is very short, but crucial for the survival of the species [71, 29]. Hatchling mortality contributes to



**Figure 7:** A) Loggerhead sea turtle adult and B) hatchling (*Caretta caretta*). A) Reproduced from [24].



**Figure 8:** A) Photo illustrates a female nesting on a beach with part of the nest wall removed to view the laying process. B) Drawing shows the nest environment with closed eggs and partially hatched animals at the bottom of the nest. Further it illustrates social facilitation with hatchlings emerging as a group. A hatchling is shown to move downslope towards the ocean. A) Reproduced from [20]. B) Redrawn from [20].

stable adult and sub-adult populations, and coupled with the survival rates of benthic juveniles, significantly improves the population ecology of the species [29]. However, hatchling terrestrial locomotion, which is important for the survival of the species, is until recently, been poorly understood [54, 75, 45]. We choose to study loggerhead sea turtle hatchlings due to their availability at the Georgia coast, selecting a study site on Jekyll Island, GA, in collaboration with the Georgia Sea Turtle Center (GSTC) Figure 9. We conducted field studies in the summers of 2007, 2008, 2010, receiving nest locations and egg laying dates from the GSTC.

Field work permitted under State of Georgia Scientific Permits 29-WBH-08-122, 29-WCH-07-96 and 29-WBH-10-108 and IACUC A10005.



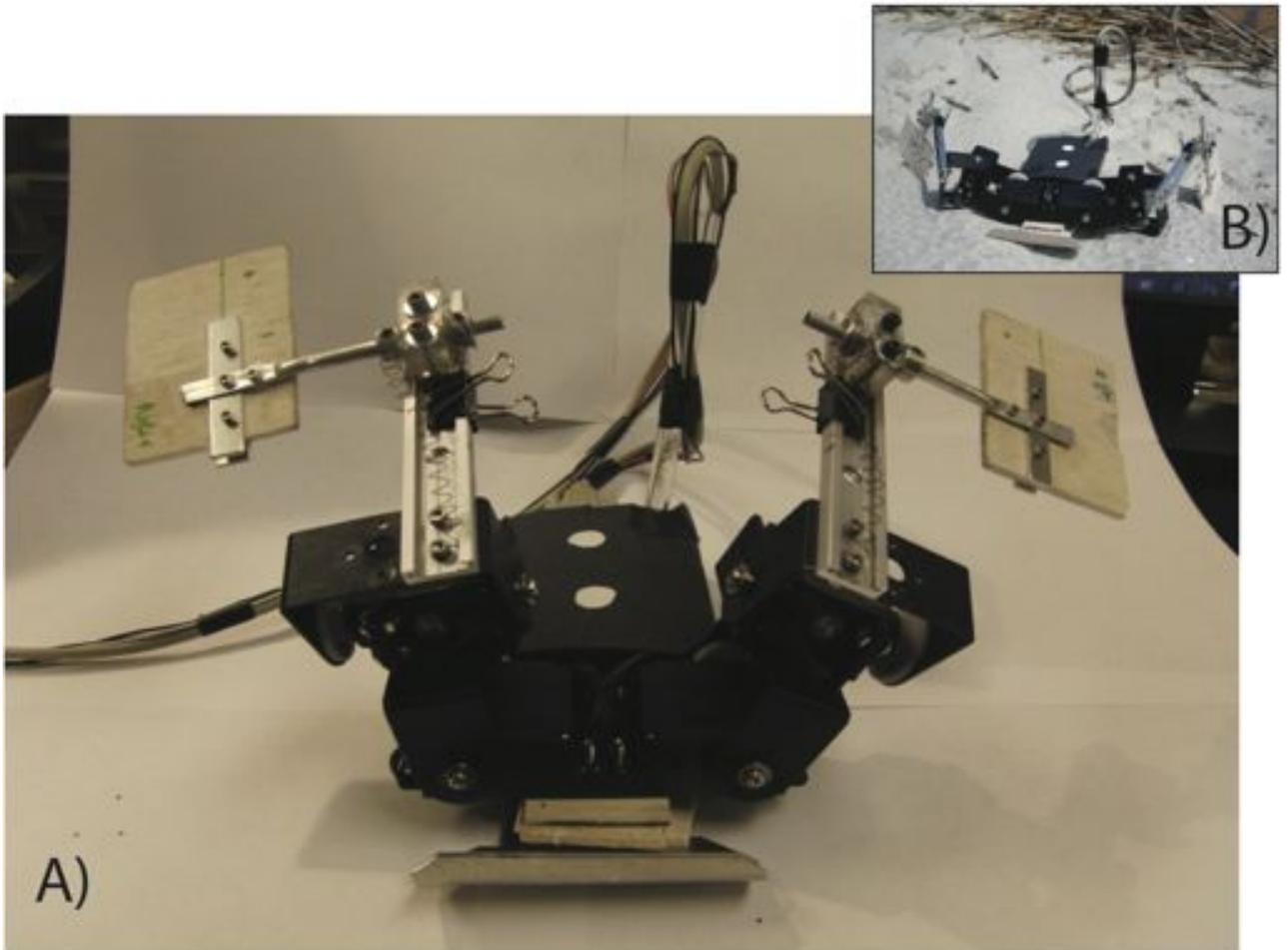
**Figure 9:** Georgia Sea Turtle Center on Jekyll Island, GA. Picture taken by Nicole Mazouchova.

## ***1.5 Experimental techniques***

### **1.5.1 Physical model: FlipperBot**

Animal experiments are valuable to expand knowledge of locomotion patterns in water [68] and on land [2]. However, research has shown that test animals may behave unnaturally due to high stress levels in their captive environment, possibly making it difficult to infer biologically relevant data as observed in their natural environment [34]. One method to complement animal experimentation is to utilize physical models (robots).

In recent years studies using physical models to investigate animal locomotion have multiplied [41, 10, 43]. The advantage of using a robotic model as opposed to an animal is the ability to simplify the model to focus on key morphological and kinematic features [41]. Additionally, robotic models can be systematically and precisely controlled over a large range of parameters. Various robots have been used successfully in studying locomotion on rigid surfaces, such as RHex, iSprawl and Whegs [56, 40, 58], or granular media, such as Sandbot [43].



**Figure 10:** A) Front view picture of FBot illustrating the body, flippers and tracking dots.  
B) Inset: Picture of FBot on a beach environment.

Our research on sea turtle hatchlings in the field [45] motivates us to build a sea turtle inspired physical model, FlipperBot (FBot) Figure 10. FBot allows us to test hypotheses beyond the capabilities of animal experimentation, like variations in running frequencies or limb kinematics. FBot is designed to incorporate features of sea turtle locomotion. Nevertheless, it is not limited to solely mimic sea turtle locomotion but rather is a model for fin and flipper locomotion on granular media. Table 2 displays a comparison between sea turtle morphological features and FBot, demonstrating similarities and differences between the biological organism and the physical model. FBot is run on poppy seeds, which prevents jamming of the motors that can be caused by sand particles.

**Table 2:** Comparison chart between sea turtles and FBot

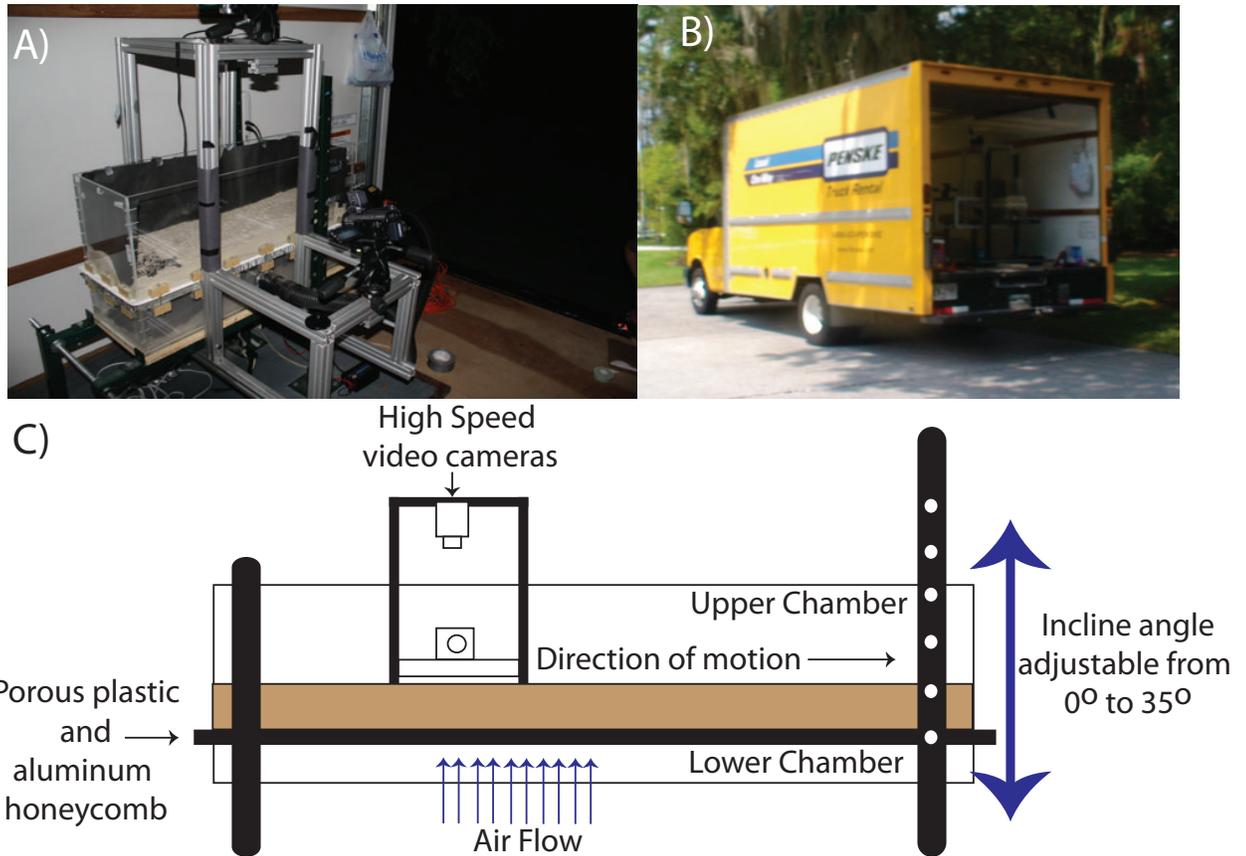
Category	Sea turtle	FBot
Weight	0.02 kg	0.4 kg
Body length	6-8 cm	20 cm
Pectoral flipper length	3.5 cm	7 cm
Pelvic flipper length	2 cm	N/A
Gait	Symmetrical/Alternating	Symmetrical
Wrist	Yes	Yes

### 1.5.2 Fluidized bed trackway

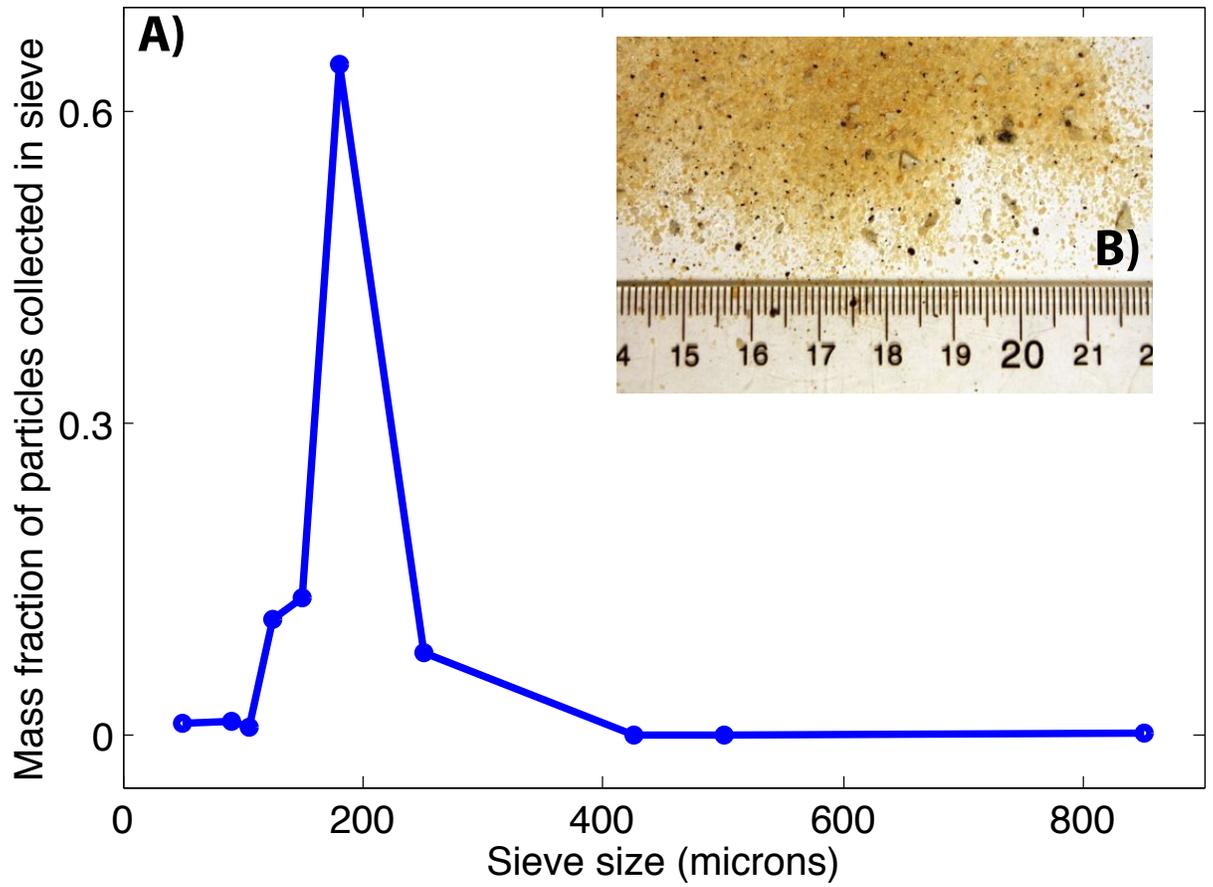
Due to the complexity of natural beaches, we built a fluidized bed trackway for field studies, Figure 11 [43]. The apparatus is used to mimic the natural beach environment by controlling for material compaction and incline angle. The bed is portable and can be transported in a small moving truck to the beach.

The experimental setup consists of two plexiglass chambers (86cm  $\times$  65cm  $\times$  20 cm), divided by a layer of porous plastic and aluminum honeycomb pressed between the chambers. The upper chamber contains dry sand collected on Jekyll Island, Figure 12. Attached to the lower part of the bed is a shop vacuum (Shop-Vac) blowing air into the chamber, which is distributed through the layer of plastic and aluminum and evenly fluidizes the material in the upper chamber.

Systematic control of the volume fraction of the medium [50] is achieved by varying



**Figure 11:** A) Picture taken on Jekyll Island, GA (study field site), showing the frame holding the plexiglass bed, filled with sand. B) Illustration emphasizing the plexiglass bed with a porous plastic and honey comb aluminum bottom. Air is directed through the porous plastic and aluminum honeycomb. The frame holds two high speed cameras recording the animals in their direction of motion. Trackway is adjustable from  $0^{\circ}$  to  $35^{\circ}$ .



**Figure 12:** A) Graph showing the fraction of mass of particles collected in various sieve sizes. B) Natural distribution of Jekyll Island sand, photo courtesy Nick Gravish.

the air flow. Flow above the onset of fluidization generates loosely packed sand states. Closely packed sand states are created by vibrating the fluidized bed using an off-axis motor attached to the underside of the apparatus. The packing state of the media is set prior to placing the animal on the sand trackway. The air flow is off during all animal trials. Incline angle can be varied on the trackway by tilting it to predetermined settings, varying from  $0^\circ$  to  $35^\circ$ . A frame holds the fluidized bed and two high-speed cameras, equipped with infrared lights, (Sony Handycam, 250 fps) recording dorsal and lateral images.

### **1.5.3 3-D tracking**

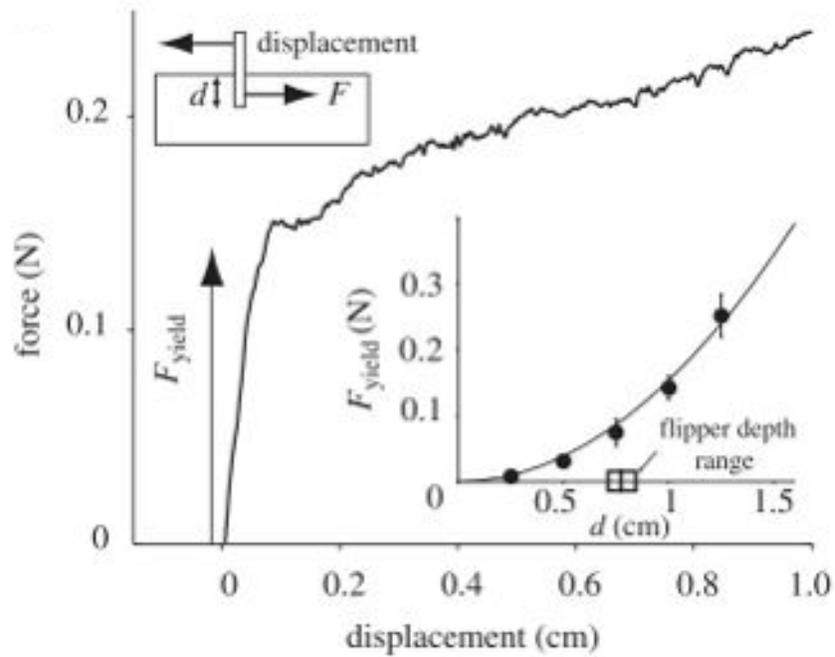
Animal and robot data was recorded using high-speed camera imaging. Markers were attached to the carapace of the hatchlings and the body of the robot. We use DLT, an algorithm to transform two-dimensional (2-D) coordinates of an object in multiple camera views to three-dimensional (3-D) coordinates, using a set of calibration points whose spatial locations are known (calibration cube). Using a software package, DLTcal3 and DLTdv3 (courtesy of Ty Hedrick [27]), we analyze the data using Matlab (Matlab 2009). We utilize a custom calibration cube (courtesy Chen Li), which we set in the field of view of the high-speed cameras, take still images and using our transformation matrix (via DLTdv3) we are capable of obtaining 3-D coordinates.

Robot data was tracked using a custom Labview program, which allowed for simultaneous video image acquisition and 2-D tracking (courtesy Nick Gravish).

### **1.5.4 Physics measurements with flat paddle-like intruder**

Two separate physics experiments were conducted. First, a flat paddle intruder was used to determine material properties of Jekyll Island sand. Second, a similar flipper-like intruder was used to understand the penetration and drag created when stepping into poppy seeds.

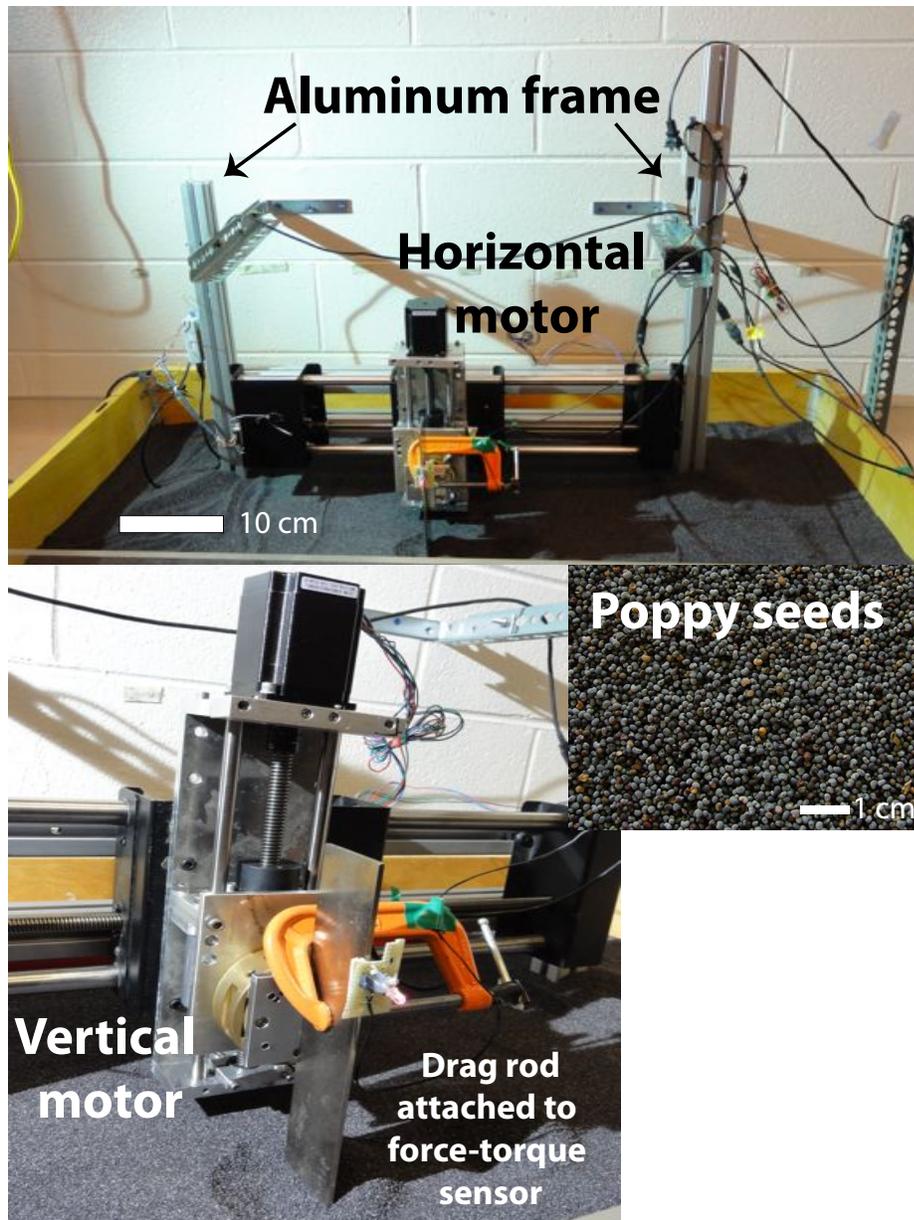
We performed laboratory measurements of a model flipper (flat, paddle-like intruder) to estimate thrust forces. The model flipper consisted of a thin (1.45 mm) aluminum plate 3 cm long (comparable to flipper length) that was inserted into the Jekyll Island sand, Figure 13. Upon insertion into the media it was dragged a distance of 5 cm. Calibrated strain gauges fixed on the model flipper provided force measurements during drag. Displacement



**Figure 13:** Graph showing yielding properties of granular media during drag of a flat, paddle-like appendage. Drag force versus displacement shows rapid rise in force (the yield force  $F_{yield}$ ) for small initial displacement. Inset: quadratic dependence of  $F_{yield}$  on insertion depth.

was controlled by a stepper motor and lead-screw. Force data was sampled at 1 kHz.

We used measurements of penetration and drag to estimate interaction effects during force production in granular media (poppy seeds) due to disturbed material. The setup consisted of an aluminum frame holding two linear motors set in a poppy seed test bed. One motor moved horizontally to the bed, the second motor moved vertically. Force was measured using a force-torque sensor attached to the vertical motor. A model flipper (width = 3 cm, height = 20 cm) was clamped to the force-torque sensor and used to penetrate (inserted to 3 cm) and drag (3 cm) through the material Figure 14.



**Figure 14:** Depiction of penetration and drag experimental setup. Aluminum frame holds two linear motors (horizontal and vertical). Drag rod is attached to force-torque sensor. Rod is inserted and dragged through poppy seeds to mimic a step profile as observed from FBot.

## 1.6 *Physics of granular media*

### 1.6.1 Physical properties

Granular media is defined as a collection of discrete particles that interact through dissipative, repulsive contact forces [38]. Examples of granular media include, but are not limited to, sand, debris, snow, or loose materials on forest floors [16]. In order to locomote on granular substrates, animals use their limbs to intrude into the material, generating thrust forces. As has been shown in previous research, granular media are governed by  $F_{yield}$  [45] (force per unit area at which non-reversible material deformation occurs). For a given geometry, for forces below  $F_{yield}$  the material behaves like a solid, while above  $F_{yield}$  the material flows like a fluid [45] Figure 13. The  $F_{yield}$  increases as the square of the penetration depth [45] Figure 13. This suggests that small changes in insertion depth affect locomotor performance, with a deeper insertion depth allowing for greater thrust generation during forward movement.

