Burrowing Biomechanics of the Ghost Crab, *Ocypode quadrata*

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Introduction

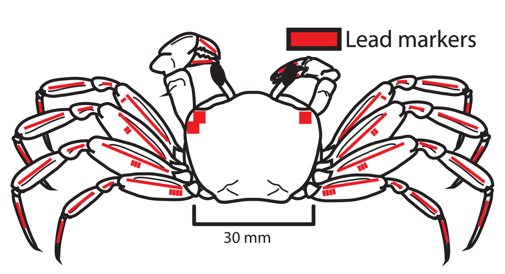
Over the past decade, the field of bio-inspired robotics has experienced unprecedented advancements. We now have robots that can run, climb, and swim. Despite these advancements, however, animals remain substantially more versatile; the same animal is often capable of all three tasks with the same set of appendages. Although incremental technological improvements may partially address this performance gap, we will make more progress by understanding the synthesis of biomechanics, neural programming and learned behavior that is responsible for animals' multifunctional capabilities.

Ghost crabs are ideal subjects for this research because they are remarkably multi-functional. They use their legs and claws (chelae) to capture and manipulate prey, dig complex burrows and run more than 20 body lengths per second. Burrowing encompasses a particularly wide range of behaviors, including specialized postures, locomotion in confined environments, and goal-directed manipulation. To understand this suite of behaviors, we have developed novel x-ray imaging methods and examined crab burrowing to an unprecedented level of detail. These new observations are the first step in a series of experiments to understand the more general features of animal multifunctionality.

Understanding these features and the associated trade-offs, will provide a more comprehensive understanding of animal movement, translating into improved bio-inspired robots, prosthetic devices and rehabilitative techniques. We believe this will lead to new technologies with multi-use parts that permit, not simply obstacle negotiation, but modification of the environment, thus permitting increased mobility in complex environments, such as buildings possibly collapsed by natural disasters.

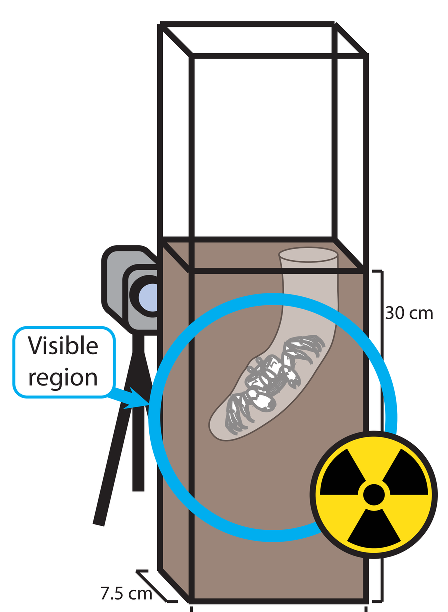
Methods

Subjects:
Wild-caught ghost crabs
3 females, 2 males
Avg. carapace width: 31 mm +/- 3 mm.
Avg. body mass: 20 +/- 5 g.

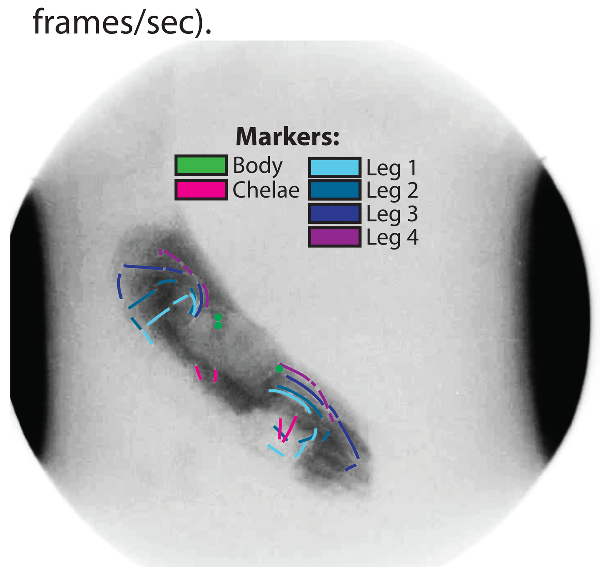


Marking:
Wild-caught ghost crabs were marked with lead foil on the legs, chelae and body (left).

Artificial Beach Environment:
Crabs burrowed on thie own in an plastic enclosure filled with damp sand (gravimetric moisture content: 0.16).
The chamber could be configured in either vertical (shown right) or horizontal positions.



Recording:
Behavior was recorded with a fluoroscope (100 KVp, 3ma) and a digital camera (24 frames/sec).



Video still modified to increase contrast and highlight markers.

Analysis:
Videos (right) were analyzed with CV 2.0 (Vision Research) to extract behavioral characteristics. Extracted features include: limb use, posture, behavioral timing and burrowing speed.