Granular media can be controlled by setting the volume fraction [50]), to mimic natural environments that animals encounter.

$$\phi = \frac{V_{solid}}{V_{occupied}} \quad (1)$$

In nature, the volume fraction of dry granular media ranges from  $\phi = 0.55$  to  $\phi = 0.64$  [15]. Volume fraction is sensitive to small percent changes [59]. A foot interaction with granular media deforms the material surface creating a crater, which is contrary to running on hard ground where no material deformation occurs. Disturbed ground can lead to a decrease in locomotor performance as has been demonstrated in Sandbot [43]. A robot tested on granular media showed that during penetration into previously disturbed ground the step length decreased, leading to failure at subsequent steps [43].

Although level ground in nature is common, many environments such as the beach have varying incline angles. Granular substrates on an incline are more prone to yielding than on level ground and further complicate limb-ground interactions [14]. Therefore it is important for us to understand the physical properties of granular media in order to understand the ecology of the animals that live within it.

### 1.6.2 Environmental and anthropogenic effects on beaches

Beaches are exposed to environmental as well as anthropogenic factors that alter their shape. The east coast of the US is identified as a major rookery for our study animal, the loggerhead sea turtle. These beaches are exposed to high wave action causing substantial erosion [23]. Winds, called the westerlies, govern the wave pattern across the Atlantic ocean, which depend on wind speed, distance over which the wind blows, and the duration that the wind blows [52]. These factors contribute to a higher ocean level and stronger currents towards the eastern coast of the US causing substantial beach erosion [52].

This results in concern for the home owners owning properties close to the beach that are threatened to be destroyed by erosion [23], leading to expensive beach renourishment projects pioneered by the government in order to preserve human habitats [66].

Renourished beaches have been shown to have negative ecological effects on sea turtle nesting and hatchling development [62]. This results in adult sea turtles actively avoiding renourished beaches for several nesting seasons [55, 62]. Hatchlings experience negative effects on their physiological development [48], demonstrating a decrease in swimming stamina when reared in nests stemming from renourished beaches. The conservation needs of these species demand better understanding of animal and environment interactions.

## 1.7 *Specific aim*

The overall objective of this dissertation is to discover principles of fin and flipper locomotion on granular media. To achieve this goal, we integrate biological, robotic and physics studies, with specific aims summarized below:

### **Biological studies:**

- Conduct a field study of hatchling loggerhead sea turtle locomotion on level ground granular media, by using high-speed cameras to capture kinematics in a controlled beach mimic (fluidized bed trackway), **Chapter II**.
- Use a fluidized trackway bed to measure the impact of granular compaction and angular incline on performance of hatchling sea turtle locomotion in the field, using high-speed imaging to capture the three-dimensional kinematics during running, **Chapter IV**.

### **Robotics study:**

- Develop and use a sea turtle bio-inspired physical model to test principles of fin and flipper locomotion on granular media in a controlled laboratory environment using high-speed camera imaging, **Chapter III**.

### **Physics studies:**

- Use a flat paddle to mimic a fin or flipper and measure the intrusion and drag force through granular media to determine principles governing the limb-ground interaction, **Chapter II and III**.

## CHAPTER II

# PRINCIPLES OF FLIPPER LOCOMOTION ON GRANULAR MEDIA ON LEVEL GROUND OF THE LOGGERHEAD SEA TURTLE HATCHLING (*CARETTA CARETTA*)

### *2.1 Summary*

Biological terrestrial locomotion occurs on substrate materials with a range of rheological behavior, which can affect limb-ground interaction, locomotor mode, and performance. Surfaces like sand, a granular medium, can display solid or fluid-like in response to stress. Based on our previous experiments and models of a robot moving on granular media, we hypothesize that solidification properties of granular media allow organisms to achieve performance on sand comparable to that on hard ground. We test this hypothesis by performing a field study examining locomotor performance (average speed) of an animal that can both swim aquatically and move on land, the hatchling Loggerhead sea turtle (*Caretta caretta*). Hatchlings were challenged to traverse a trackway with two surface treatments: hard ground (sandpaper) and loosely packed sand. On hard ground, the claw use enables no-slip locomotion. Comparable performance on sand was achieved by creation of a solid region behind the flipper that prevents slipping. Yielding forces measured in laboratory drag experiments were sufficient to support the inertial forces at each step, consistent with our solidification hypothesis.\*

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\*This Chapter is a published paper by Nicole Mazouchova, Nick Gravish, Andrei Savu, and Daniel I. Goldman, *Biology Letters*, 2010. [45]

## 2.2 Introduction

Locomotion [14, 2] on sand, a granular medium [38], is challenging because sand surfaces can flow during limb interaction and slipping can result, causing both instability and decreased locomotor performance [42]. An important parameter that governs interaction of limbs with sand is the yield stress, defined as the force per unit area at which non-reversible material deformation occurs [50]. For a given geometry, for forces below  $F_{yield}$ , material behaves as an elastic solid, while above  $F_{yield}$  material flows like a fluid dominated by friction between grains. This transition can have major effects on locomotor performance: our systematic studies of a bio-inspired physical model [a robot SandBot [43]] running on granular media revealed that, when limb kinematics were adjusted to utilize solidification features of the medium, the robot could achieve top speeds  $\sim 50\%$  of those for hard ground. Slight changes in frequency and gait parameters lead to fluidization of the medium by the limb and catastrophic reductions in speed to 1% of hard ground, predominantly due to decreased support forces and increased belly drag.

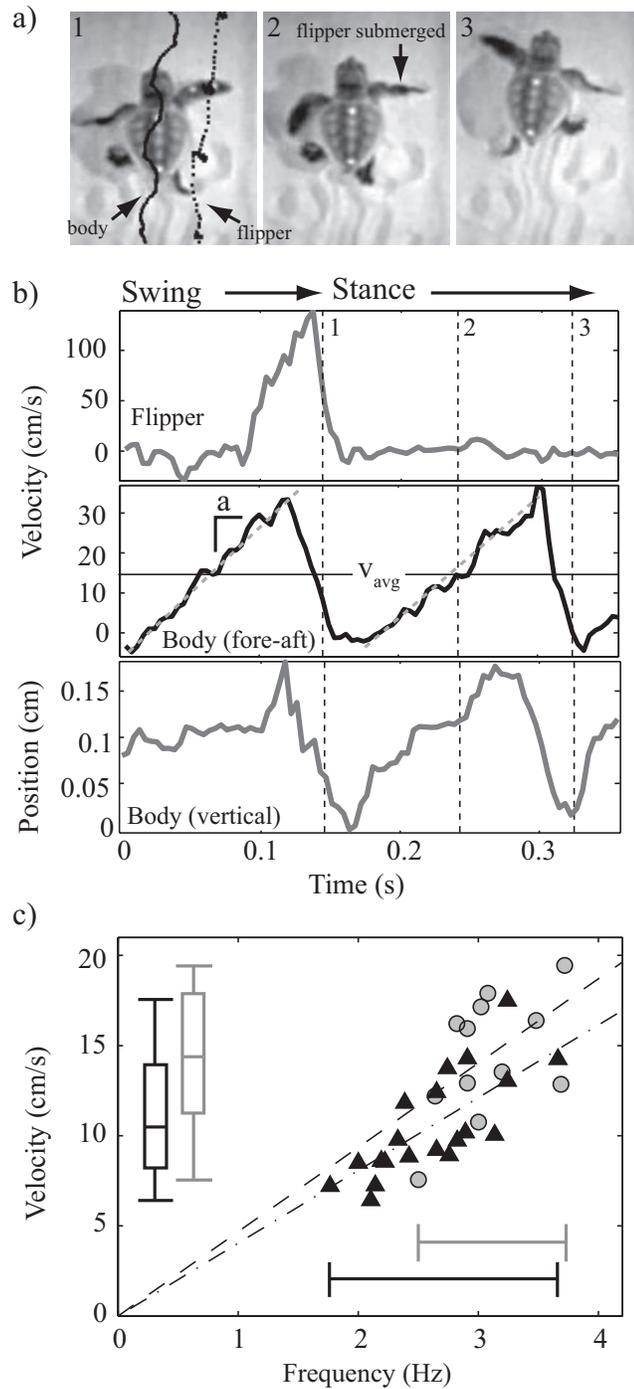
If organisms that move on sand exploit solidification properties of the medium, they could reap the benefits of anchored limb use during a step these include reduction in dissipative energy loss associated with ground fluidization [42] and slipping. We hypothesize that organisms that move on sand can achieve performance comparable to that on non-yielding, rigid ground (which we assume provides the opportunity for maximal performance), by utilizing the solid properties of the granular media during stance. We test this hypothesis in an aquatic animal, the hatchling Loggerhead sea turtle (*Caretta caretta*), that must perform well on land to reach the ocean and avoid predation. Periodically, adult females travel to their natal beaches [75] emerging from the sea to nest on land. After hatching, juveniles (hatchlings) climb from the nest and, travel distances up to several thousand body-lengths (BL) at speeds of several BL/sec (personal observation). In the water they swim at average speeds of 5 BL/sec using their aquatically adapted paddle-like flippers to generate hydrodynamic lift and thrust [75]. Although flippers are used on land for a tiny fraction of their lives [31], they enable excellent mobility over dune grass, rigid obstacles, and sand of varying compaction and moisture content.

Aerial and aquatic locomotive reaction forces (e.g. thrust and lift) generated through interaction of wings and flippers can be analyzed in detail through solution of the Navier-Stokes equations [64]. Equivalent mechanisms have not yet been described and analyzed at the same level for terrestrial locomotion on granular media (and other flowing terrain), in part because comprehensive governing equations do not exist [38]. However, empirical models can function well [44, 43]. In the SandBot experiments, a simple granular penetration model explained running speed versus limb frequency [43]. Here we use an empirical model of flipper interaction to support our biological observations, and demonstrate that on loose sand turtles can achieve high performance by utilizing solidification features of the granular medium.

### 2.3 *Materials and Methods*

The study was conducted on Jekyll Island, GA, USA in cooperation with the Georgia Sea Turtle Center. In 2008 there was a total of 166 nests, of which 10 nests were tested ( $N_{sand}=18$ ,  $N_{sandpaper}=8$ ,  $N_{total}=26$ ) with turtle mass ( $19.5 \pm 2.2$  grams), body length ( $6.9 \pm 1.6$  cm), flipper length ( $3.5 \pm 0.9$ cm), and flipper width ( $1.3 \pm 0.2$  cm). Hatchlings (Video S1) were collected during natural immersion and tests were performed in a mobile laboratory containing a fluidized bed trackway [43] filled with dry Jekyll Island sand. The bed allows preparation of the sand in a reproducible loosely packed state; air flow was off during the experiments. A sandpaper board placed in the trackway was used to mimic hard ground. Two high-speed cameras (Sony Handycams, 240 fps under IR light) recorded dorsal (Fig. 1a) and lateral images. Natural and removable markers (located on the carapace and the mid-point of the flipper) aided tracking of movement. Three runs per animal, with up to five animals, were recorded in a two hour span. A run was considered successful if the animal took more than three steps such that cycle average velocity returned to within 35% of the preceding step. Hatchlings were released at their collection location.

We performed laboratory measurements on a model flipper to estimate thrust forces. The model flipper consisted of a thin (1.45mm) aluminum plate 3cm long (comparable to flipper length) that was inserted into the Jekyll Island sand to given penetration depth ( $d=0.25$  to  $1.25$  cm) and dragged at  $0.05$  cm/s over a distance of 5cm; as in other experiments [44], drag force was independent of speed up to 20 cm/sec. Calibrated strain gauges mounted to the model flipper provided force measurements during drag. Displacement was controlled by a stepper motor and lead-screw. Force data were sampled at 1kHz. Yield force of the media was determined from the y-intercept of a linear fit to the drag force after motion of the plate began (Fig. 2b).

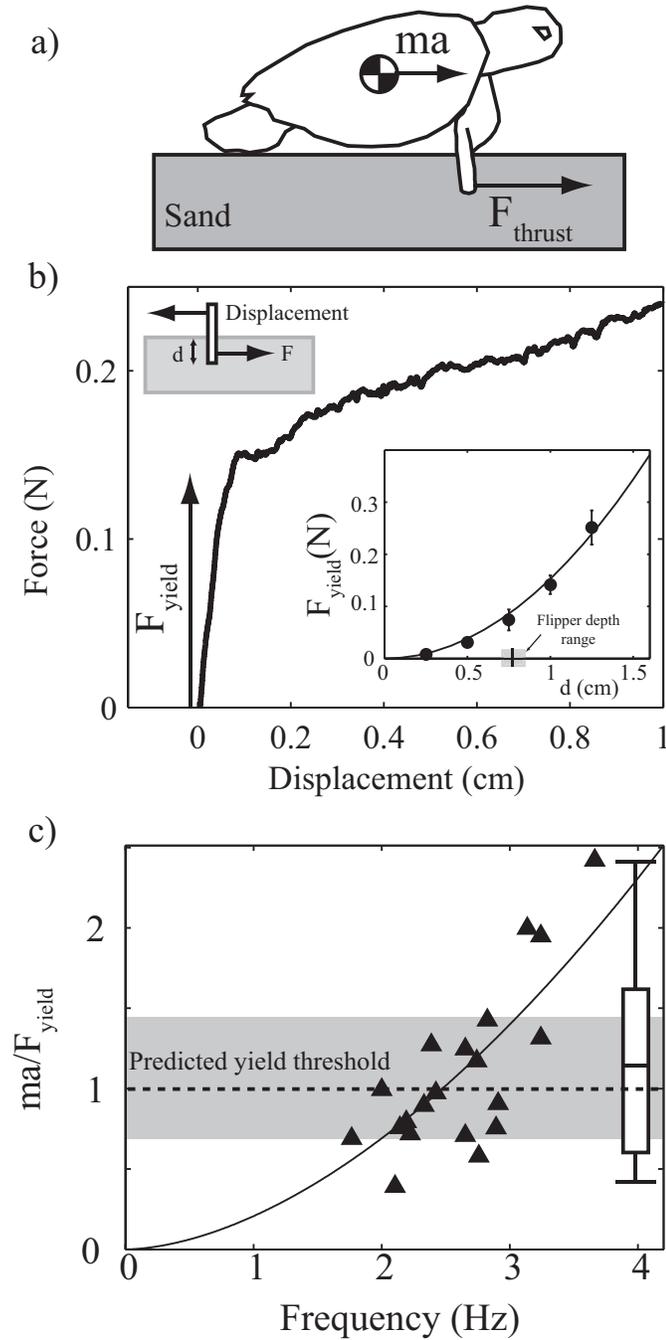


**Figure 15:** Sea turtle locomotion on sand. (a) Frame captures of tracked hatchlings on sand. (b) Flipper, body fore-aft velocity and vertical position over time; numbers correspond to frames in (a). (c) Velocity versus frequency for sand (black triangles) and hard ground (grey circles). Vertical bars show mean, s.d. and range of velocity while horizontal bars show range of frequency.

## 2.4 Results

Despite the different contact mechanics associated with sand and sandpaper, forward velocity of the body (close to center of mass)  $v_x$  vs time was similar on both substrates. At each step,  $v_x$  increased from zero to a maximum then dropped rapidly to zero again (Fig. 1b). Average speed on sand was reduced by 28% (better than SandBot performance loss) relative to hard ground, but maximal speeds were the same on both treatments. Turtles employed a diagonal gait [75] with average stance duty factors (DF) of  $0.66 \pm 0.05$ . During each stride, the body was lifted off the ground by an average of  $2.2 \pm 0.9$  mm, and then touched down at the end of the cycle (Fig 1b). Average  $v_x$  increased linearly with stride frequency  $f$  (in Hz) as  $\langle v_x \rangle = sf$  with similar stride length,  $s = 4.0 \pm 1.9$  cm on sand and  $s = 4.7 \pm 2.9$  cm on hard ground;  $s$  was significantly different from 0 for all treatments ( $p < 0.0001$ ) and the slope of the regressions were not statistically different ( $p > 0.05$ ). Average inertial force ( $ma$ ) on sand increased with frequency ( Fig. 2c). Limb kinematic measurements revealed that the angular extent of the shoulder excursion did not depend on the treatment (Sand:  $111 \pm 17^\circ$ , Sandpaper:  $114 \pm 6^\circ$ ;  $p > 0.05$ ) in accord with the derived stride length.

On sand, at touchdown, pressure owing to the thin (approx. 2 mm wide) edge of the flipper exceeded the vertical yield stress and it penetrated into the sand. The limb (shoulder) rotated as the flipper penetrated until the flipper was perpendicular to the surface. The rotation served to lift (Fig. 1b) the body (see discussion of model below and in SI). During thrust, the portion of the flipper in the sand (approx. 3 cm long and 0.76 cm deep on average) at first remained perpendicular to the direction of motion (relative flipper surface-forward velocity angle during mid-stance was  $99.4^\circ \pm 16.9^\circ$ ) and later was adducted, as both the wrist and shoulder rotated and the body moved forward and upward (Video S2). On sandpaper a claw at the wrist engaged irregularities and propelled the animal forward; during thrust the shoulder rotated towards the body and the wrist did not bend keeping the limb fully extended. A tracked marker on the mid-point of the flipper (Fig. 1a,1b) demonstrated that limb slip was minimal on both substrates (net displacement of  $> 1$  flipper-width in only 2.6% of steps on sandpaper and 5.6% on sand) during forward movement, consistent with equivalent stride lengths.



**Figure 16:** Model of locomotion on sand: (a) flipper ground reaction force  $F_{thrust}$  and inertial force  $ma$ . (b) Drag force versus displacement shows rapid rise in force (the yield force  $F_{yield}$ ) for small initial displacement. Inset: quadratic dependence of  $F_{yield}$  on insertion depth  $d$ . The bar shows range of measured flipper depths. (c) Normalized turtle inertial force ( $ma/F_{yield}$ ) versus limb frequency (fit curve is  $ma/F_{yield} = cf^n$ ;  $c = 0.21$ ,  $n = 1.74$ ,  $r^2 = 0.65$ ). Dashed line indicates predicted yielding threshold for a single flipper inserted to average measured turtle depth (grey region is yield for mean  $\pm$  s.d. depth).

## 2.5 Discussion

Our results imply that speeds on sand and hard ground are similar, because for both treatments limbs do not slip during locomotion, stride length is constant, and  $\langle v_x \rangle = sf$ . On hard ground no-slip is maintained by a claw engaging irregularities. On sand entirely different mechanics account for no-slip: in successful runs, material behind the flipper did not move during the thrust phase, supporting the hypothesis that the turtle advances via solidification of the material behind it.

Forward movement of the body on sand without slipping of the flipper requires that net thrust forces  $F_{thrust}$  remain below the yield force of the granular medium,  $F_{thrust} < F_{yield}$ . We assume that the mechanics of the large front flipper (maintaining surface normal vector parallel to  $v_x$ ) produces the dominant contribution to  $F_{thrust}$ . Observation of the smaller hind limbs indicate that at initiation of stance the foot remains plantar and above the surface during the entire step, presumably contributing to lifting the body and less to thrust (force measurements in a different turtle species [75] shows evidence that they are used for lifting although no force data exists for Loggerheads). Since the animal lifts at each stride using both hind and fore-limbs (see Fig. 2a), we assume that the plastron is not in contact during the thrust phase and thus body drag is not significant.

Therefore  $F_{thrust}$  need only generate the inertial forces (mass  $x$  acceleration;  $ma$ ) required to accelerate the animal from rest to its maximum velocity (Figs. 1b,2a). As plastron elevation removes drag during the stride, locomotion is governed by  $F_{thrust} = ma$ . We estimate average inertial forces from linear fits of the body velocity during the acceleration phase of the movement (Fig. 1b, and Fig. 2b). Since  $v_{peak} = 2.88 \langle v_x \rangle$  ( $r^2 = 0.88$ ), and  $v_x$  is proportional to  $f$  we expect average inertial forces ( $ma \propto v_{peak} f$ ) during a step to increase as  $f^2$  (see Supporting Material). The data are consistent with this prediction (Fig 2c).

We estimated ground reaction forces from the drag of a model flipper. Drag force on a plate (Fig. 2b) increased sharply within the first millimeter of displacement. We identify the force at the end of this sharp increase as  $F_{yield}$ , since it is generated in a short distance and no large scale flow of material occurs.  $F_{yield}$  increases as the square of the penetration

depth (Fig 2b) and linearly with plate width [70]. The existence of  $F_{yield}$  thus provides a possible mechanism for solidification and generation of thrust forces on sand without slipping, by utilization of the solid properties of the media. If  $ma < F_{yield}$  (or  $ma/F_{yield} < 1$ ), material solidifies during the power stroke.

Choosing  $F_{yield}$  at the average measured flipper insertion depth  $d=0.76 \pm 0.13$  cm reveals that the majority of the derived fore-aft acceleration data satisfy the criterion  $ma/F_{yield} < 1$  (Fig. 2c) and thus indicates that the material can remain solid with use of a single flipper. Only at the greatest accelerations does the model predict slip. We do not observe limb slip in these runs, and speculate that, at these large accelerations, the hind limb contributes by friction from its plantar surface (we estimate that if the hind flipper supports half the turtles weight on sand, with a measured surface friction coefficient of  $\mu=0.6$ , the thrust/ $F_{yield}$  from friction  $\mu mg/(2F_{yield}) \approx 0.6$  would be sufficient to account for the largest observed inertial forces). Force platform data are needed to determine the individual contributions to thrust from fore and hind limbs. In addition, we hypothesize that  $F_{yield}$  can be increased if limb rotation during entry (which could enhance normal loading and material compaction) is considered; further physics experiments are needed to test this hypothesis.

Our model reveals that a major challenge for rapid locomotion on sand is the balance between high speed, which requires large inertial forces, and the potential for failure through fluidization, which can occur when inertial forces (which increase sensitively like  $f^2$ ) exceed  $F_{yield}$ . In the SandBot experiments, failures through fluidization could be induced by reduction of  $F_{yield}$  through changes in material compaction [43]. Since  $F_{yield}$  depends on many factors, including particle properties and hill angle, it may be ecologically important to examine performance (and possible locomotor failures) as a function of substrate properties like beach topography (inclines) or sand type (e.g. through renourishment [62]).

In conclusion, high performance locomotion on yielding substrates such as sand can be achieved using the solid-like response governed by the yield stress. Further biological studies and physical models of turtles (and other organisms) are required to determine if and how organisms control limb movements to remain below the yield stress on granular media. More broadly, to discover principles of passive and active nervous and mechanical

system control [51], as well as to understand energetic costs [42] in locomotion on and within realistic terrain, will require advances in theory and experimental characterization of complex media. Otherwise we must continue to rely on empirical force laws specific to particular geometries, kinematics and granular media.

## CHAPTER III

### TESTING OF A SEA TURTLE INSPIRED PHYSICAL MODEL, FLIPPERBOT, ON GRANULAR MEDIA TO UNDERSTAND PRINCIPLES OF FLAT-PADDLE LIMB KINEMATICS IN YIELDING SUBSTRATES

#### *3.1 Summary*

Animals, like sea turtles, that must locomote at the water–land interface use flippers for swimming in water and crawling on a sandy beach environment. To reveal locomotor principles of flipper–based interaction with granular media, we study the detailed mechanics behind the success and failure of a hatchling sea turtle–inspired robot (19 cm, 775 g) during quasi–static movement on a granular medium of poppy seeds. The device propels itself with a symmetric gait using two servo–motor driven limbs consisting of flat–plate flippers with passively flexible or rigid wrists. For a wide range of conditions a flexible flipper achieves a greater distance traveled per step than a rigid flipper. For the flexible flipper, at each step the limb penetrates vertically into the medium; once weight balances penetration force, the body lifts. The flipper remains in place, and as the limb retracts the robot is geometrically translated forward. During the step the belly remains lifted off the ground minimizing drag. In contrast, during rigid flipper locomotion, the penetration phase is similar, but the material begins to yield during retraction of the flipper as it slips through the material. Associated with the yielding, the body drops immediately during the step, and drag force increases. The rigid flipper creates a larger region of disturbed material than the flexible flipper. If subsequent steps interact with the previously disturbed ground, forward progress per step is decreased resulting in failure within a few steps. Measurements of intrusion force on a flat plate (3 cm wide) reveal that the penetration resistance (and thus lift) on a second intrusion decreases as the intrusion site approaches the site of first intrusion. Thus a combination of adequate distance, coupled with increased lift, and less disturbed ground

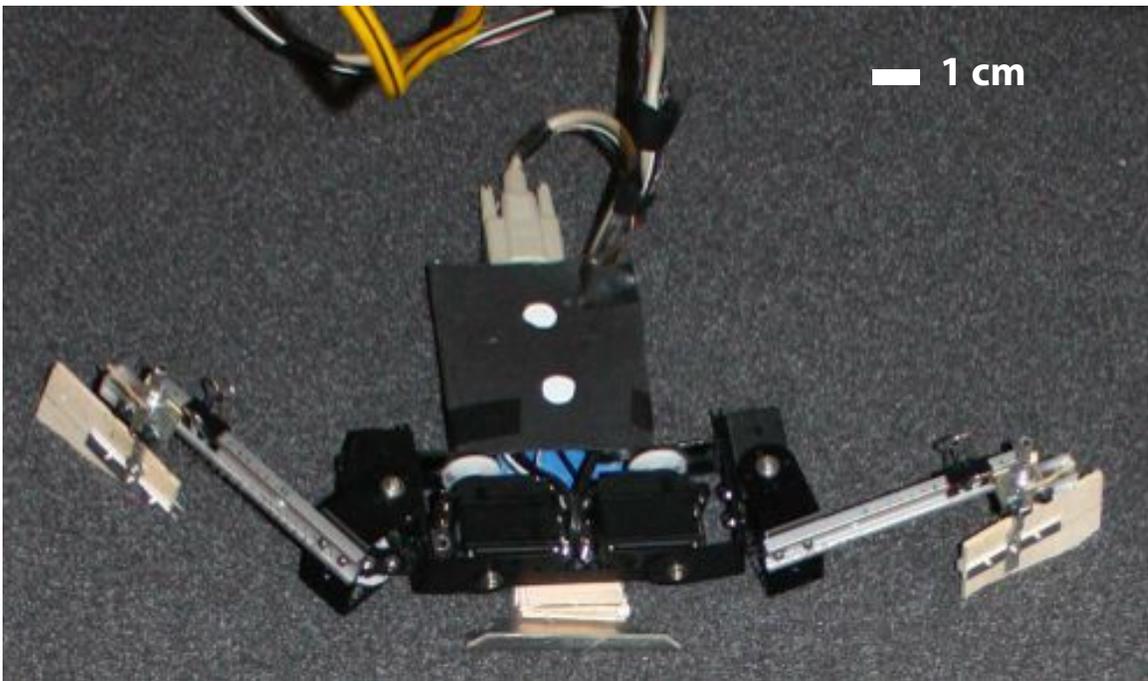
allows for successful performance in the robot model. We demonstrate that using a robot model is a valuable tool to investigate principles of flipper locomotion on granular media and in the future would like to expand its use to conservation of the species.\*

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\*This Chapter is part of a paper by Nicole Mazouchova, Matthew Jacobson, Azeem Bande–Ali, Paul Umbanhower, and Daniel I. Goldman, to be submitted to *Bioinspiration & Biomimetics* [46].

### 3.2 Introduction

Aquatic and terrestrial environments are complex, resulting in functionally diverse animals that swim, walk, run or burry in order to survive [13]. Research in bio-inspired robotics focuses on the functional principles of biological design and their validity in animal and physical model studies [41]. Bio-inspired robots such as AmphiBot, Snake Bot or RHex [10, 73, 41], are being used to study locomotor patterns during swimming, crawling or walking [56]. RHex was inspired by research on arthropod runners with the intent of uncovering the control architecture that enables rapid locomotion in complex terrestrial environments [41]. Although RHex was the first legged robot to achieve autonomous locomotion at speeds of  $\sim 1$  body length per second (bl/s) [56], its performance (speed) does not approach that of cockroaches ( $\sim 50 - 70$  bl/s) [65] or the tiger beetle ( $\sim 170$  bl/s) [39]. Nevertheless, studying physical models provides insight into the mechanics of motion beyond descriptive studies and helps generate quantitative hypotheses for integrated systems [41]. Legged robots locomote successfully over hard ground or uneven complex terrain, e.g. forest floor [8], however their performance on substrates such as rubble or sand can lead to failure [43].



**Figure 17:** FBot on poppy seeds.

Granular media (e.g. sand) can act as a solid or a fluid, when stress is applied [45]. Sandbot, a robot based on the design of Rhex, is used to study the sensitivity of a legged robot on granular media [43].<sup>†</sup> Locomotor performance depends on limb kinematics, morphology and the strength of the granular media [43]. Top speeds of  $\sim 50\%$  of those for hard ground are achieved, when the limb kinematics are adjusted to use the solid features of the medium [43]. Terrestrial organisms encounter granular media in rain forests, grasslands, mountains or deserts, however, even aquatic animals can be exposed to terrestrial media such as on the beach [24].

For example sea turtles, which emerge on sandy, ocean-facing beaches in order to lay eggs [24]. After their incubation and hatching period, young sea turtles will dig themselves out of the nest and walk up to several meters over yielding sand back towards the ocean [24]. Research on how animals with aquatically adapted appendages such as flippers, traverse on granular terrestrial environments is in its infancy [75, 45]. Previous research on loggerhead sea turtle hatchlings has uncovered trends in limb-ground interaction dependent on the granular compaction (ratio between the solid volume of the medium and the volume it occupies [2]) of the medium [45]. The flipper of the sea turtle is bent during locomotion on yielding substrates utilizing the solid features of the medium, which allows the animals to achieve comparable speeds on hard ground [45].

Through this research new questions arise, which lead to interest in understanding the principles that govern fin and flipper locomotion on granular media. We developed FlipperBot (FBot), a sea turtle inspired robot, to study these principles beyond the capacity of animal experimentation Figure 17. FBot is the first robot to employ flippers instead of legs, wheels or other appendages to interact with yielding terrestrial substrates. We test the effects of limb kinematics, and dynamics of FBot on granular media.

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<sup>†</sup>This robot was developed by Haldun Komsuoglu and Daniel E. Koditschek

### ***3.3 Materials and Methods***

#### **3.3.1 Body, electronics, power supply and motors**

FBot was built using an aluminum sheet as the body, Figure 18. Fixed to the body were four servomotors, that were used to mimic flipper motion and produce thrust. A servo control board was connected to the computer and programmed to control kinematics. Two masts equipped with light emitting diode lights (LED) for high-speed video tracking were mounted (Figure 18) on the body. The robot weighed 0.8 kg, was 20 cm long and 9 cm wide, and had a flipper span of 40 cm.

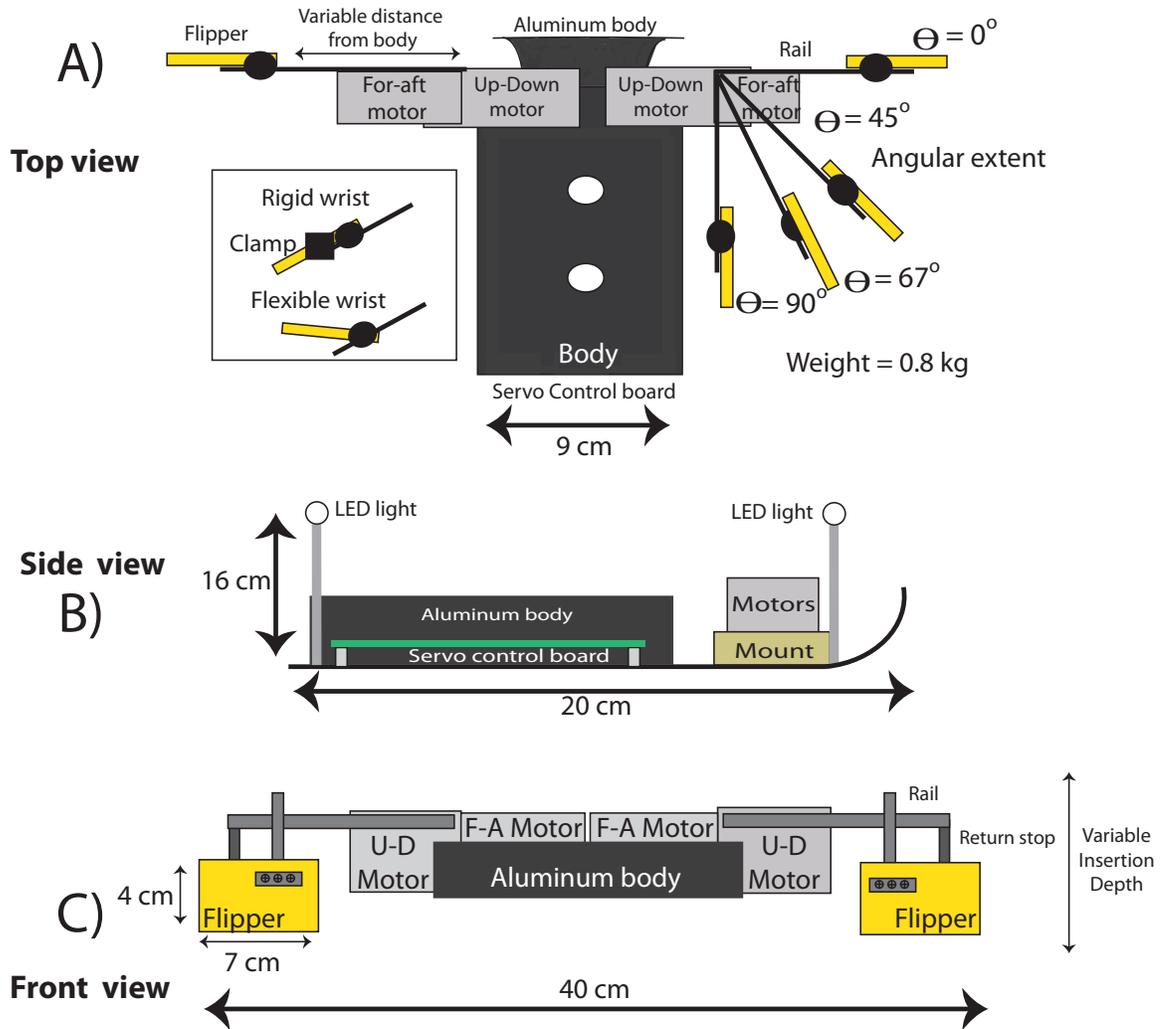
The aluminum body was flat-shaped, mimicking a sea turtle's plastron, with the front and side edges of the aluminum body bent upwards. The four servomotors (HiTec 5980SG) were mounted anterior to the servo controller, comparable in position to the pectoral flippers of a sea turtle. Two motors were set on the left and right lateral side of FBot, mimicking flipper-like movement; up-down motors moved the flipper vertically, and fore-aft motors moved the flipper horizontally, backwards and forward (18). The two lateral motors on each side of FBot moved in four distinct motor movements, see Appendix.

Two 16 cm masts topped with LED lights were mounted on FBot, one anterior of the servo motors, the second posterior behind the servo control board for side view tracking using a high-speed camera. Posterior to the servo motors the servo control board was covered by black material with two white plastic balls attached for top view tracking with a high-speed camera. All cables leading away from FBot were tied together with tape.

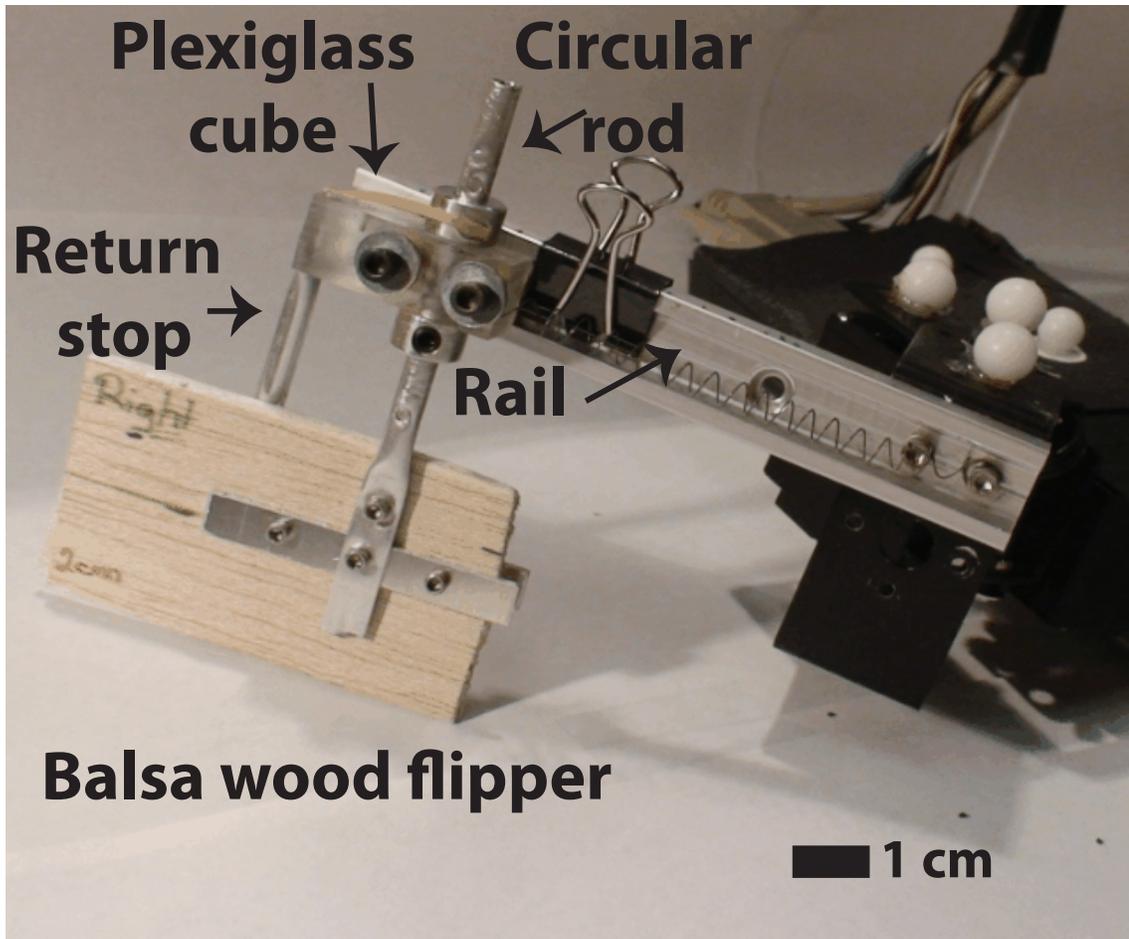
#### **3.3.2 Flippers**

FBot was equipped with two anterior, flipper-like structures (constructed from balsa wood to avoid additional weight to the distal end of the flipper) that were attached to the fore-aft servo motors via a rail Figure 18. The rail was designed to allow for the flipper to be positioned distal at various distances from the body. Attached to the rail was a plexiglass cube, holding a circular rod connecting the flipper to the rail Figure 19.

The rod could rotate 360° around its own axis within the plexiglass cube. The flipper attached to the rod was restricted by a spring (elastic band) to movements up to 90°

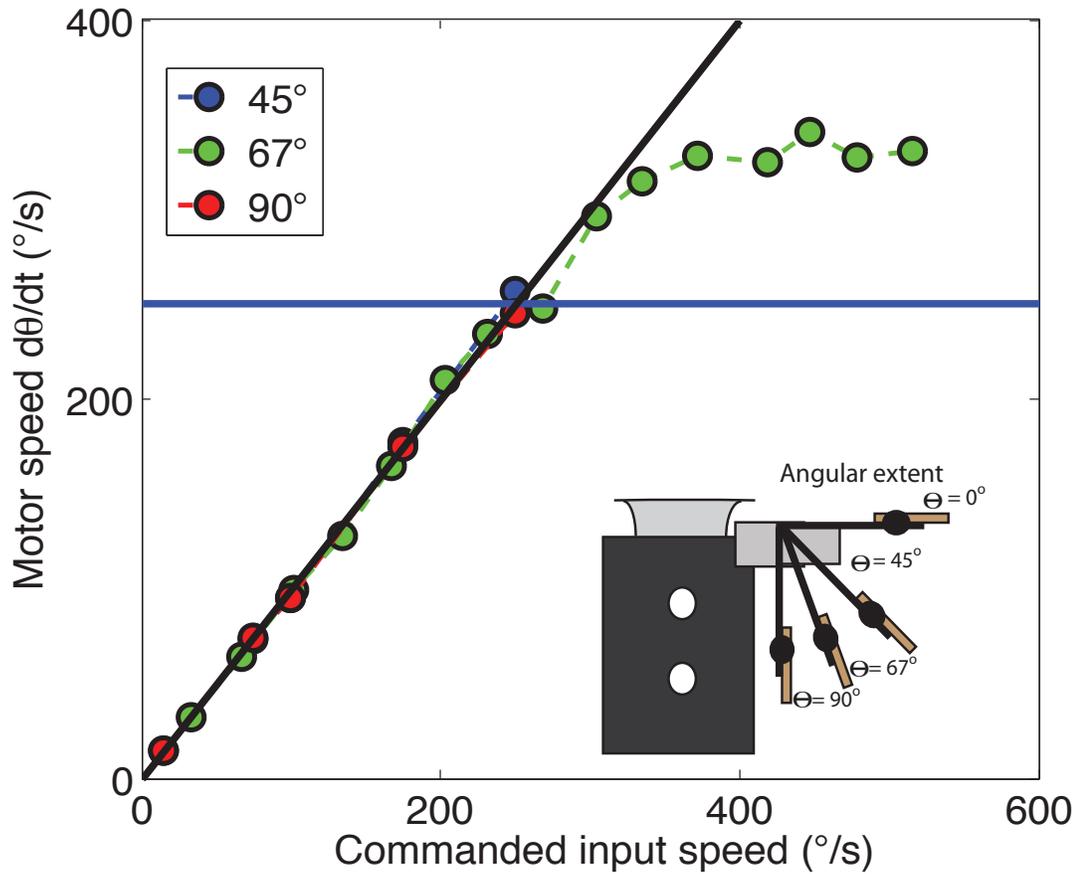


**Figure 18:** A) Top view of FBot: depicting servo–motor positions (two up–down motors, two fore–aft motors), servo control board (underneath of dark cover with two white dots for tracking) and angular extent of flipper–like appendage ( $\theta = 45^\circ$ ,  $\theta = 67^\circ$  and  $\theta = 90^\circ$ ) Inset: Box shows rigid and flexible wrist setup). B) Side view: FBot is 20 cm long, and contains two 16 cm masts with LED lights for tracking. C) Front view: Wing span (up to 40 cm) and insertion depth (3 cm) are adjustable, Flipper dimensions are 4 cm by 7 cm, flipper held in place by return stop attached to rail.



**Figure 19:** Right flipper showing rail holding plexiglass cube with circular rod. Balsa flipper is attached to the circular rod. Return stop is attached to rail.

perpendicular to the rail. The end of the rail contained a return stop, against which the flipper rested while it was not contacting the ground. FBot featured two types of wrist conditions: flexible and rigid wrist (Figure 18). A flexible wrist was achieved by allowing the flipper to passively rotate around its rod which was connected to the rail. For the rigid wrist an alligator clip was used to clamp the flipper to the return stop. Three angular extensions (angle traveled by the flipper during stance phase) had been chosen,  $\theta = 45^\circ$ ,  $\theta = 67^\circ$  and  $\theta = 90^\circ$  (Figure 18). Commanded input speed was tested versus motor speed to determine accuracy of motor movement and angle trajectory of flipper for given motor frequencies ( $\omega$ ), Figure 20. Insertion depth,  $d_{insert}$ , (distance the flipper was inserted into



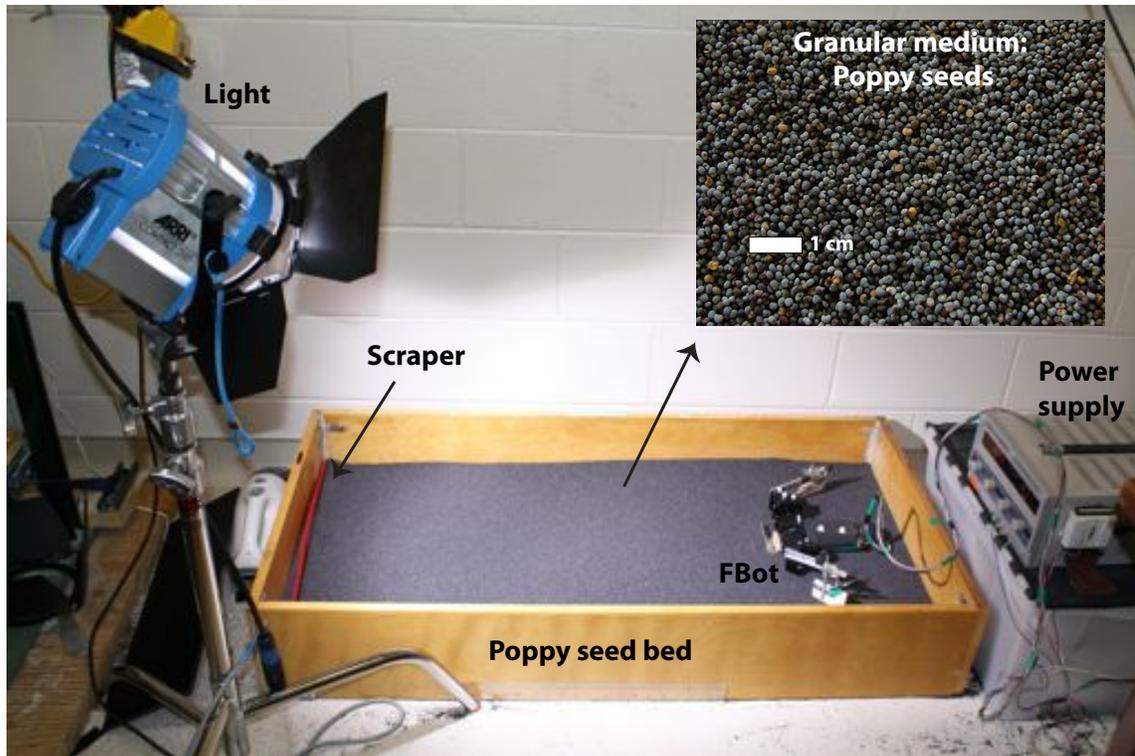
**Figure 20:** Motor speed versus commanded input speed for various angular extent. Inset: Top view of FBot with a depiction of angular extent.

the material below the belly of the robot) was set at 3 cm; this could be varied manually

by moving the circular rods position within the plexiglass cube (up or down), or through controlling the  $d_{insert}$  via computer, by changing the alignment of the motors in relation to the body ( $+1^\circ$  to  $-1.5^\circ$ , Figure 25)

### 3.3.3 Computer control and camera tracking

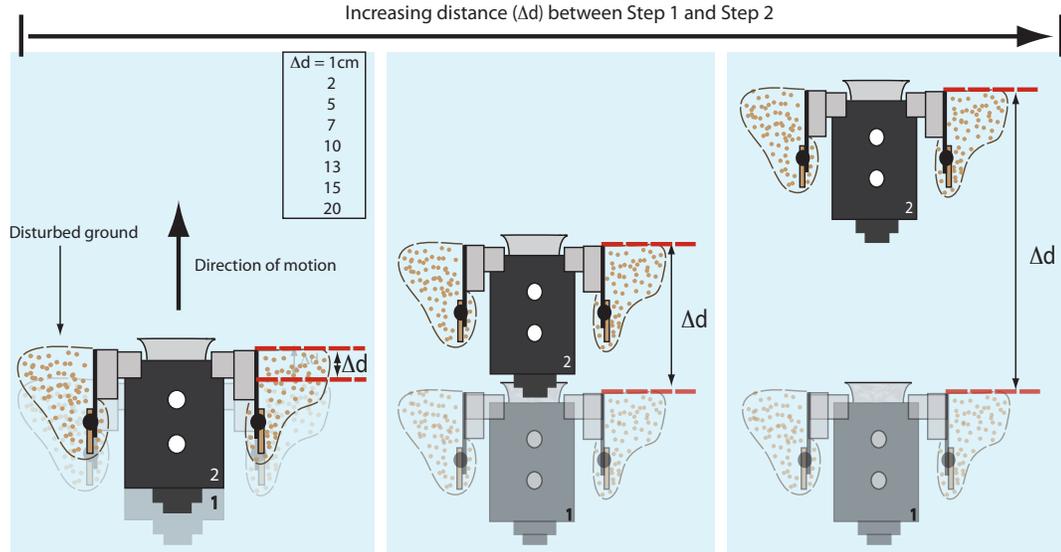
The experimental setup consisted of a bed ( $122\text{cm} \times 60\text{cm} \times 20\text{cm}$ ) filled with poppy seeds (grain diameter  $\sim 1\text{ mm}$ ) as poured ( $\phi = 0.605$ ), see Figure 21. Videos were filmed with one high speed camera (200 frames per second (fps), AVT Pike F-032 1/3 CCD Fire-Wire-B Monochrome Camera) from a horizontal or vertical view. The high speed



**Figure 21:** Experimental setup of the poppy seed bed depicting granular material, FBot, power supply and light.

camera was controlled through a customized LabView (NI LabView 2009) program with integrated tracking (courtesy Nick Gravish). FBot was computer controlled through a customized Python program (courtesy Matthew Jacobson). Data was analyzed using Matlab (MathWorks 2009).

### 3.3.4 Translation experiment

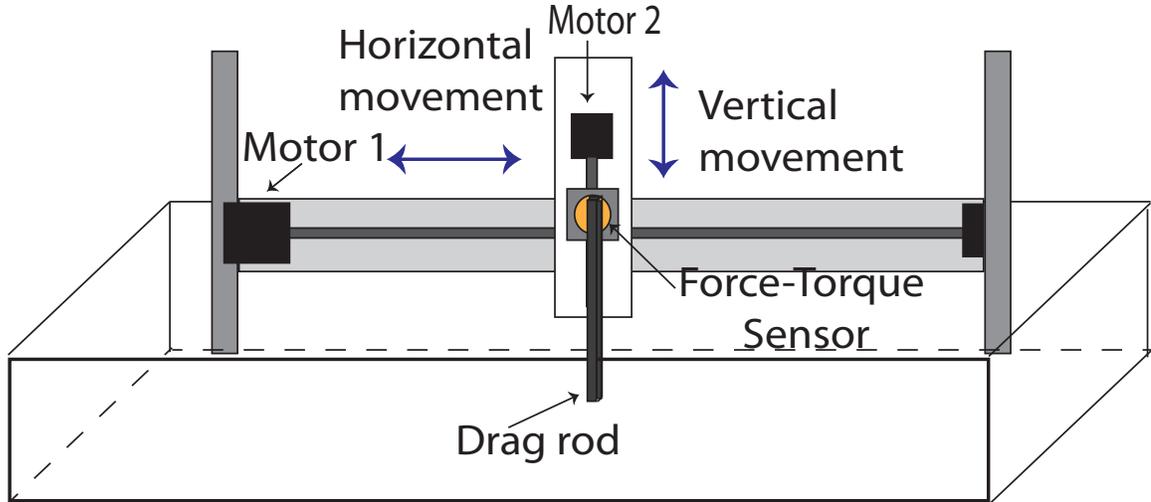


**Figure 22:** Translation experiment: Depiction of FBot taking step 1 (light grey) and subsequent step 2 (black). Distance between steps is increased by  $\Delta d$

To test for performance effects on FBot due to disturbed ground we setup an translation experiment, Figure 22. FBot was set into the poppy seed bed and controlled to run one step. A measuring tape was used to measure variable distances ( $\Delta d$ ) from the disturbed ground at step one, and FBot was moved manually a predetermined distance away from the hole.  $\Delta d$  moved manually varied from 1cm to 20 cm (1 cm, 2 cm, 3 cm, 5 cm, 7 cm, 10 cm, 12 cm, 15 cm, 17 cm, 20 cm). A second step was performed and the step distance advanced was measured.

### 3.3.5 Penetration and drag experiment

A penetration and drag experiment was setup using an aluminum frame (80/20) which held two linear motors, one setup to move horizontally the other to move vertically (Figure 23). The motors (Lin Engineering Nema 23) were powered by separate power supplies (Jameco 24V). Attached to the vertical motor was a force-torque sensor (ATI) capable of measuring forces in  $x$  (horizontal drag) and  $z$  (vertical penetration) direction. A flat stainless steel plate (width 3 cm, height 20 cm) was clamped to the force sensor and used to penetrate



**Figure 23:** Apparatus setup using an aluminum frame holding two linear motors (vertical and horizontal). A force–torque sensor is attached to the vertical motor. Drag rod is clamped to the force-torque sensor. Apparatus is setup over the poppy seed bed.

(distance = 3 cm) and drag (distance = 3 cm) through granular material. The voltage output during penetration and drag was recorded with a customized LabView program (courtesy Azeem Bandee–Ali) and converted to force via calibration. Data was analyzed using Matlab.

### 3.3.6 Experimental protocol

Prior to running FBot, the surface of the poppy seed bed was flattened and leveled with a scraper. To ensure repeatability, the surface was always prepared by the same researcher and tested with a level for surface control Figure 21. The high–speed camera was mounted either vertically or horizontally to the experimental setup. FBot was set into the poppy seed bed while ensuring that the cables were positioned behind the test apparatus. Both power supplies, for the servo controller and the motors, were set to their respective voltages (9V for servo controller, and 7V for servo motors). The Python program for controlling FBot and the Labview program for controlling the high–speed camera and automatic tracking were set to the test variables. For the following results,  $\omega = 30^\circ/\text{s}$  during stance phase. During a test run, the cables were held by a researcher to avoid drag.

### 3.4 Results

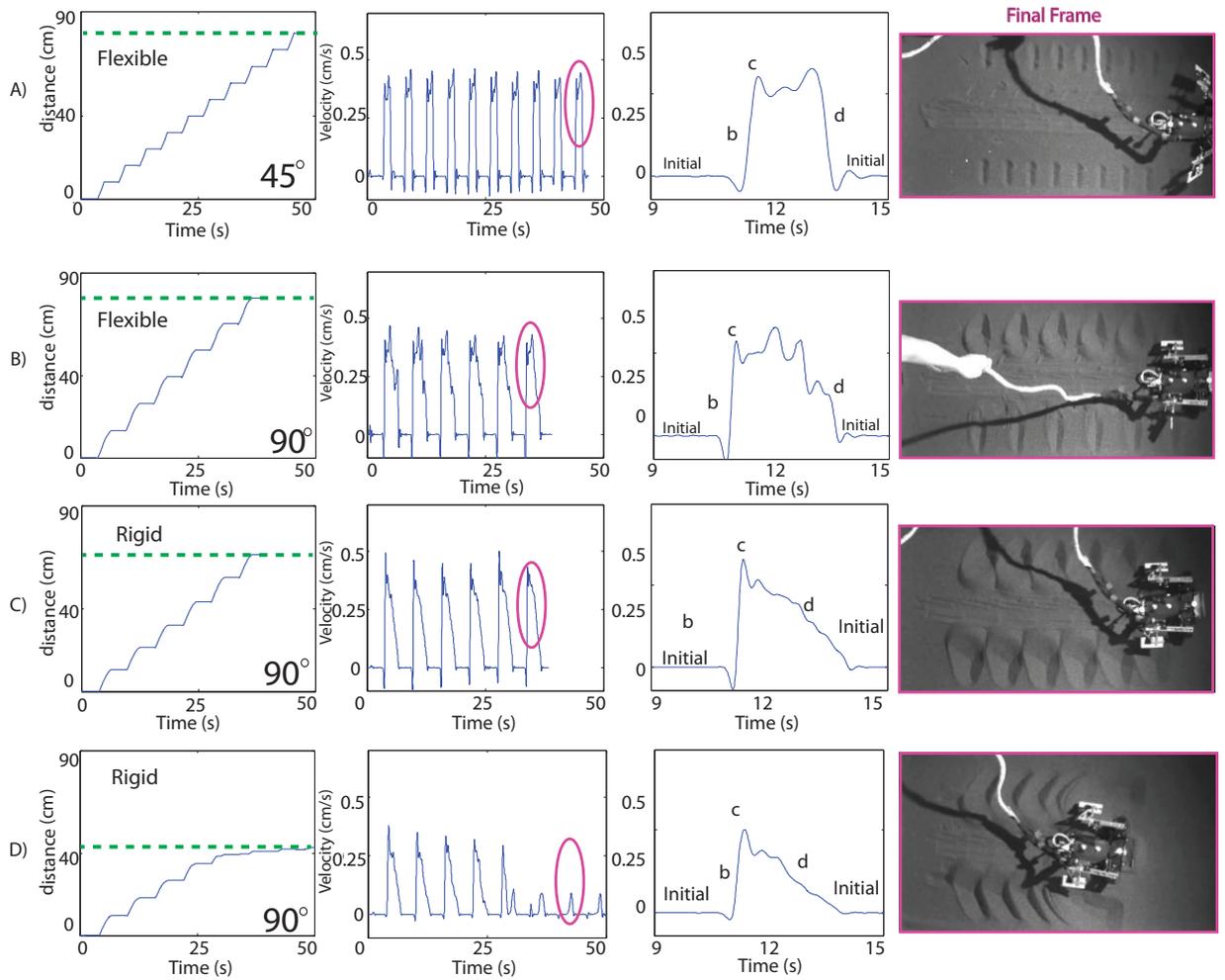
#### 3.4.1 Mechanics of FBot

FBot moved with a symmetrical gait, employing both flippers in parallel. Distance vs time profiles were extracted from tracking center of mass (COM). During body movement  $d$  increased, whereas during the flipper's swing phase  $d$  remained zero (Figure 24A).

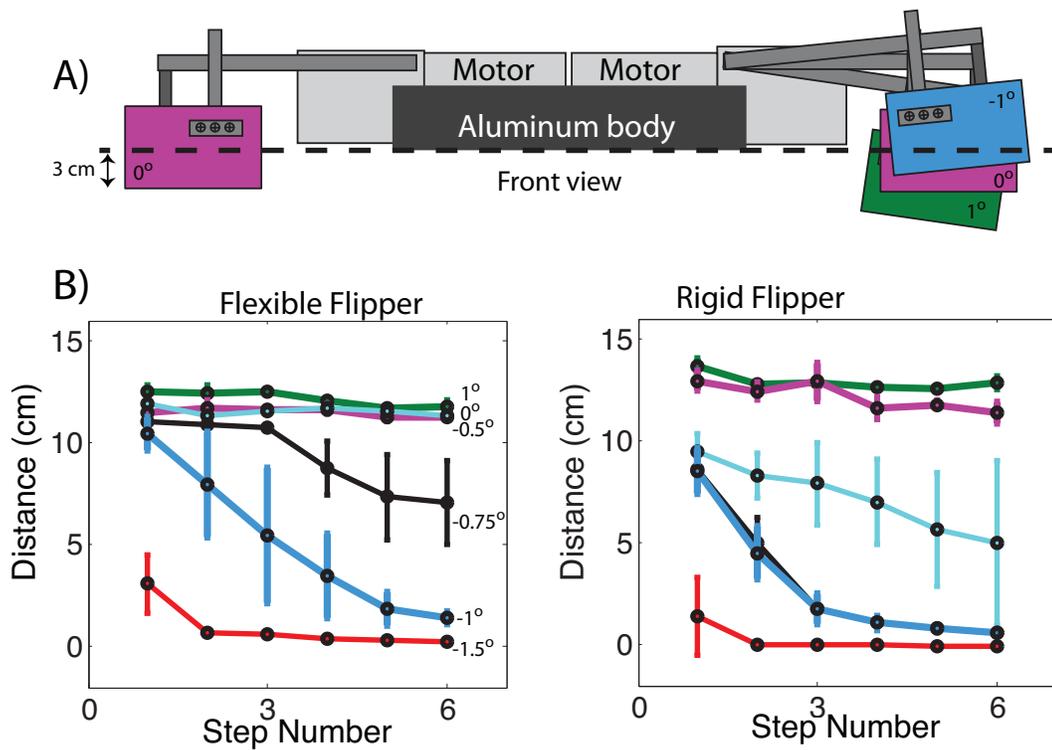
At  $\theta = 45^\circ$  using a flexible flipper the total distance achieved over 10 steps was 85 cm, the peak step velocity ( $v_{peak}$ ) = 0.45 cm/s at a  $\omega = 30^\circ/\text{s}$ . The speed profile of one step displayed an initial phase, followed by flipper insertion into the material (b); during stance phase the flipper remained vertically and horizontally anchored in the material (c), only moving the body forward (no slip locomotion). The flipper was moved out of the material (d) the body velocity returned to zero, during which no body movement occurred. At  $\theta = 90^\circ$  with a flexible wrist, the distance vs time profile looked similar to  $\theta = 45^\circ$  and reached a comparable total distance of 83 cm, with fewer steps (six steps). The  $v_{peak} = 0.45$  cm/s.

However, the single step profile at  $\theta = 90^\circ$  (Figure 24B) deviated during stance phase (d) from  $\theta = 45^\circ$ . During stance phase the flipper stayed vertically and horizontally locked until  $\theta$  passed  $67^\circ$ , at which the flipper was pulled to the body causing the flipper to slip towards the body. Using a symmetrical gait with a rigid wrist resulted in constant yielding of the flippers in the medium during stance phase. At  $\theta = 90^\circ$  using a rigid wrist (Figure 24C) the distance vs time profile increased similar to that of the flexible wrist, the total distance was reduced to 73 cm. The  $v_{peak} = 0.5$  cm/s and the single step profile clearly showed the constant yielding of the flipper Figure 24C. After insertion into the material (b), the velocity profile decreased (c) until the end of stance phase at which the body velocity returned to zero. A reduction in step length during distance vs time profile was observed at  $\theta = 90^\circ$  using a rigid wrist, Figure 24D, total distance = 44 cm over ten steps. The  $v_{peak}$  of FBot initially achieved comparable values of 0.45 cm/s ( $\omega = 30^\circ/\text{s}$ ), after five steps it decreased to  $v_{peak} = 0.15$  cm/s. The single step profile showed the initial insertion into the material (b), the reduced  $v_{peak}$  and a steeper decline of the velocity as the flipper was yielding the material (d).

Performance decrease in FBot Figure 24D, was achieved by decreasing the insertion

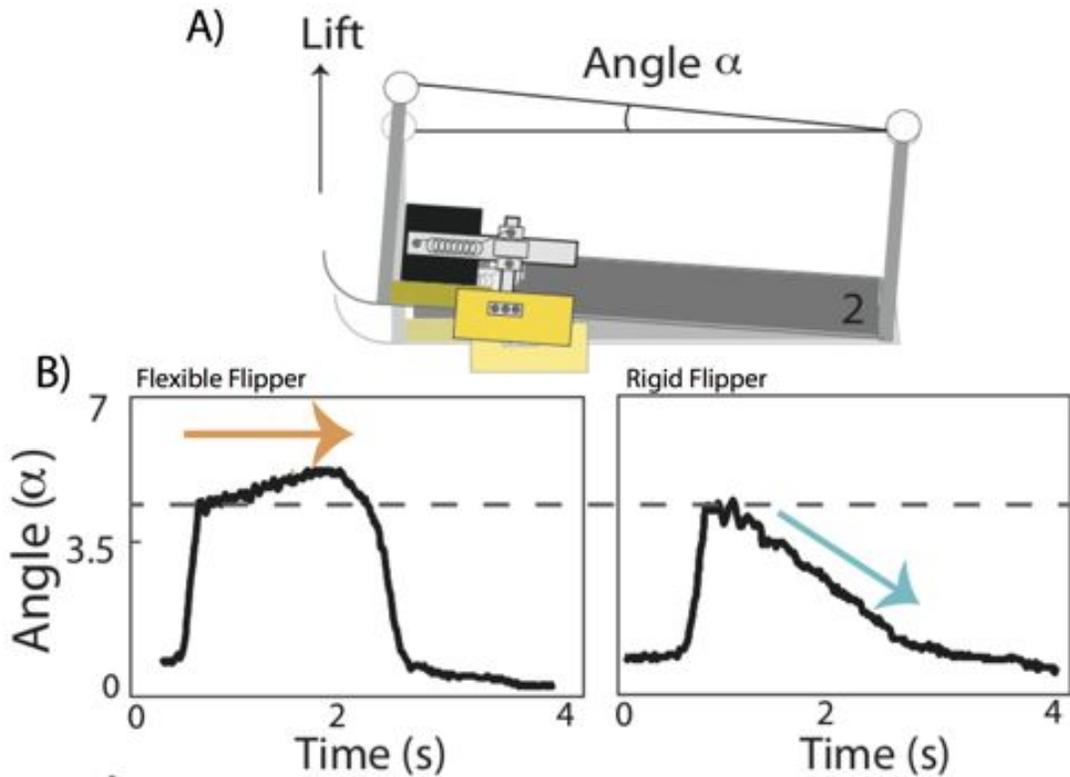


**Figure 24:** Kinematic performance of FlipperBot at angular extent of  $45^\circ$  and  $90^\circ$  with flexible and rigid wrist (A, B, C,D). From left: First graph shows the distance travelled vs time with the total distance indicated by green dashed line, second graph illustrates the instantaneous velocity vs time showing the start–stop motion of FBot, third frame highlights one individual step velocity vs time to depict the kinematic propulsion profile of FBot. Final frame shows the total distance travelled at various angular extent and wrist treatments.  $\omega=30^\circ/s$ .



**Figure 25:** A) Front view of FlipperBot showing potential insertion depth of 3 cm and variations in insertion depth by  $1^\circ$  ( $= 1.4\text{mm}$ ). B) Graph pictures distance moved per step at varying potential insertion depths ( $1^\circ$ ,  $0^\circ$ ,  $-0.5^\circ$ ,  $-0.75^\circ$ ,  $-1^\circ$  and  $-1.5^\circ$ ) with a flexible and a rigid wrist. Angular extent =  $90^\circ$ ,  $\omega = 30^\circ/\text{s}$ .

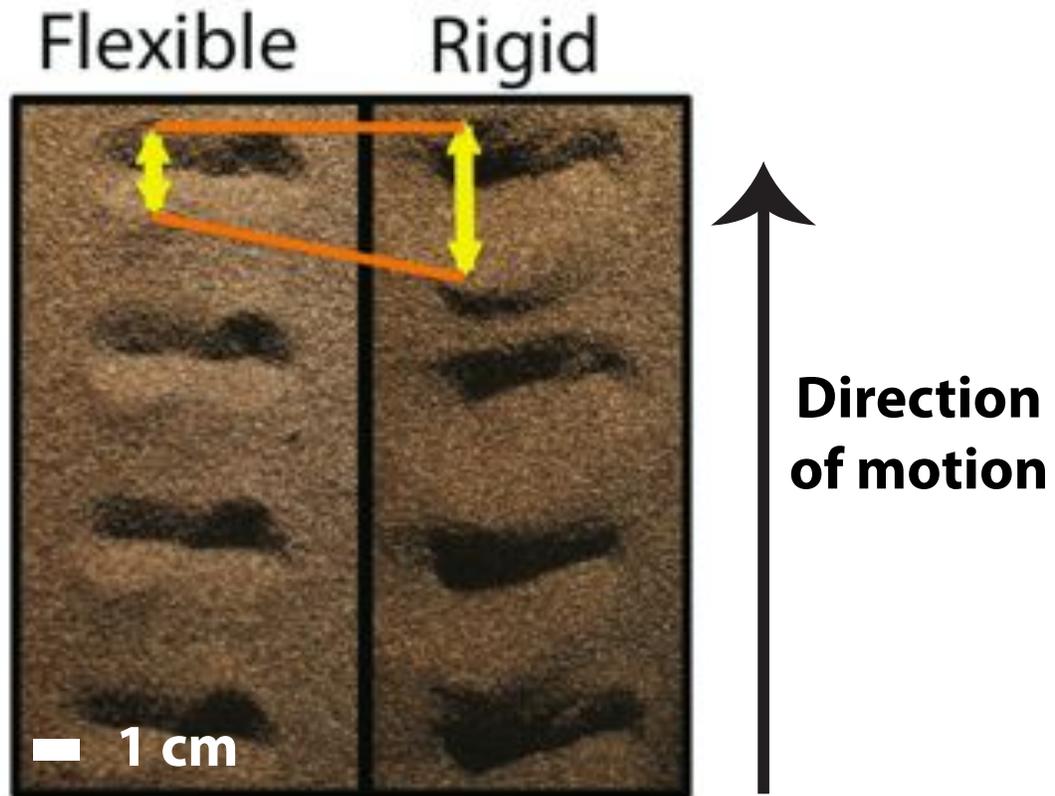
depth ( $d_{insert}$ ) of the flipper into the material as seen in Figure 25. A front view of FBot depicted the motor and flipper alignment at the end of the insertion phase into the material. The flipper rail was parallel with the aluminum body and the potential  $d_{insert} = 3$  cm. An adjustment in the  $d_{insert}$  could be achieved by programming the control software for FBot; changes of  $d_{insert} = -1.5^\circ$  to  $+1^\circ$  ( $1^\circ = 1.4$  mm) were tested. Performance at six varying  $d_{insert}$  ( $-1.5^\circ, -1^\circ, -0.75^\circ, -0.5^\circ, 0^\circ, 1^\circ$ ) were measured by noting the distance advanced per step in a run. Using a flexible wrist at angle  $\theta = 90^\circ$  showed that at  $d_{insert} = 1^\circ$  to  $d_{insert} = -0.5^\circ$  change in insertion depth had no effect ( $d = 11.5$  cm) on performance.



**Figure 26:** A) Side view of FlipperBot depicting the lift angle  $\alpha$  during stance time. B) Angle  $\alpha$  vs time for two wrist treatments flexible and rigid with arrow indicating slope during stance time.  $\omega = 30^\circ/s$ .

At  $d_{insert} = -0.75^\circ$  step distance decreased past the first three successful steps. Performance at  $d_{insert} = -1^\circ$  linearly decreased and by the sixth step, FBot did not advance further. At  $d_{insert} = -1.5^\circ$  FBot did not advance further after one step. Using a rigid wrist, distance advanced was further in  $d_{insert} = 1^\circ$  and  $d_{insert} = 1.5^\circ$  ( $d = 13$  cm) than compared

to  $d_{insert}$  using a flexible wrist. However, FBot started to decrease step distance at  $d_{insert} = -0.5^\circ$ . Distance advanced decreased for  $d_{insert} = -0.75^\circ$  and  $d_{insert} = -1^\circ$  and little distance was advanced after 3 steps. Failure after one step occurred at  $-1.5^\circ$  similarly to the flexible wrist.



**Figure 27:** Picture of FBot tracks on poppy seeds. Left: Flexible flipper, Right: Rigid flipper. Arrows show amount of disturbed ground. Direction of motion indicated on the side.

In order to establish a kinematic profile of FBot moving using flexible or rigid wrists we analyzed lift angle  $\alpha$ , see Figure 26. Angle  $\alpha$  during insertion and stance phase of the flipper was recorded over time. Using a flexible wrist  $\alpha$  increased to  $4^\circ$  and stayed constant or slightly increased during stance phase. Using a rigid wrist  $\alpha$  initially increased to  $4^\circ$  decreased until the body was flat on the ground, decreasing lift continuously throughout stance phase, Figure 26. During testing we observed the amount of disturbed material using

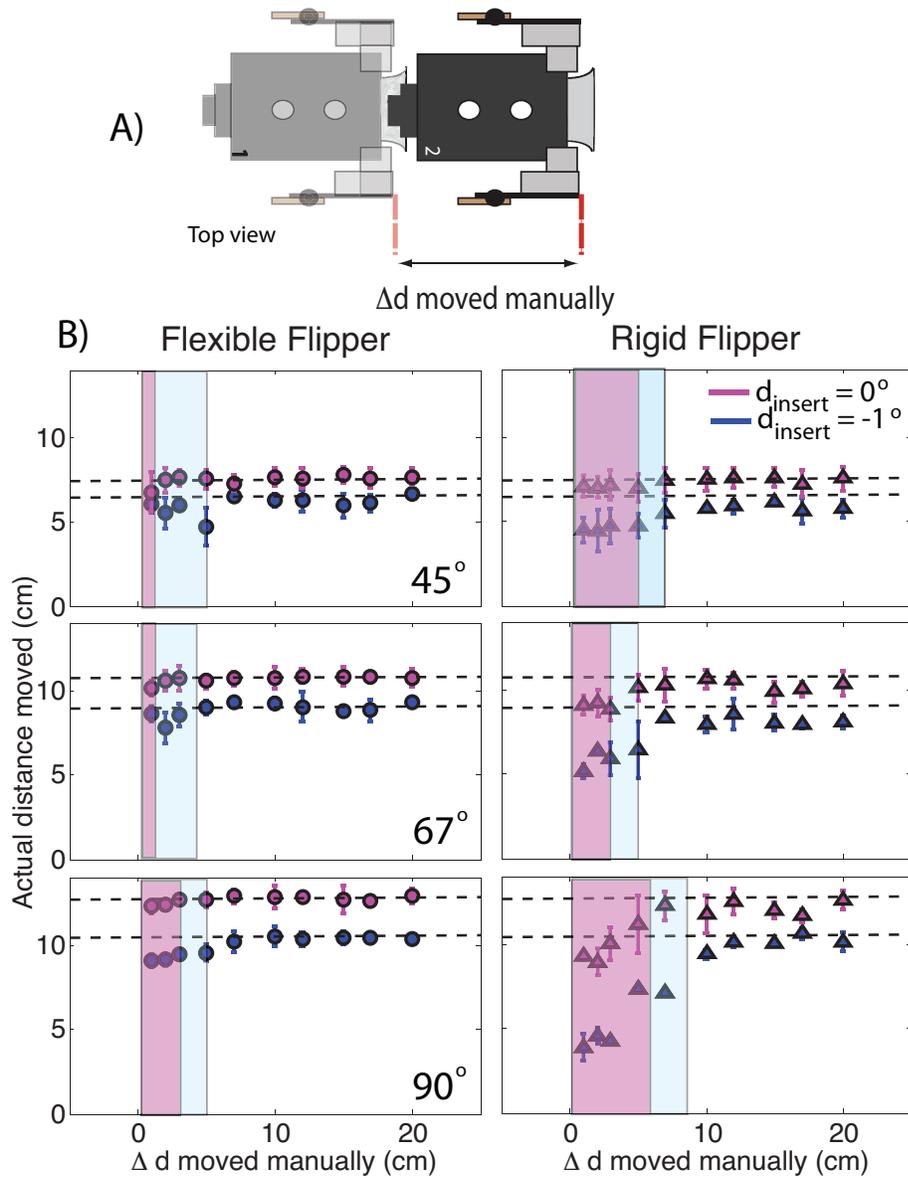
flexible and rigid wrist conditions and noticed a larger area of material displaced when using rigid wrist, creating a large hole, Figure 27.

### 3.4.2 Translation experiment

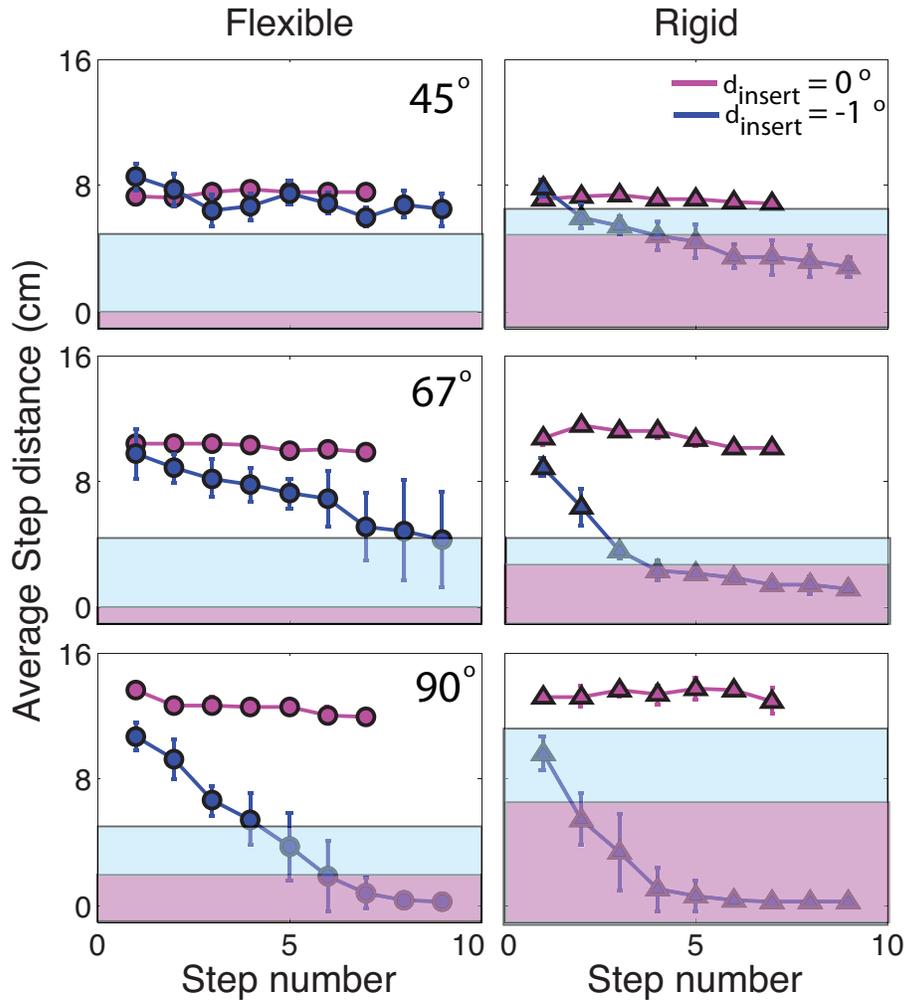
Effects of disturbed ground were tested by carrying out a translation experiment. Figure 28 showed the performance of FBot on the second step. At  $\theta = 45^\circ$ ,  $\theta = 67^\circ$  and  $\theta = 90^\circ$  using a flexible wrist the zone of disturbance (depicted in pink for  $d_{insert} = 0^\circ$  and blue for  $d_{insert} = -1^\circ$ ) varied from 1 to 3 cm for  $d_{insert} = 0^\circ$  and 5 to 7 cm for  $d_{insert} = -1^\circ$ , Figure 28. The zone of disturbance was determined by measuring step distance at  $\Delta d = 20\text{cm}$  from the translation experiment and highlighting data that performed below 95% of the step distance measured at  $\Delta d = 20\text{cm}$ . The zone of disturbance was determined for all  $\theta$ , wrist conditions and  $d_{insert}$ , Figure 28.

The dashed line indicated maximum step distance as measured for step distance at  $\Delta d = 20\text{cm}$ . Using a rigid wrist revealed a larger zone of disturbance and therefore a more pronounced step interaction between consecutive steps. At  $d_{insert} = 0^\circ$  (pink) the zone of disturbance varied from 5 cm ( $\theta = 45^\circ$ ), to 3 cm ( $\theta = 67^\circ$ ) and 7 cm ( $\theta = 90^\circ$ ), at a shallower insertion depth  $d_{insert} = -1^\circ$  (blue), the zone of disturbance varied from 7cm ( $\theta = 45^\circ$ ), 5 cm ( $\theta = 67^\circ$ ) and 10 cm ( $\theta = 90^\circ$ ). The zone of disturbance between consecutive steps increased when the wrist was locked in FBot.

Average step distance per step number ( $S_{num}$ ) for runs at  $\theta = 45^\circ$ ,  $\theta = 67^\circ$ , and  $\theta = 90^\circ$  were displayed Figure 28. To demonstrate failure in locomotor performance as affected by the zone of disturbance the data was superimposed onto the average step distance versus step number graph Figure 29. At  $d_{insert} = 0^\circ$  the step distance, regardless of angular extent ( $\theta = 45^\circ$ ,  $\theta = 67^\circ$ , or  $\theta = 90^\circ$ ) or wrist condition (flexible or rigid), never approached the critical zone of disturbance, FBot never decreased performance, Figure 25. However, when  $d_{insert} = -1^\circ$  ( $= -1.4\text{ mm}$ ), the step distance decreased for all ( $\theta = 67^\circ$ ,  $\theta = 90^\circ$  for flexible and  $\theta = 45^\circ$ ,  $\theta = 67^\circ$  and  $\theta = 90^\circ$  for rigid wrist condition) but one angular extent ( $\theta = 45^\circ$ ) and approached the zone of disturbance. Once the step distance overlapped with the zone of disturbance FBot's performance continued to decrease.



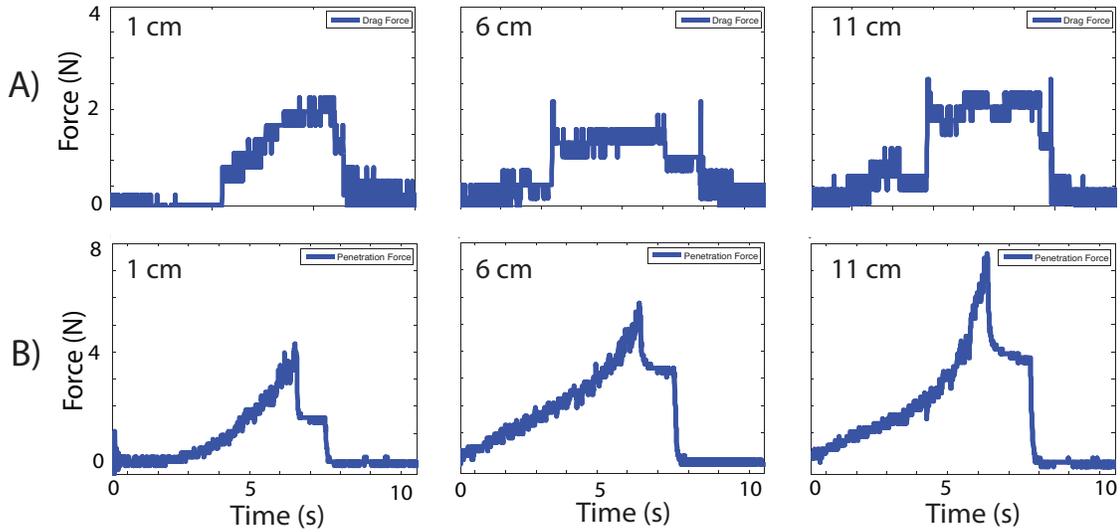
**Figure 28:** A) Picture of FBot showing experimental procedure, step 1 in light grey colors, step 2 in dark grey colors, red lines shows distance moved manually. B) Translation experiment:  $\Delta d$  between Step 1 and Step 2 is depicted vs the actual  $\Delta d$  moved manually for varying wrist, angular extent and insertion depth treatments. Magenta and blue color blocks indicate zone of disturbance.



**Figure 29:** Average step distance vs step number for varying angular extent (45°, 67° and 90°), wrist treatments (flexible and rigid) and insertion depth (0° = pink box and -1° = blue box). The zone of disturbance established from Figure 28 is superimposed onto the data.

### 3.4.3 Drag and penetration force experiment with flat, paddle-like rod in granular media

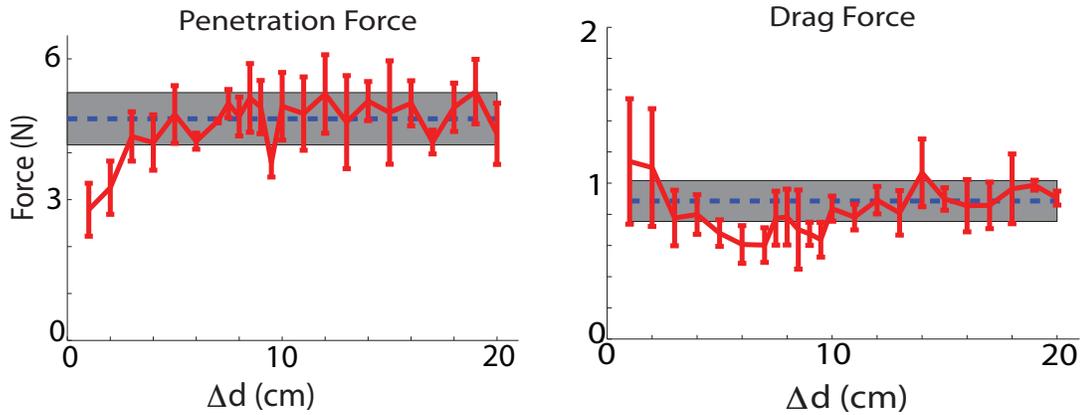
A flat paddle-like rod was attached to a vertical motor, which in turn was attached to a horizontal motor, see Figure 23. The experiment was setup with a force-torque sensor allowing measurements of insertion and drag force to be taken. Figure 30, illustrated the drag (top) and penetration force (bottom) at varying  $\Delta d$  (1 cm, 6 cm and 11 cm).



**Figure 30:** Penetration and Drag experiment with flat paddle. A) Experimental setup with two motors (horizontal and vertical) holding a force sensor with a flat paddle attachment. B) 3D depiction of hole profile during 1 step. C) Force vs Time plots for Penetration and Drag force over 3 different interaction distances.

The protocol for the penetration and drag experiment was similar to the translation experiment with FBot. A hole was created by penetrating (3 cm) and dragging (3 cm) the rod through the material. A second hole was created at varying  $\Delta d$ . The drag force increased to  $\sim 2$  N, for data taken at varying  $\Delta d$ , Figure 30A. Penetration force was smaller at  $\Delta d=1$  cm (4.9 N), increased for  $\Delta d=6$  cm (6.0 N) and approached max penetration force (7.8 N) at  $\Delta d=11$  cm, Figure 30B. The average penetration force profile over varying  $\Delta d$  (Figure 31), illustrated a lower force profile at a  $\Delta d$  up to 6 cm. The average penetration force fluctuated around 4.5 N, with the dashed blue line indicating average penetration force at first step and the grey bar showing standard deviation for the first step. The average drag force on the second step was initially higher than the average drag for for the first step

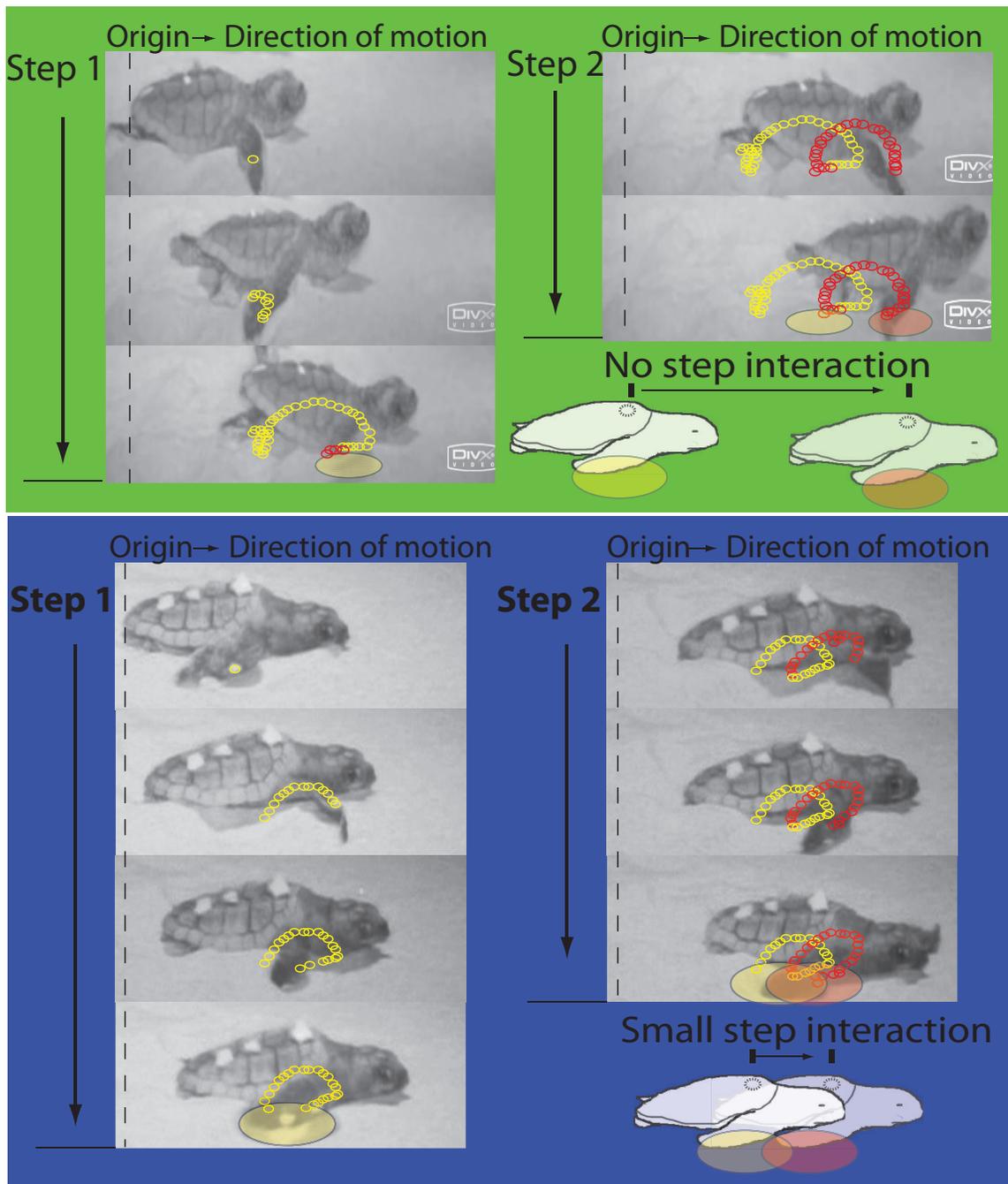
(up to  $\Delta d = 2$  cm,  $\sim 1.15$  N), followed by a decline in average drag force up to  $\Delta d = 8$  cm (0.65 N), to average out at 0.95 N for  $\Delta d = 20$  cm.



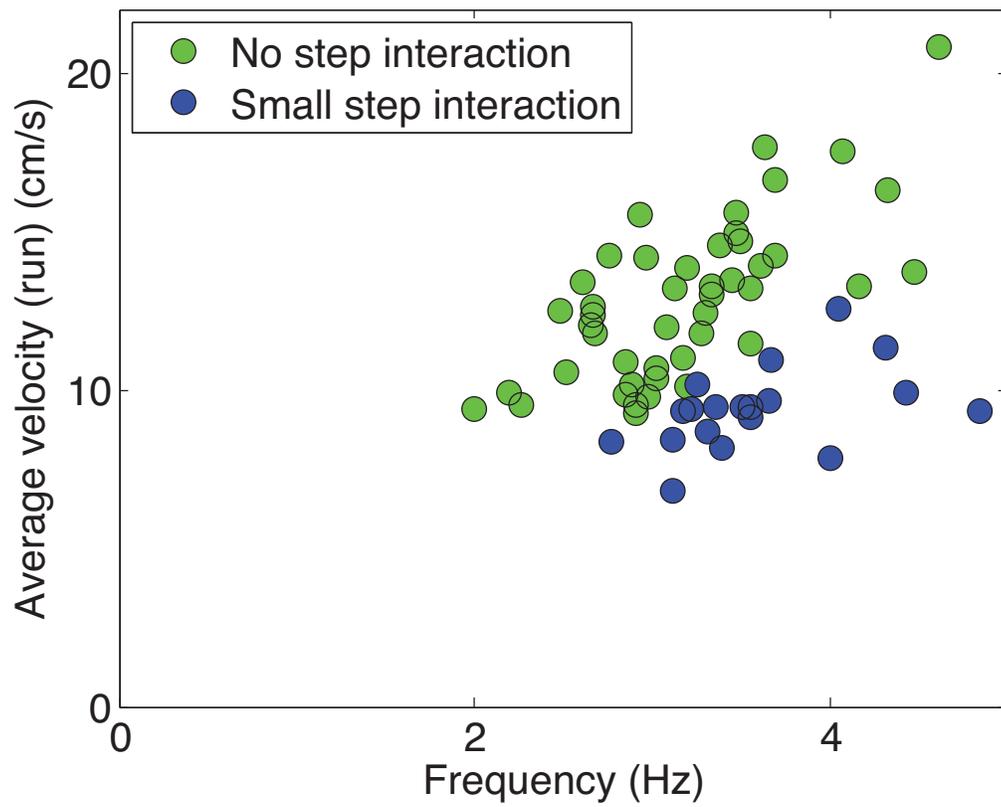
**Figure 31:** Average force profile over varying  $\Delta d$  (1 to 20 cm) taken on penetration and drag experimental setup with flat paddle.

#### 3.4.4 Biological relevance

Animal data taken in the field in Jekyll Island, GA on the year 2010 was analyzed using the principle of step length and its interaction effect with the zone of disturbance Figure 32. Data on level ground was divided visually by the researcher into runs with no step interaction between sequential steps and small step interaction. The average velocity per run vs frequency showed that runs with no step interaction had a higher performance than runs with small step interaction, Figure 33.



**Figure 32:** Biological data depicting no step interaction (green) and small step interaction (blue) in loggerhead sea turtle hatchlings on level ground in the field. Tracked path of first step (yellow circles) and second step (red circles).



**Figure 33:** Average velocity per run (cm/s) vs frequency for no step interaction and small step interaction.

### 3.5 Discussion

Our results imply that a flexible wrist outperforms a rigid wrist. The added degree of freedom of a flexible wrist allows the robot to maintain stress applied by the flippers to the substrate below the yield stress of the granular material to anchor them within the substrate, and propel the body kinematically with no slip (defined as kinematic propulsion). A single step velocity profile reveals that during a run using a flexible wrist  $\alpha$  increases to a maximum angle remaining at this angle during the stance phase. However, using rigid wrist employs a drag-based mode of propulsion, in which a single step profile shows an increase to a max  $\alpha$ , followed immediately by a constant decrease in lift angle during stance phase. As the body is moved forward the body lift decreases continuously, increasing drag, with the flipper yielding the material. Drag-based mode of propulsion at  $\theta = 90^\circ$  can result in failure, where step distance starts to decrease and body velocity is reduced to near zero after a few steps. Velocity vs time profile reveals that peak velocity per step = 0.45 cm/s for given motor frequency of 30°/s, remains unchanged over a variety of test treatments ( $\theta$  or wrist condition).

During testing we observe the flipper tracks in the material and note that the rigid flipper causes a larger amount of disturbed material than the flexible flipper, Figure 27. We hypothesize that during forward motion the disturbed ground will cause an interaction effect in subsequent steps, resulting in the observed failure of FBot.

Failure in FBot performance is interesting and outlines kinematic restrictions coupled with material properties that are relevant to understanding how animal fitness is affected by yielding substrates. Our previous research highlighted the significance of insertion depth, in hatchling sea turtle locomotion [45], where the material has yield forces ( $F_{yield}$ ) that increase quadratically with insertion depth. A shallower insertion depth will result in yielding of the material during forward movement. Figure 25 shows the robots sensitivity to varying insertion depth.

The  $d_{insert} = 0^\circ$  allows the flipper to penetrate the material up to 3 cm deep, small changes ( $\sim 1.4$  mm) in insertion depth were tested, Figure 25. While using a flexible wrist distance advanced is not affected until the insertion depth is decreased by  $-0.75^\circ$  ( $\sim 1.05$

mm). Failure of the FBot occurs at an insertion depth of  $-1.5^\circ$ , where after one step the body of the robot does not advance forward. This trend is amplified using the rigid wrist with decrease in locomotor performance starting at  $-0.5^\circ$  ( $\sim 0.7$  mm),  $d_{insert}$  of 2.93 cm, resulting in failure after one step at  $-1.5^\circ$ . FBot demonstrates acute sensitivity to small changes of just mere mm in insertion depth, which opens questions in regards to how failure occurs when flat, paddle-like appendages are used on granular media.

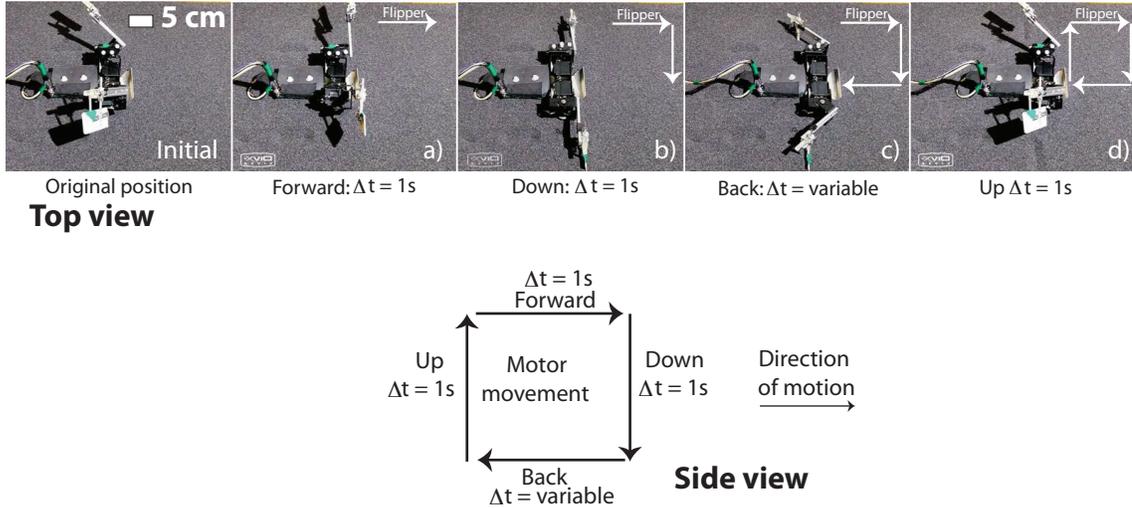
Our results show that the zone of disturbance is affected by wrist condition. Using a flexible wrist decreases the interaction effect and successful performance is achieved after no more than  $\Delta d = 7$  cm, where the actual distance advanced compares to that of  $\Delta d = 20$  cm, the furthest step distance tested. Using a rigid wrist doesn't allow for successful performance after  $\Delta d = 10$  cm, where step distance advanced correlates to maximum distance achieved. We clearly demonstrate that disturbing more ground, while using a locked wrist, negatively effects FBot performance. In addition to the amount of disturbed ground, we predict that a decrease in  $d_{insert}$  will result in declining step distance per step number, since the  $F_{yield}$  properties of the medium follow the square of the insertion depth [45]. A shallower insertion depth produces less thrust forces potentially exposing FBot to slip.

Our results show that penetration force, not drag, are affected by disturbed ground as peak penetration forces declined when step distance is decreased Figure 30. These findings are relevant in comparison to biological data (see Figure 32). Animals with no step interaction between subsequent steps during forward motion, exhibit higher velocity than animals whose step distance is decreased.

In conclusion, a coupled interaction effect between lift force, body drag, disturbed ground and step distance affect the success of locomotion with fins and flippers on granular media. To successfully move over yielding substrates using flat, paddle-like appendages the body is lifted to allow for minimal body drag. A large step distance, which allows the body to be moved past the zone of disturbed ground, enables sequential steps to be unaffected by the deformable material. Further biological and physics studies are required to determine how compaction of the material as well as incline angle can affect the performance of animals and FBot (or other organisms and physical models that interact with granular media).

### 3.6 Appendix

The initial position was up above the servo control board Figure 24, Initial. The first movement was forward (a) (average time ( $\Delta t$ ) = 1s, fore–aft motor), followed by down (b) (insertion into the medium,  $\Delta t$  = 1s, up–down motor), back (c) (stance phase,  $\Delta t$  = variable, fore–aft motor), and fourth, the motors moved back above the servo control board (d) to the initial position (up–down motor,  $\Delta t$  = 1s), see Figure 34. These four motor movements made up one step. The motors were connected through servo channels (00, 01, 16, 17) to the servo control board (Lynxmotion SSC–32). The servo control board was powered by a 9 Volt energy source (Jameco ADR–9V500mA–2.1), and the servo motors were powered by a separate 7 Volt power source (Mastech DC Power Supply HY–3020E).



**Figure 34:** The initial position was up above the servo control board Figure 24, Initial. The first movement was forward (a) (average time ( $\Delta t$ ) = 1s, fore–aft motor), followed by down (b) (insertion into the medium,  $\Delta t$  = 1s, up–down motor), back (c) (stance phase,  $\Delta t$  = variable, fore–aft motor), and fourth, the motors moved back above the servo control board (d) to the initial position (up–down motor,  $\Delta t$  = 1s).

## CHAPTER IV

### EFFECTS OF GRANULAR INCLINE ANGLE ON THE LOGGERHEAD SEA TURTLE HATCHLING (*CARETTA CARETTA*) LOCOMOTION IN THE FIELD

#### 4.1 *Summary*

Natural environments are complex with animals running over difficult substrates to ensure survival. Animals that traverse on granular substrates can experience slipping, which decreases their performance, since granular media can act as a solid or a fluid when stress is applied. Kinematics of loggerhead sea turtle hatchlings (*Caretta caretta*) reveal that limb use varies significantly depending on granular compaction. These studies are done on level ground. However, on sandy beaches hatchlings rarely encounter level ground, having to crawl up and down sandy slopes. As sand is tilted it approaches a critical incline value (angle of repose) at which the material will cease to act as a solid and start to flow. Depending on substrate particle properties the angle at which flow is induced varies. Little is known how legged intruders are affected by sandy inclines.

We are interested in investigating the effects of granular inclines on the locomotor performance of hatchling sea turtles, hypothesizing that as incline angle increases the animals will adjust limb-ground interactions to prevent slipping, which negatively affects their performance (speed). We capture 25 hatchlings from 5 different nests on our field site on Jekyll Island, GA testing them on loose and hard packed sand, and on inclines of  $\theta= 0^\circ$ ,  $\theta= 10^\circ$  and  $\theta= 20^\circ$ .

Using a fluidized bed trackway, we control for granular compaction and incline angle, mimicking a natural beach environment. Two infrared high speed cameras (250 fps) are attached to the trackway to film the detailed mechanics of hatchling locomotion. Results show that the total distance travelled and velocity decrease as incline angle increase, without granular compaction affecting performance. Maximum angular extent of the flipper at the

beginning of stance phase in relation to the body remains the same at  $\theta= 0^\circ$  and  $\theta= 10^\circ$  ( $\alpha= 128.17^\circ \pm 12.12^\circ$ ;  $\alpha= 127.80^\circ \pm 11.40^\circ$ ;  $p>0.05$ ), however at  $\theta= 20^\circ$  it significantly increases ( $\alpha=143.19^\circ \pm 12.86^\circ$ ,  $P<0.0001$ ). The duty factor during stance phase, remains unchanged among compaction levels, at 0.69, which is similar to terrestrial turtles that have a duty factor of 0.75 or higher on level ground [26]. On close packed materials the duty factor decreases at the highest incline angle  $\theta= 20^\circ$  to 0.66.

Taking indications of the step interaction effect due to disturbed ground from a bio-inspired sea turtle robot (FBot) (Mazouchova in prep.), the hatchling data is divided into three step distance categories: No interactions between steps, small step interactions, and large step interactions. Results show that average velocity increases with frequency when turtles utilize adequate step distance to avoid interaction effects for  $\theta= 0^\circ$  and  $\theta= 10^\circ$ . However, little effect is seen at  $\theta= 20^\circ$  suggesting that at higher angular inclines slip dominates performance.

## 4.2 *Introduction*

Rapid locomotion is believed to increase fitness of animals by enhancing their ability to escape predators, capture prey and defend territories [2, 30]. Consequently, research has focused on studying sprinting speed to gain insight into organismal performance [36]. Locomotor performance is affected by the physical properties of the environment such as substrate type [14].

Flow of sandy inclines is dependent on particle-particle friction, requiring granular media to be inclined above a critical angle (angle of repose) in order to flow [19]. For example, sand at rest, with a slope lower than the angle of repose behaves like a solid, whereas, if the sand is tilted above the angle of repose grains start to flow [38]. Few studies have looked into the effects of legged locomotor performance on granular media slopes [35, 36, 9]. Further, little is known about the physics of intruders on inclined granular media. Research on box turtles [9] and lizards in the field [35, 36] shows that animal speed, stride frequency and stride length are affected on sandy inclines. These tests are conducted on animals whose natural habitat contain granular media on a regular basis [36]. We are interested in understanding how species with aquatically adapted limbs, who emerge onto beaches infrequently, successfully traverse complex sandy environments containing slopes.

Previous research on hatchling locomotion on level ground [45], demonstrates that limb-ground interactions are dependent on compaction of material, and that hatchlings avoid slipping by utilizing the solid features of the medium. As hatchlings travel from their nest to the ocean they encounter various beach slopes, beginning with very dry and soft sand as they climb out of their nest to hard packed sand near the water line.

For many years researchers are interested in understanding how sea turtles with their rigid bodies and flat, paddle-like appendages are capable of dealing with sandy, slippery incline angles. A quote by Robert Bustard (1972), author of several sea turtle biology books:

As I climbed wearily up the twelve-foot bank I wondered, as I had done on countless previous nights, how the turtles ever make their way up these slopes.

[5]

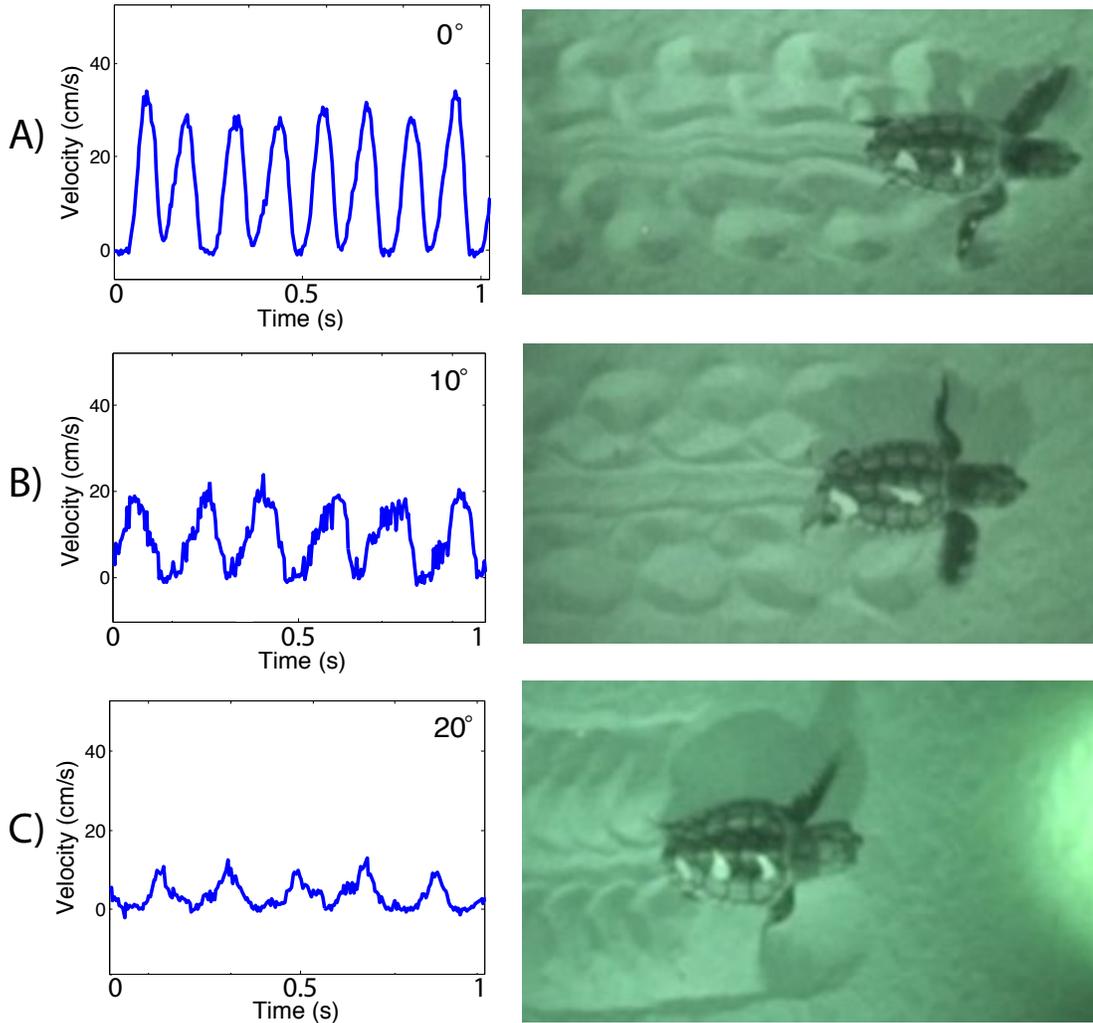
To our knowledge, we have conducted the first kinematic study of locomotor performance of hatchling sea turtles up sandy incline angles in the field. We hypothesize that as incline angle increases the locomotor performance of the animals declines and slipping may occur. Twenty five individual loggerhead sea turtle hatchlings (*Caretta caretta*) are tested in Jekyll Island, GA, on a fluidized trackway bed, that mimics the beach environment, by controlling for volume fraction ( $\phi$ ) as well as incline angle ( $0^\circ$  up to  $35^\circ$ ).

### 4.3 *Materials and Methods*

The field study was conducted over 6 weeks in 2010 on Jekyll Island, GA in collaboration with the Georgia Sea Turtle Center. Three to five hatchlings were randomly selected from 10 nests at time of emergence. All hatchlings were transported, in a styrofoam container filled with beach sand, to a parking lot where the experimental setup was housed in a truck. The experimental setup consisted of a fluidized bed trackway, see Figure 11, (as used in our previous field study on loggerhead hatchlings [45]), two high speed cameras (Sony Handycam 250 fps) as well as a shop vacuum to fluidize the granular media. Hatchlings were tested on loose and hard packed, dry Jekyll Island sand, and tested on incline angles of ( $\theta= 0^\circ$ ,  $\theta= 10^\circ$ , and  $\theta= 20^\circ$ ). Animals were prompted to repeat each treatment (granular compaction and incline angle) three times. Runs were accepted when the hatchlings were running straight at constant average velocity, for at least 20 cm. For loose and close packed treatment at  $\theta= 0^\circ$ ,  $\theta= 10^\circ$ ,  $\theta=$  and  $20^\circ$  an N=25 animals were tested, originating from N=5 nests. Small white removable markers were attached to the carapace of the animals for tracking with two high speed cameras (top and side view). Tracking was done in Matlab (Matlab2009) using a tracking program (courtesy Daniel Goldman). The data was analyzed in Matlab and Excel (Microsoft Office 2008) and statistics were analyzed using JMP 9.0. Upon return from the field particle density and volume fraction ( $\phi$ ) were measured. Particle density of Jekyll Island sand was measured as  $\rho = 2.68 \text{ g cm}^{-3}$ . The resulting volume fraction was determined to be  $0.54 < \phi < 0.64$ . These values were comparable to volume fractions measured in the desert ( $0.55 < \phi < 0.63$ ) [15].

A step interaction profile was deduced from the high speed video data taken in the field on the fluidized bed trackway Figure 41. Three modes of step interaction were visually identified from the video data, and categorized by the researcher. Small yellow and red circles were drawn over the disturbed ground created by the flipper and used to identify individual subsequent steps. When the boxes were not touching the data was categorized as no step interaction. When the boxes were close together or slightly overlapping the data was categorized as small step interactions. When the boxes were overlapping by more than half their surface area, the steps were considered to be overlapping steps.

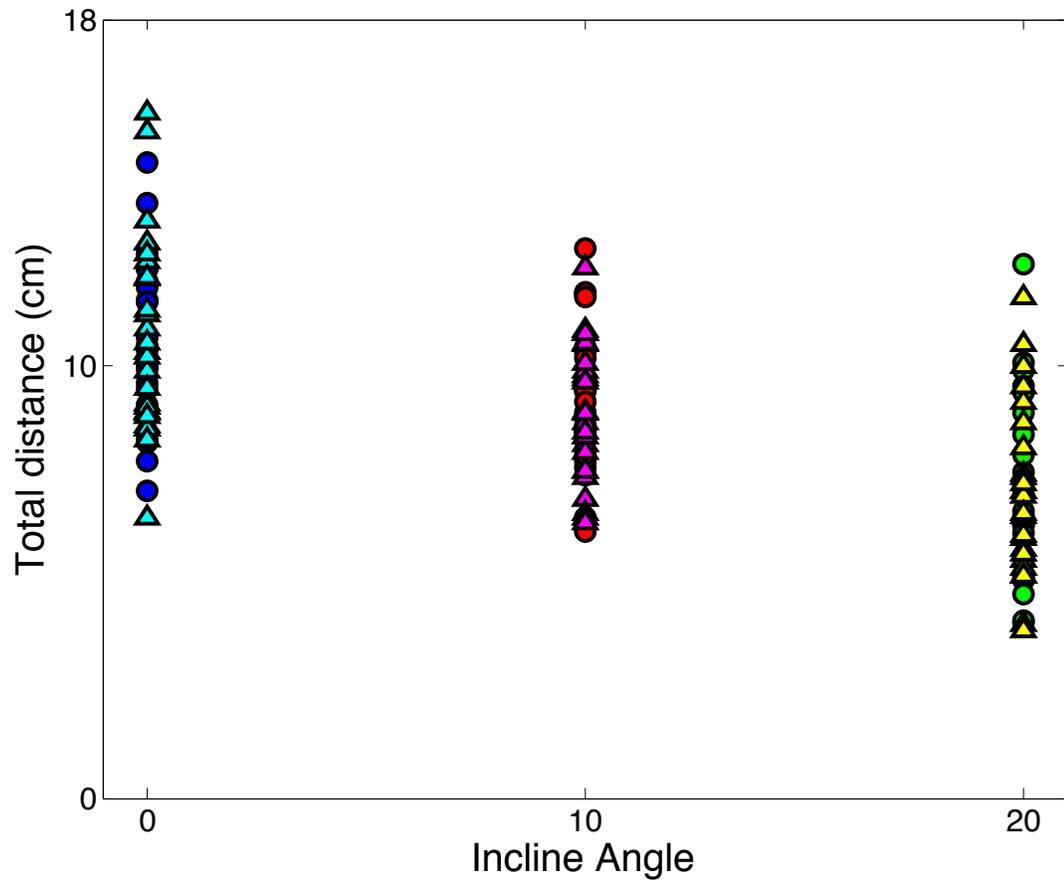
#### 4.4 Results



**Figure 35:** Kinematic profile of hatchlings on inclines. A) Velocity vs time for level ground, B) for  $\theta = 10^\circ$ , and C) for  $\theta = 20^\circ$ . Pictures depict hatchling runs that were tracked for kinematic profile.

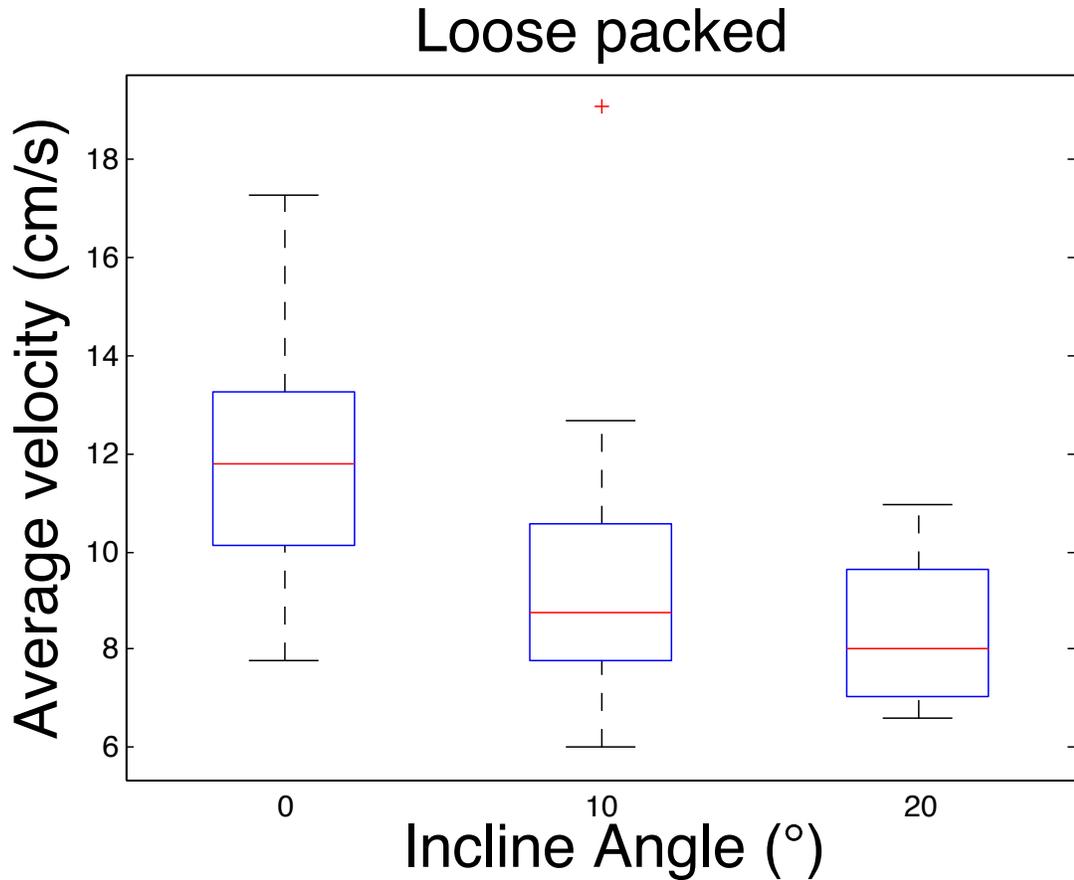
Hatchling sea turtles used a start-stop motion on terrestrial media, as shown in our previous study [45]. At each step the animal's body was accelerated to a peak velocity, then returned back to zero. Average peak velocity on level ground was highest at level ground (approx. 37 cm/s) and decreased at  $10^\circ$  (approx. 20 cm/s), and  $20^\circ$  (approx. 11 cm/s) Figure 35.

Hatchlings were tested on incline angles of  $\theta = 0^\circ$ ,  $10^\circ$  and  $20^\circ$  as well as two granular compaction levels (loose packed and close packed), Figure 36. Mean distance travelled



**Figure 36:** Graph showing total distance (cm) travelled for hatchlings walking over varying incline angles ( $0^\circ$ ,  $10^\circ$  and  $20^\circ$ ). Blue circle:  $0^\circ$  on loose packed sand; cyan triangle:  $0^\circ$  on close packed sand; red circle:  $10^\circ$  on loose packed sand; magenta triangle:  $10^\circ$  on close packed sand; green circle:  $20^\circ$  on loose packed sand; yellow triangle:  $20^\circ$  on close packed sand.

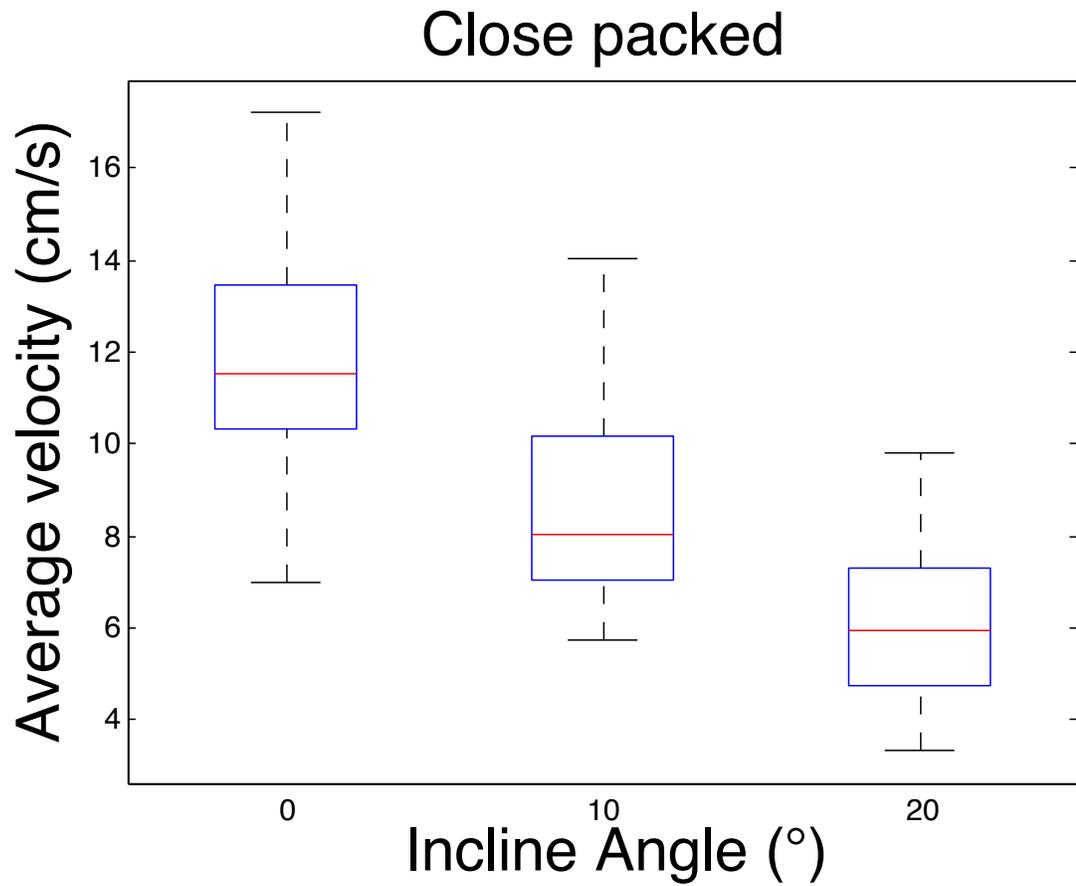
by the hatchlings significantly decreased with incline angle (ANOVA,  $F(2,144)=43.02$ ,  $p < 0.001$ ). Distance travelled was not significantly affected by compaction of the material (ANOVA,  $F(1,144)=0.1340$ ,  $p > 0.05$ ). Mean distance travelled at various compaction levels are the same, resulting in comparable decrease in performance as incline rises (ANOVA,  $F(2,144)=1.31098$ ,  $p > 0.05$ ) Figure 36.



**Figure 37:** Boxplot of average velocity (cm/s) versus incline angle ( $0^\circ$ ,  $10^\circ$  and  $20^\circ$ ) on loose packed sand.

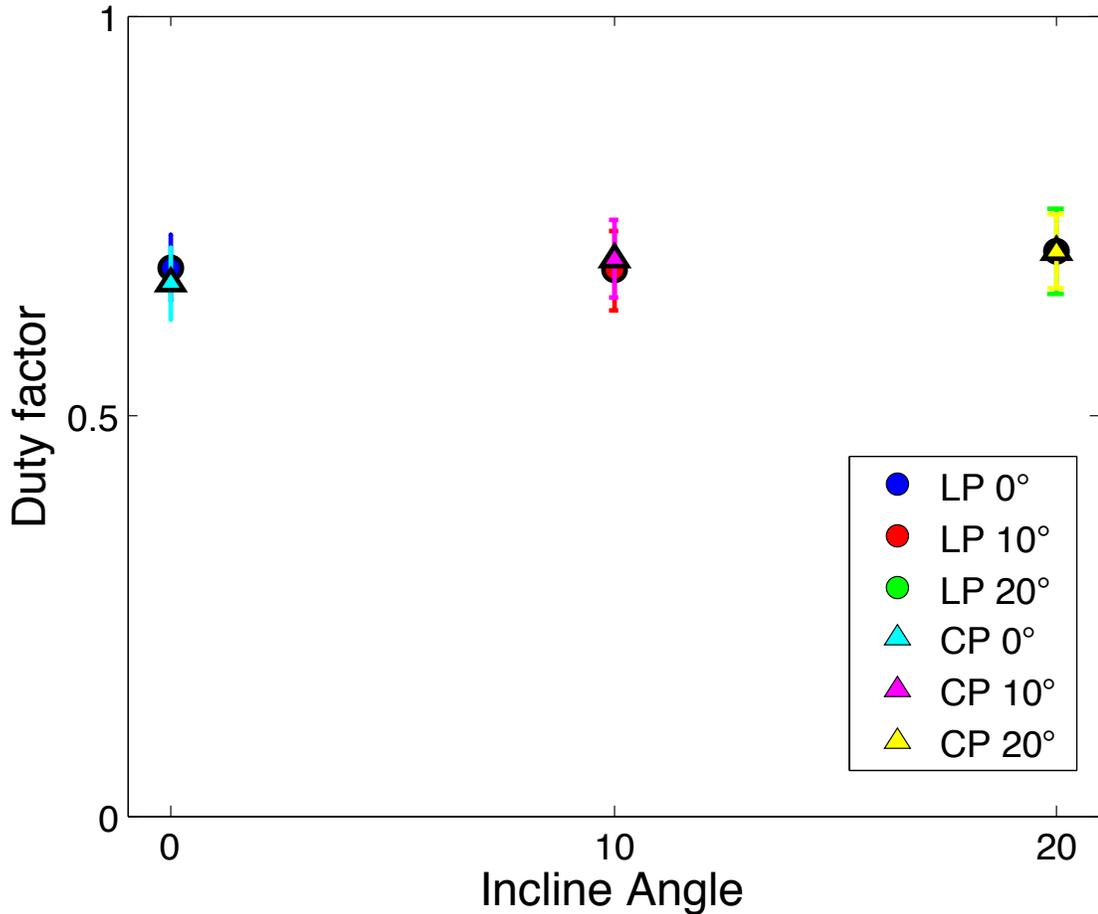
Average velocity significantly decreased with incline angle (ANOVA,  $F(2, 59)=10.5230$ ,  $p < 0.001$ ) on loose packed material Figure 37. Incline angles  $\theta = 0^\circ$  and  $\theta = 10^\circ$  showed a significant decrease in velocity (t-test,  $p < 0.05$ ). Average velocity did not decrease from  $\theta = 10^\circ$  to  $\theta = 20^\circ$  (t-test,  $p > 0.05$ ).

On closed packed sand the average velocity followed a similar trend as on loose packed sand and decreased significantly (ANOVA,  $F(2, 71)=44.4058$ ,  $p < 0.001$ ) Figure 38. All



**Figure 38:** Boxplot of average velocity (cm/s) versus incline angle (0°, 10° and 20°) on close packed sand.

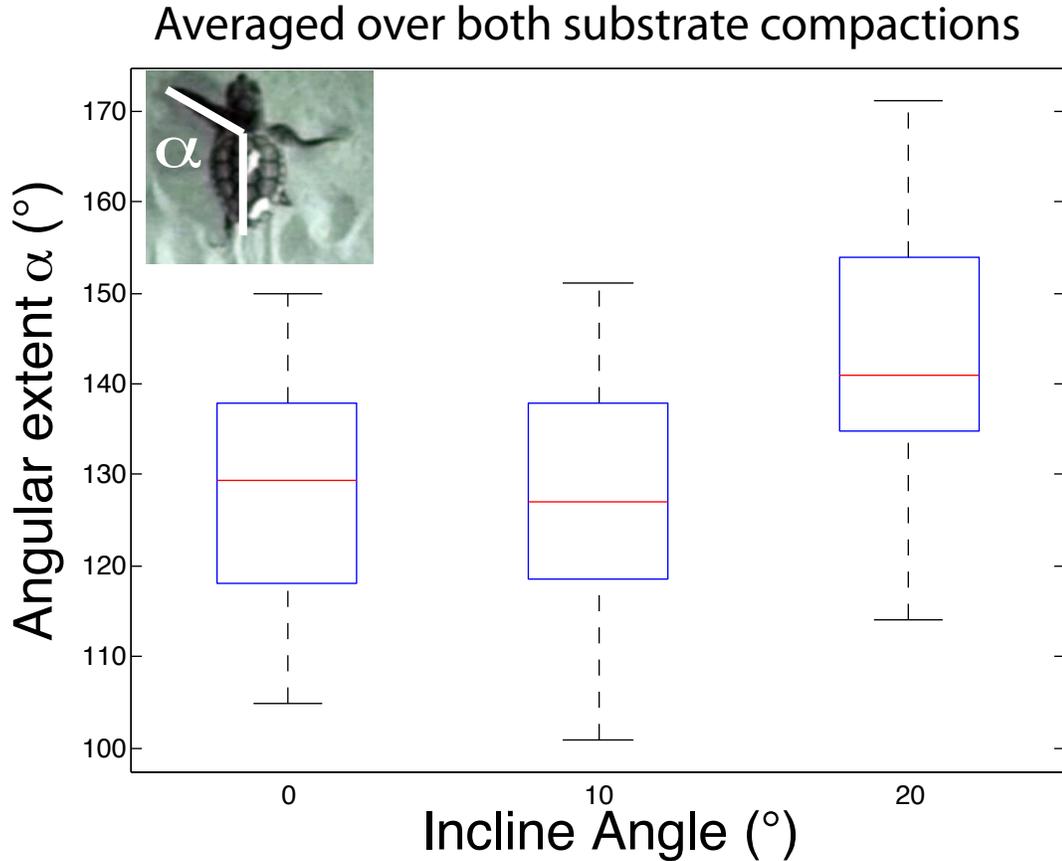
angles ( $\theta= 0^\circ, 10^\circ,$  and  $20^\circ$ ) were statistically different from each other over varying incline angles (t-test,  $p < 0.05$ ). Tests revealed that average velocity is not affected by granular compaction at varying incline angles (ANOVA,  $F(1, 130)=0.0035, p > 0.05$ ), except for  $\theta= 20^\circ$  when comparing loose and close packed material mean velocities (t-test,  $p < 0.05$ ).



**Figure 39:** Plot of duty factor versus incline angle ( $0^\circ, 10^\circ$  and  $20^\circ$ ). Blue circle:  $0^\circ$  on loose packed sand; cyan triangle:  $0^\circ$  on close packed sand; red circle:  $10^\circ$  on loose packed sand; magenta triangle:  $10^\circ$  on close packed sand; green circle:  $20^\circ$  on loose packed sand; yellow triangle:  $20^\circ$  on close packed sand.

Duty factor (fraction of duration of a stride in which the foot is in contact with the ground) on loose packed materials averaged at  $0.69 \pm 0.05$  and was not significantly different over all incline angles (but one) and material compactions (ANOVA,  $F(2, 72)=1.7498, p > 0.05$ ) Figure 39. On close packed sand the duty factor slightly decreased when animals were prompted to run on  $\theta= 20^\circ$  (ANOVA,  $F(2, 71)=4.8440, p = 0.0106$ ). Duty factor

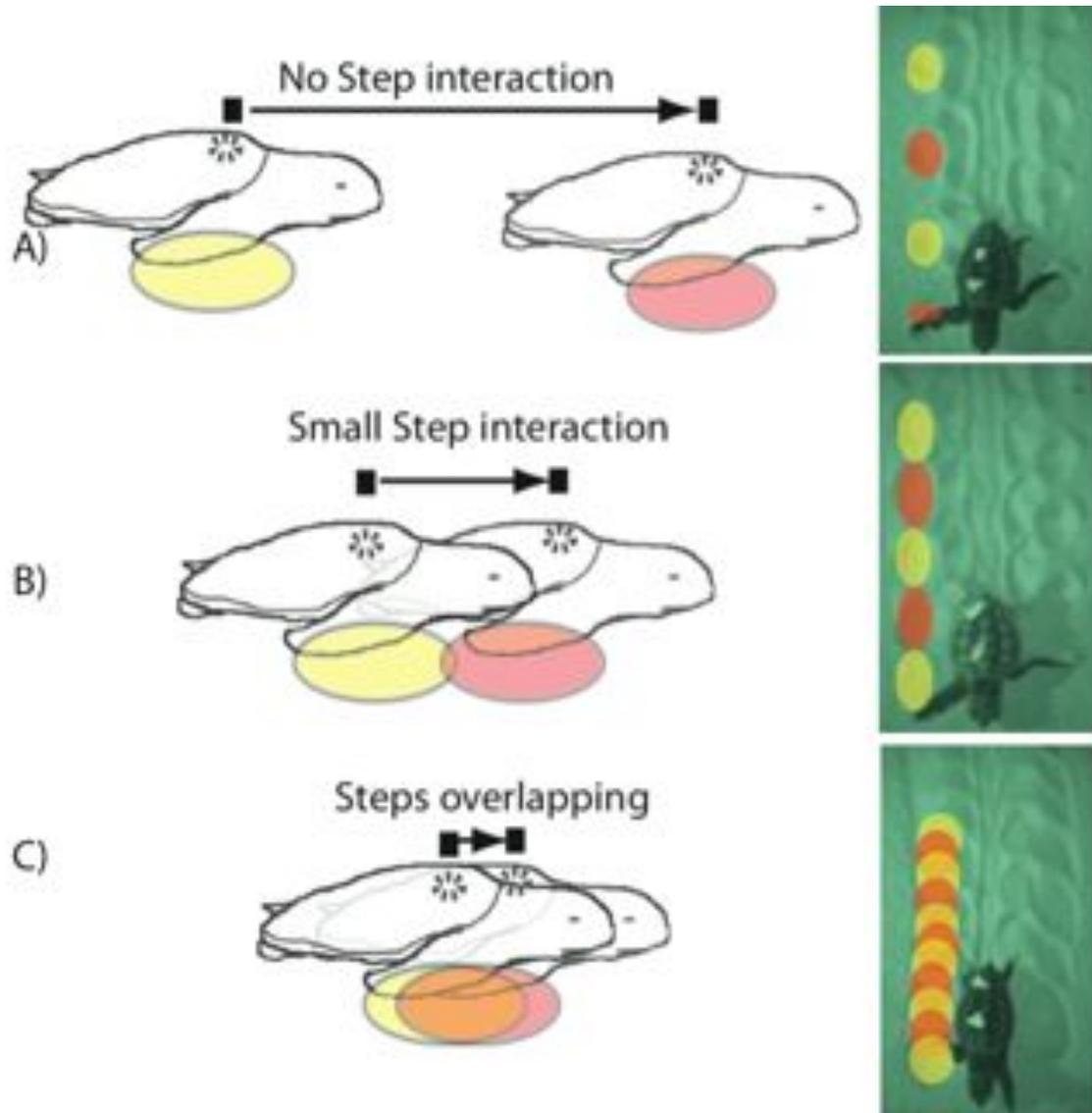
decreased from 0.71 at  $\theta= 0^\circ$  and 0.70 at  $\theta= 10^\circ$  to  $0.66 \pm 0.04$  at  $\theta= 20^\circ$ . Compaction had no significant impact on duty factor of animals running at various inclines (ANOVA,  $F(1, 144)=1.8772, p >0.05$ )



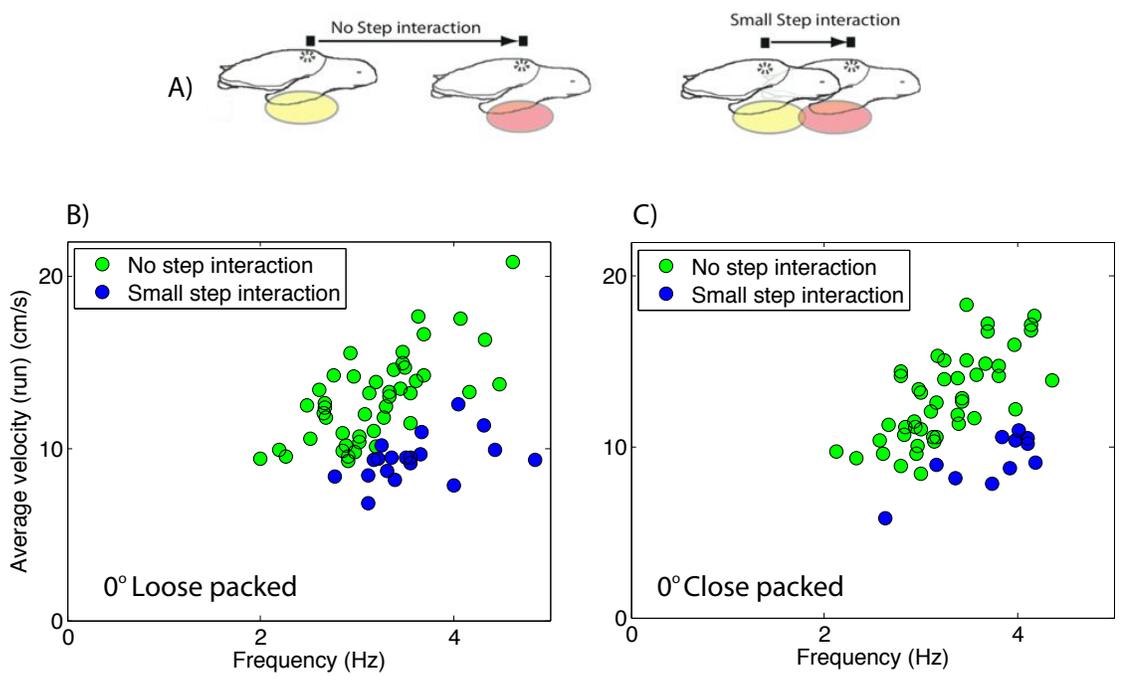
**Figure 40:** Boxplot of angular extent ( $\alpha$ ) of flipper vs incline angle. Angular extent increases at  $\theta= 20^\circ$ . Inset: Outline of hatchling showing  $\alpha$ .

The angular extent of the animals exhibited a significant trend with higher slopes (ANOVA,  $F(2, 262)=46.0908, p <0.001$ ). No statistical difference was recorded between  $\theta= 0^\circ$  and  $\theta= 10^\circ$  (t-test,  $p >0.05$ ), however both incline angles were statistically different from  $\theta= 20^\circ$  (t-test,  $p <0.05$ ).

In Figure 41A an illustration depicts a large step distance between steps during forward motion resulting in no step interaction, whereas Figure 41B, shows a smaller step length resulting in minimal step interaction during a run, termed small step interaction, lastly in Figure 41C, a large overlapping area results during subsequent steps (overlapping steps).

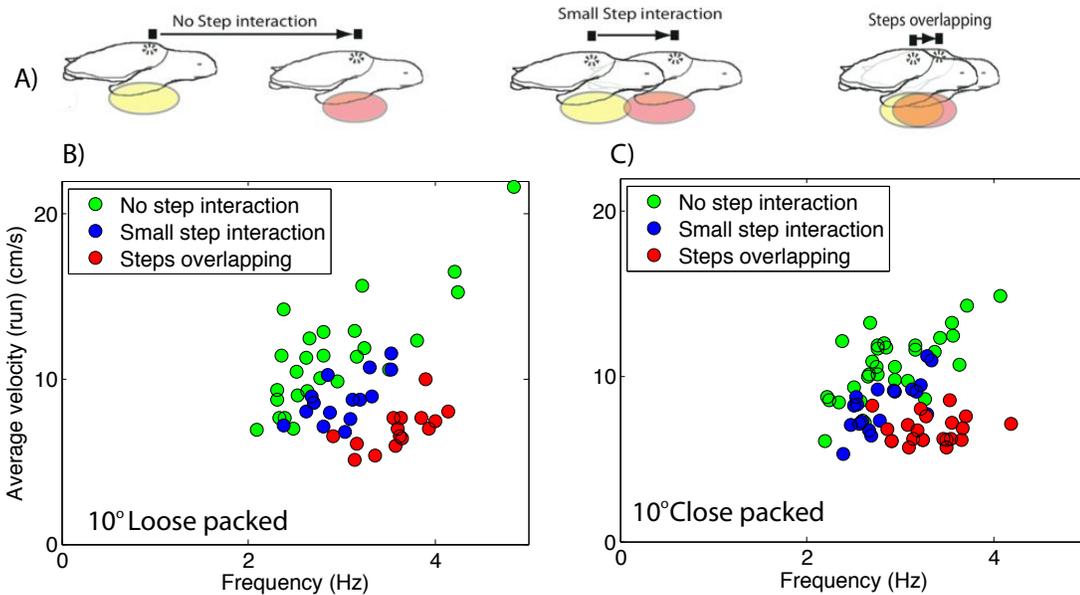


**Figure 41:** Picture of hatchling step interaction observed: A) Large step distance between steps, no step interaction, B) Small step interaction distance, C) Small step distance, steps are overlapping. Pictures taken from video data, showing selection technique to determine three step interaction profiles.



**Figure 42:** Observed hatchling performance on level ground: A) Illustration of step interaction pattern. B) Average velocity per run (cm/s) versus frequency (Hz) for 0° loose packed material. C) Average velocity per run (cm/s) versus frequency (Hz) for 0° close packed material.

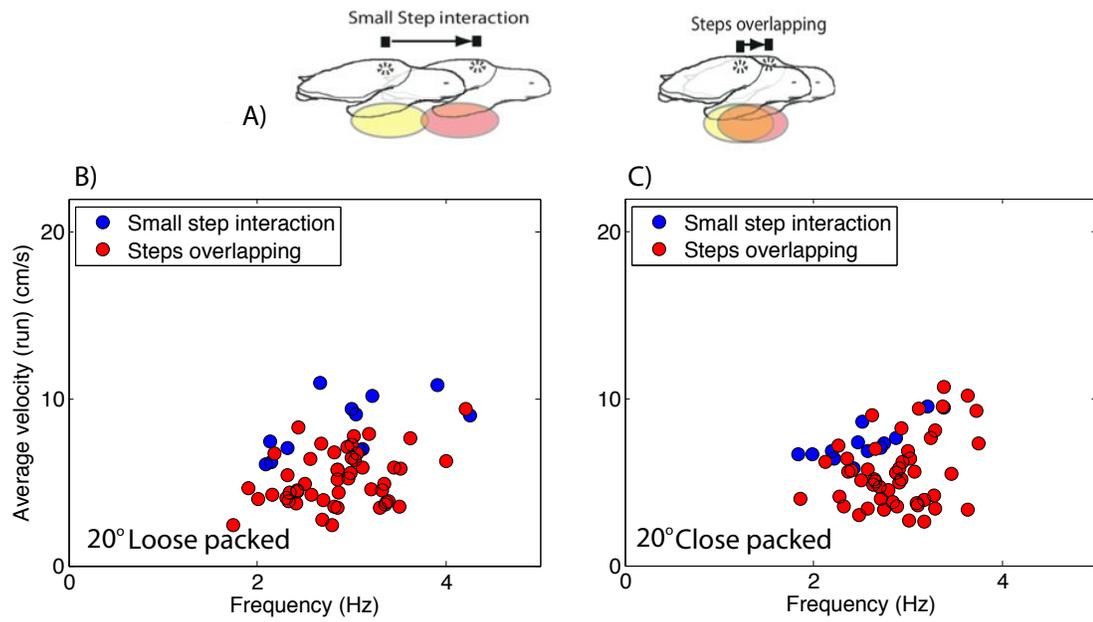
On level ground two step interaction profiles were observed, no step interaction, and small step interaction as depicted in Figure 42A. On loose packed sand the average velocity increased with frequency and was higher for no step interactions than for small step interactions (Figure Figure 42B), and follows a similar trend to that on close packed sand, see Figure 42C.



**Figure 43:** Observed hatchling performance at  $10^\circ$  incline angle: A) Illustration of step interaction pattern. B) Average velocity per run (cm/s) versus frequency (Hz) for  $10^\circ$  loose packed material. C) Average velocity per run (cm/s) versus frequency (Hz) for  $10^\circ$  close packed material.

On an incline angle of  $\theta = 10^\circ$  all three step interaction profiles were observed, no step interaction, small step interaction, and overlapping steps, see Figure 43A. Average velocity per run versus frequency revealed that animals running with no step interaction perform better than animals with small step interactions, or with overlapping steps. Fastest average velocities measured were at no step interaction followed by small step interaction, with slowest performance at overlapping steps for loose sand Figures 43B,C. A similar trend was observed for animals running on close packed sand.

At  $\theta = 20^\circ$  the step interactions were predominantly small step interactions, and overlapping steps (Figure 44A). In loose packed and close packed sand the animals performed in



**Figure 44:** Observed hatchling performance at 20° incline angle: A) Illustration of step interaction pattern. B) Average velocity per run (cm/s) versus frequency (Hz) for 20° loose packed material. C) Average velocity per run (cm/s) versus frequency (Hz) for 20° close packed material.

a similar way without one step interaction distinctly outperforming the other Figure 44B,C.

## 4.5 Discussion

We are interested in understanding how hatchlings can climb on sandy inclines, which they naturally encounter on the beach, from emergence out of their nest, to their run towards the ocean. Incline angle has effects on the total distance that the hatchlings run, with further distances achieved when traveling on smaller slopes  $\theta = 0^\circ$  or  $\theta = 10^\circ$ , as compared to  $\theta = 20^\circ$ . The mean total distance per angle is the same, compaction has no effects on running performance. That material compaction has no effect on total distance run by the animals is contrary to our believe that volume fraction affects running performance.

Hatchling speed declines as angle increases on loose packed materials. Animal locomotor performance decreases significantly at  $\theta = 10^\circ$  but we see no significant difference in the speed achieved at  $\theta = 20^\circ$ . Similar to close packed materials the running performance decreases with slope, however, speed on all incline angles significantly decreases.

Interestingly duty factor does not seem to be affected by incline angle averaging at 0.69, a duty factor higher than 0.5 is considered to be a walking gait, with terrestrial turtles averaging their duty factor at 0.75 [1, 2]. We expect the duty factor to increase as incline angle increases, expecting the hatchlings to maintain a longer stance phase to possibly counteract slipping. Contrary, on close packed materials duty factor decreases to 0.66 at  $\theta = 20^\circ$ .

Angular extent is compared to our previous research on hatchling locomotion on level ground [45]. The angular extent is larger ( $128^\circ \pm 12.12^\circ$ ) than previously measured ( $111^\circ \pm 17^\circ$ ), this could be due to more individuals tested in 2010 than in 2008 [45]. However, at  $\theta = 10^\circ$  we observe no change in angular extent ( $127.8^\circ \pm 11.40^\circ$ ) compared to  $0^\circ$ . Contrary to the results at  $\theta = 20^\circ$  ( $143.19^\circ \pm 12.86^\circ$ ). Clearly angular extent increases at  $\theta = 20^\circ$  with the hatchlings trying to reach further to avoid slipping.

Incline angles affect step interaction distances, which in turn affects performance speed as shown in Figure 41. Previous research with FBot, a sea turtle inspired physical model (Mazouchova in prep.) and Sandbot, a cockroach inspired robot [43], show that failure is achieved when subsequent steps are affected by disturbed ground, thereby decreasing performance.

On level ground, no step interactions outperform small step interactions. The velocity of the animals decreases when subsequent step distance shortens. This trend can be observed on both loose and hard packed materials. These results demonstrate that a large step distance aids in forward motion by avoiding interaction with previously disturbed ground, that is shown to have negative impact on performance. At  $\theta = 10^\circ$ , we observe the hatchlings using all three step profiles (no step interaction, small step interaction, and overlapping steps), with no step interactions outperforming small step interactions, as well as overlapping steps. Performance on both loose and close packed substrates is comparable at  $\theta = 10^\circ$ . At incline angle of  $\theta = 20^\circ$ , subsequent steps are always interacting, either in small step interaction or as overlapping steps, there is no clear dominant trend visible, suggesting that hatchlings are struggling to climb at this angle and are constantly yielding the material. Their average velocity decreases significantly compared to  $\theta = 10^\circ$  and  $\theta = 20^\circ$ . We have demonstrated that granular inclines pose difficulty for hatchling sea turtles to run on as the material properties cause slipping during forward motion, which decreases the distance advanced per step. A detailed study of slip, step length and insertion depth is necessary to uncover more principles of legged intruders into sandy inclines. To compare the data to animal locomotion on yielding substrates an analysis of downhill running is needed, to cover the broad scope of locomotion observed in the field.

## CHAPTER V

### CONCLUSIONS

#### *5.1 General remarks*

In this dissertation, we integrated biological, robotic, and physics studies to discover principles of fin and flipper locomotion on granular media. We showed for both biological organisms and bio-inspired robots, effective locomotion (running) on granular surfaces was achieved by generating body lift, decreasing drag and reaching an adequate step distance to avoid previously disturbed ground. The use of a flexible wrist during locomotion on yielding substrates outperformed a rigid wrist, it disturbed less ground and decreased the zone of interaction in which locomotor performance was negatively affected. Granular inclines showed that as flipper like appendages interacted with the yielding substrate slopes the velocity decreased as incline angle increased. Based on these findings we expanded on our knowledge of fin and flipper locomotion on granular media, built a sea turtle inspired physical model that allowed us to test various hypotheses and generated new questions that guided our field work.

Sea turtles are fascinating species and are widely popular among adults and children alike. Many people travel yearly to the nesting beaches, just to catch a glance at these mysterious sea creatures. A growing number of environmental predators, and anthropogenic factors are threatening to diminish the sea turtle population and their hatching environment. Findings in this dissertation can have large impact on conservation of these species, in aiding beach re-nourishment projects, and improving the nest environment of sea turtles.

## 5.2 *Specific accomplishments*

### **Biological studies:**

- Captured the kinematics and modeled the mechanics of sea turtle hatchlings running in the field on yielding granular substrates. We found that the use of the wrist adjusted according to the compaction level of the ground to allow for comparable performance on solid and yielding granular media. On hard ground the hatchlings used a rigid wrist and their claw to clasp asperities during forward motion. On soft sand they bent their wrist utilizing the solid properties of the granular medium (**Chapter II**).
- Discovered that hatchlings when running on granular slopes decreased their performance as slope increased. Their angular reach increased at higher slopes to avoid slipping backwards while climbing up inclines. Identified three zones of step interaction that can affect locomotor performance, no step interaction, small step interaction and steps are overlapping at subsequent steps (**Chapter IV**).

### **Robotics study:**

- Develop and used a sea turtle bio-inspired physical model to test principles of fin and flipper locomotion on granular media in a controlled laboratory environment using high-speed camera imaging. Found that a flexible wrist outperforms a rigid wrist on yielding materials, since it allows for less disturbed ground. An interaction effect due to disturbed material at subsequent steps established a zone of disturbance in which locomotor performance of the robot was decreased. Coupling of body lift, decreased drag and step distance allowed for successful movement with a flat, paddle-like appendage on granular substrates (**Chapter III**).

### **Physics studies:**

- Discovered granular physics properties through the use of a flat paddle to mimic a fin or flipper and measured the intrusion and drag force on granular substrates. Drag force exhibited an initial rapid rise in force (solid properties), followed by a slow rise (fluid properties), that exhibited the solid and fluid nature of the material.

Penetration and drag measurements through granular media showed that intrusion into the material was crucial for generating body lift and enabled successful forward movement (**Chapter II and III**).

### 5.3 *Future directions*

As is often the case in initial investigations, many questions have been raised, and many interesting observations have not been thoroughly studied. Below are a few possible future directions, which are natural extensions of the work presented in this dissertation and may be worth pursuing.

**Hatchlings running downhill.** Natural beach environments contain a slope from the dunes to the sea, used by hatchlings to guide themselves to the ocean. Downhill running is equally important as running up sandy slopes. Further, we have observed animals in the field to use their plastron as a sled and tuck their legs to their body, sliding down the hill to gain speed. Fitness on terrestrial media for hatchling sea turtles is measured by their ability to reach the ocean rapidly and our observations suggest that the hatchlings employ several locomotor strategies to ensure survival [3]. Understanding of the animal's locomotion is needed to reveal a more detailed picture of the animal's kinematics.

**Use of hind flipper during terrestrial locomotion.** The use of the hind flipper during terrestrial locomotion is little understood. On level ground the hind flipper is used to aid lift generation of the body during rapid running [45]. On inclines it was observed that the hind flippers were kept closer to the body as opposed to their sprawled posture on level ground, seemingly preventing the body from slipping backward. A detailed analysis of the video data recorded in the field would aid in the understanding of the function of the hind flippers during locomotion on yielding substrates.

**Energetics of running with flippers on granular media.** During our research with both, the hatchlings sea turtles and the physical model, we became interested in understanding the energetics required during locomotion with fin and flipper like appendages on granular media. We observed that a rigid wrist utilizes the solid features of the medium, as well as disturbed less ground. We hypothesize that using a flexible wrist uses less energy. We base our hypothesis on the fact that using the flexible wrist allows the FBot to use kinematics propulsion, which ensures the body to be lifted at a fixed body lift angle throughout the thrust generating phase of locomotion. The resulting decrease in body drag could allow for less energy to be used. Further, using a rigid wrist, FBot is forced to continuously yield

the material during thrust generation. Future studies should intend to measure the energy used during forward motion by measuring the torque output for the motors and comparing it's values when using a flexible wrist or when the flipper is used in air.

**Testing FBot performance on granular inclines.** The study of hatchling locomotion on granular inclines showed that performance is decreased as incline angle of granular slopes rose. A preliminary study with FBot showed that it's performance decreased at slopes of  $5^\circ$  and  $10^\circ$ . Most runs at  $10^\circ$  failed to advance past a few steps and resulted in failure. These results were interesting since our studies with hatchling sea turtles showed them being capable of traversing slopes of up to  $20^\circ$ . Failure occurred due to the body of FBot slipping backwards on the granular substrates during swing phase of the flippers. Future studies should identify the importance of front and hind limb use during climbing of sandy inclines.

**Modifications to FBot.** As mentioned above, the role of the hind limbs are poorly understood. Adding a capability of reproducing hind flipper action on FBot would enable it to use an asymmetrical gait, which is used by many hatchling and adult sea turtles [75]. Further, to measure thrust generation a force plate has been built as an optional addition to be mounted onto FBot. Preliminary data has shown that using varying wrist conditions and substrate compactions display varying thrust force profiles. Understanding thrust generation would vastly improve our knowledge of fin and flipper locomotion on granular media.

## REFERENCES

- [1] ALEXANDER, R., “Optimum walking techniques for quadrupeds and bipeds,” *Journal of Zoology*, vol. 192, no. 1, pp. 97–117, 1980.
- [2] ALEXANDER, R., *Principles of Animal Locomotion. 2003*. Princeton: Princeton University Press.
- [3] BJORNDAL, K. and JACKSON, J., “Roles of sea turtles in marine ecosystems: Reconstructing the past,” *The biology of sea turtles*, vol. 2, p. 259, 2002.
- [4] BOWEN, B., “What is a loggerhead turtle? the genetic perspective,” *Loggerhead Sea Turtles*.
- [5] BUSTARD, H., *Sea turtles: natural history and conservation*. Taplinger Pub. Co., 1973.
- [6] CARR, A. and HIRTH, H., “Social facilitation in green turtle siblings,” *Animal Behaviour*, vol. 9, no. 1-2, pp. 68–70, 1961.
- [7] CHECHINA, O., KOVALENKO, Y., KULAGINA, O., and MIKHAILENKO, A., “Development of locomotion in sea lions *Eumetopias jubatus* in early ontogenesis,” *Journal of Evolutionary Biochemistry and Physiology*, vol. 40, no. 1, pp. 66–71, 2004.
- [8] CLARK, J. and CUTKOSKY, M., “The effect of leg specialization in a biomimetic hexapedal running robot,” *Journal of dynamic systems, measurement, and control*, vol. 128, p. 26, 2006.
- [9] CLAUSSEN, D., LIM, R., KURZ, M., WREN, K., and GATTEN JR, R., “Effects of slope, substrate, and temperature on the locomotion of the ornate box turtle, terrapene ornata,” *Copeia*, vol. 2002, no. 2, pp. 411–418, 2002.
- [10] CRESPI, A., BADERTSCHER, A., GUIGNARD, A., and IJSPEERT, A., “Swimming and crawling with an amphibious snake robot,” in *Proceedings of the 2005 IEEE International Conference on Robotics and Automation, 2005. ICRA 2005.*, pp. 3024–3028, IEEE, 2005.
- [11] DALEY, M., USHERWOOD, J., FELIX, G., and BIEWENER, A., “Running over rough terrain: guinea fowl maintain dynamic stability despite a large unexpected change in substrate height,” *Journal of experimental biology*, vol. 209, no. 1, p. 171, 2006.
- [12] DE PINNA, M., “Teleostean monophyly,” *Interrelationships of fishes*, pp. 147–162, 1996.
- [13] DELCOMYN, F., “Biologically inspired robots,” *Bioinspiration and robotics: walking and climbing robots. I-Tech, Vienna*, pp. 279–300, 2007.
- [14] DICKINSON, M., FARLEY, C., KOEHL, M., KRAM, R., LEHMAN, S., and OTHERS, “How animals move: an integrative view,” *Science*, vol. 288, no. 5463, pp. 100–106, 2000.

- [15] DICKINSON, W. and WARD, J., “Low depositional porosity in eolian sands and sandstones, namib desert,” *Journal of Sedimentary Research*, vol. 64, no. 2a, pp. 226–232, 1994.
- [16] EZCURRA, E., *Global deserts outlook*. UNEP, 2006.
- [17] FISH, F., HURLEY, J., and COSTA, D., “Maneuverability by the sea lion *Zalophus californianus*: turning performance of an unstable body design,” *Journal of experimental biology*, vol. 206, no. 4, p. 667, 2003.
- [18] FLAMMANG, B. and LAUDER, G., “Caudal fin shape modulation and control during acceleration, braking and backing maneuvers in bluegill sunfish, *leporis macrochirus*,” *Journal of Experimental Biology*, vol. 212, no. 2, p. 277, 2009.
- [19] FORTERRE, Y. and POULIQUEN, O., “Flows of dense granular media,” *Annu. Rev. Fluid Mech.*, vol. 40, pp. 1–24, 2008.
- [20] FRETEY, J. and LESCURE, J., “Prédation des tortues marines par les oiseaux en guyane française,” *Oiseau*, vol. 51, pp. 139–145, 1981.
- [21] GIBB, A., ASHLEY-ROSS, M., PACE, C., and LONG JR, J., “Fish out of water: terrestrial jumping by fully aquatic fishes,” *Journal of Experimental Zoology Part A: Ecological Genetics and Physiology*, vol. 315A, no. 10, pp. 649–653, 2011.
- [22] GODFREY, S., “Additional observations of subaqueous locomotion in the california sea lion (*Zalophus californianus*),” *Aqu. Mamm*, vol. 11, pp. 53–57, 1985.
- [23] GRAIN, D., BOLTEN, A., and BJORN DAL, K., “Effects of beach nourishment on sea turtles: Review and research initiatives,” *Restoration Ecology*, vol. 3, no. 2, pp. 95–104, 1995.
- [24] GULKO, D. and ECKERT, K., *Sea turtles: an ecological guide*. Mutual Pub., 2004.
- [25] HAILMAN, J. and ELWSON, A., “Ethogram of the nesting female loggerhead (*caretta caretta*),” *Herpetologica*, pp. 1–30, 1992.
- [26] HAYES, G. and ALEXANDER, R., “The hopping gaits of crows (*corvidae*) and other bipeds,” *Journal of Zoology*, vol. 200, no. 2, pp. 205–213, 1983.
- [27] HEDRICK, T., “Software techniques for two-and three-dimensional kinematic measurements of biological and biomimetic systems,” *Bioinspiration & Biomimetics*, vol. 3, 2008.
- [28] HENDRICKSON, J., “The ecological strategies of sea turtles,” *American Zoologist*, vol. 20, no. 3, pp. 597–608, 1980.
- [29] HEPPELL, S., SNOVER, M., and CROWDER, L., “Sea turtle population ecology,” *The biology of sea turtles*, vol. 2, p. 275, 2002.
- [30] HERTZ, P., HUEY, R., and GARLAND JR, T., “Time budgets, thermoregulation, and maximal locomotor performance: are reptiles olympians or boy scouts?,” *American Zoologist*, vol. 28, no. 3, pp. 927–938, 1988.

- [31] HIRTH, H., “Some aspects of the nesting behavior and reproductive biology of sea turtles,” *American Zoologist*, vol. 20, no. 3, pp. 507–523, 1980.
- [32] HOPKINS-MURPHY, S., OWENS, D., and MURPHY, T., “Ecology of immature loggerheads on foraging grounds and adults in interesting habitat in the eastern united states,” *Loggerhead sea turtles*, pp. 79–92, 2003.
- [33] HSIEH, S., “A locomotor innovation enables water-land transition in a marine fish,” *PloS one*, vol. 5, no. 6, 2010.
- [34] IRSCHICK, D., HERREL, A., VANHOODYDONCK, B., HUYGHE, K., and DAMME, R., “Locomotor compensation creates a mismatch between laboratory and field estimates of escape speed in lizards: A cautionary tale for performance-to-fitness studies,” *Evolution*, vol. 59, no. 7, pp. 1579–1587, 2005.
- [35] IRSCHICK, D. and JAYNE, B., “Effects of incline on speed, acceleration, body posture and hindlimb kinematics in two species of lizard *Callisaurus draconoides* and *Uma scoparia*,” *Journal of Experimental Biology*, vol. 201, no. 2, p. 273, 1998.
- [36] IRSCHICK, D. and JAYNE, B., “A field study of the effects of incline on the escape locomotion of a bipedal lizard, *Callisaurus draconoides*,” *Physiological and Biochemical Zoology*, vol. 72, no. 1, pp. 44–56, 1999.
- [37] ISHIMATSU, A., HISHIDA, Y., TAKITA, T., KANDA, T., OIKAWA, S., TAKEDA, T., and HUAT, K., “Mudskippers store air in their burrows,” *Nature*, vol. 391, no. 6664, pp. 237–238, 1998.
- [38] JAEGER, H., NAGEL, S., and BEHRINGER, R., “Granular solids, liquids, and gases,” *Reviews of Modern Physics*, vol. 68, no. 4, pp. 1259–1273, 1996.
- [39] KAMOUN, S. and HOGENHOUT, S., “Flightlessness and rapid terrestrial locomotion in tiger beetles of the *Cicindela* l. subgenus *Rivacindela* van nidek from saline habitats of australia (coleoptera: Cicindelidae),” *The Coleopterists’ Bulletin*, pp. 221–230, 1996.
- [40] KIM, S., CLARK, J., and CUTKOSKY, M., “isprawl: Design and tuning for high-speed autonomous open-loop running,” *The International Journal of Robotics Research*, vol. 25, no. 9, pp. 903–912, 2006.
- [41] KODITSCHKEK, D., BUEHLER, M., and OTHERS, “Mechanical aspects of legged locomotion control,” *Arthropod Structure & Development*, vol. 33, no. 3, pp. 251–272, 2004.
- [42] LEJEUNE, T., WILLEMS, P., and HEGLUND, N., “Mechanics and energetics of human locomotion on sand,” *Journal of Experimental Biology*, vol. 201, no. 13, p. 2071, 1998.
- [43] LI, C., UMBANHOWAR, P., KOMSUOGLU, H., KODITSCHKEK, D., and GOLDMAN, D., “Sensitive dependence of the motion of a legged robot on granular media,” *Proceedings of the National Academy of Sciences*, vol. 106, no. 9, p. 3029, 2009.
- [44] MALADEN, R., DING, Y., LI, C., and GOLDMAN, D., “Undulatory swimming in sand: Subsurface locomotion of the sandfish lizard,” *Science*, vol. 325, no. 5938, p. 314, 2009.
- [45] MAZOUCHOVA, N., GRAVISH, N., SAVU, A., and GOLDMAN, D., “Utilization of granular solidification during terrestrial locomotion of hatchling sea turtles,” *Biology letters*, vol. 6, no. 3, pp. 398–401, 2010.

- [46] MAZOUCHOVA, N., JACOBSON, M., BANDE-ALI, A., UMBANHOWAR, P., and GOLDMAN, D., “Testing of a sea turtle inspired physical model, flipperbot, on granular media to understand principles of flat-paddle limb kinematics in yielding substrates,” *Bioinspiration & Biomimetics*.
- [47] MILLER, J., LIMPUS, C., and GODFREY, M., “Nest site selection, oviposition, eggs, development, hatching, and emergence of loggerhead turtles,” *Loggerhead Sea Turtles. Smithsonian Books, Washington, DC*, pp. 125–143, 2003.
- [48] MOTA, M., “Beach restoration in florida: Effects on sea turtle nesting and hatchling physiology,” *Dissertation*, 2009.
- [49] MUEGEL, L. and CLAUSSEN, D., “Effects of slope on voluntary locomotor performance in the turtle, *Terrapene carolina carolina*,” *Journal of herpetology*, pp. 6–11, 1994.
- [50] NEDDERMAN, R., *Statics and kinematics of granular materials*. Cambridge Univ Pr, 2005.
- [51] NISHIKAWA, K., BIEWENER, A., AERTS, P., AHN, A., CHIEL, H., DALEY, M., DANIEL, T., HALE, M., HEDRICK, T., LAPPIN, A., and OTHERS, “Neuromechanics: an integrative approach for understanding motor control,” *Integrative and Comparative Biology*, vol. 47, no. 1, pp. 16–54, 2007.
- [52] NYBAKKEN, J. and BERTNESS, M., *Marine biology: an ecological approach*. Pearson/Benjamin Cummings, 2005.
- [53] PACE, C. and GIBB, A., “Mudskipper pectoral fin kinematics in aquatic and terrestrial environments,” *Journal of Experimental Biology*, vol. 212, no. 14, pp. 2279–2286, 2009.
- [54] PARKER, G., “The crawling of young loggerhead turtles toward the sea,” *Journal of Experimental Zoology*, vol. 36, no. 3, pp. 322–331, 1922.
- [55] RUMBOLD, D., DAVIS, P., and PERRETTA, C., “Estimating the effect of beach nourishment on *Caretta caretta* (loggerhead sea turtle) nesting,” *Restoration Ecology*, vol. 9, no. 3, pp. 304–310, 2001.
- [56] SARANLI, U., BUEHLER, M., and KODITSCHKE, D., “Rhex: A simple and highly mobile hexapod robot,” *The International Journal of Robotics Research*, vol. 20, no. 7, pp. 616–631, 2001.
- [57] SCHROEDER, B., FOLEY, A., and BAGLEY, D., “Nesting patterns, reproductive migrations, and adult foraging areas of loggerhead turtles,” *Loggerhead sea turtles*, pp. 114–124, 2003.
- [58] SCHROEDER, R., BOGGESS, M., BACHMANN, R., QUINN, R., and RITZMANN, R., “Comparing cockroach and whegs robot body motions,” in *2004 IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA '04.*, vol. 4, pp. 3288–3293, IEEE, 2004.
- [59] SCHRÖTER, M., NÄGLE, S., RADIN, C., and SWINNEY, H., “Phase transition in a static granular system,” *EPL (Europhysics Letters)*, vol. 78, 2007.

- [60] SHUBIN, N., DAESCHLER, E., and JENKINS, F., “The pectoral fin of *tiktaalik roseae* and the origin of the tetrapod limb,” *Nature*, vol. 440, no. 7085, pp. 764–771, 2006.
- [61] SPAGNA, J., GOLDMAN, D., LIN, P., KODITSCHKEK, D., and OTHERS, “Distributed mechanical feedback in arthropods and robots simplifies control of rapid running on challenging terrain,” *Bioinspiration & Biomimetics*, vol. 2, p. 9, 2007.
- [62] STEINITZ, M., SALMON, M., and WYNEKEN, J., “Beach renourishment and loggerhead turtle reproduction: a seven year study at jupiter island, florida,” *Journal of Coastal Research*, pp. 1000–1013, 1998.
- [63] SWANSON, B. and GIBB, A., “Kinematics of aquatic and terrestrial escape responses in mudskippers,” *Journal of experimental biology*, vol. 207, no. 23, p. 4037, 2004.
- [64] TRITTON, D., *Physical fluid dynamics*. Oxford science publications, Clarendon Press, 1988.
- [65] TU, M. and FULL, R., “Mechanics of a rapid running insect: two-, four- and six-legged locomotion,” *Journal of Experimental Biology*, vol. 156, no. 1, p. 215, 1991.
- [66] TUCKER, T., MOTA, M., CLARK, P., CONDRAN, S., GRIMES, J., and HAYS, A., “Sea turtle monitoring, nest evaluation & protection measures for the city of venice, venice beach renourishment project 2005.,” *Mote Marine Laboratory, Sarasota, FL.*, 2005.
- [67] VAN BUSKIRK, J. and CROWDER, L., “Life-history variation in marine turtles,” *Copeia*, pp. 66–81, 1994.
- [68] VOGEL, S., *Life in moving fluids: the physical biology of flow*. Princeton Univ Pr, 1996.
- [69] WEBB, P., “Simple physical principles and vertebrate aquatic locomotion,” *American Zoologist*, vol. 28, no. 2, pp. 709–725, 1988.
- [70] WIEGHARDT, K., “Experiments in granular flow,” *Annual Review of Fluid Mechanics*, vol. 7, no. 1, pp. 89–114, 1975.
- [71] WITHERINGTON, B., “Biological conservation of loggerheads: challenges and opportunities,” *Loggerhead sea turtles. Smithsonian Books, Washington, DC*, pp. 295–311, 2003.
- [72] WITHERINGTON, B., BJORNDAL, K., and MCCABE, C., “Temporal pattern of nocturnal emergence of loggerhead turtle hatchlings from natural nests,” *Copeia*, vol. 1990, no. 4, pp. 1165–1168, 1990.
- [73] WRIGHT, C., JOHNSON, A., PECK, A., MCCORD, Z., NAAKTGEBOREN, A., GIANFORTONI, P., GONZALEZ-RIVERO, M., HATTON, R., and CHOSSET, H., “Design of a modular snake robot,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems, 2007. IROS 2007.*, pp. 2609–2614, IEEE, 2007.
- [74] WYNEKEN, J., “Comparative and functional considerations of locomotion in turtles,” *Dissertation*, 1988.

- [75] WYNEKEN, J., “Sea turtle locomotion: mechanisms, behavior, and energetics,” *The biology of sea turtles*, vol. 1, pp. 165–198, 1997.
- [76] ZIMMER, C., *At the water’s edge: fish with fingers, whales with legs, and how life came ashore but then went back to sea*. Free Press, 1999.