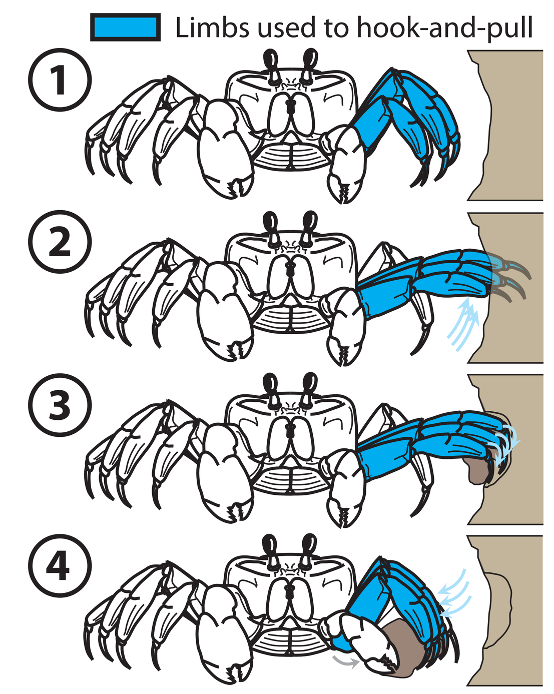
Burrowing Behaviors

Burrowing is a cyclical suite of behaviors; each complete cycle is here termed an **excavation event**. An excavation event is broadly divided into **excavation mechanisms** (several strategies that are executed in parallel) and **manipulation**.

Start of excavation event

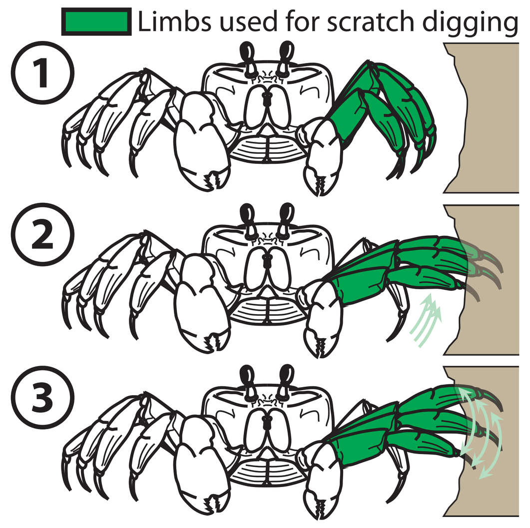
Excavation Mechanisms

Limbs used to hook-and-pull

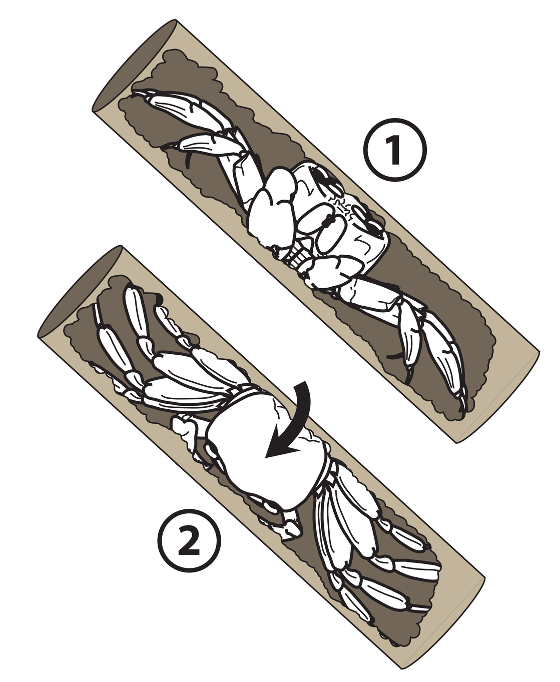


Hook-and-pull:
Crabs remove substrate from the end of the burrow using a hook-and-pull motion. To loosen material, the dactyls on the first three walking legs are inserted into the substrate (2) and contracted sharply (3). Then, the legs contract, bringing material towards the crab's body (4). The chela may be used to help hold collected material but are not used to collect substrate.

Limbs used for scratch digging



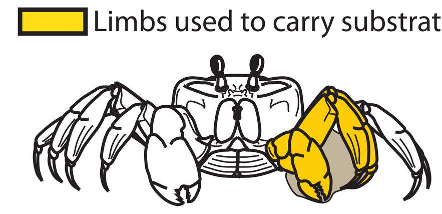
Scratch digging:
Crabs can loosen material making repeated, small amplitude scratches with the dactyls of the first three walking legs. Crabs insert their legs into the substrate (2) and make repeated small amplitude scratches (3). This behavior often precedes a series of hook-and-pull behaviors.



Anchoring posture and body rotation:
Crabs anchor within their burrows by pressing their chelae and the rear of their cephalothorax into the walls of the burrow (1). While excavating, crab maintain this posture but rotate within the burrow (2), often while simultaneously collecting material. We have observed rotatiôns up to 270. This movement, which we observe in horizontal and vertical burrowing, may allow the crabs to control the burrowing direction, aiding construction of complex burrows.

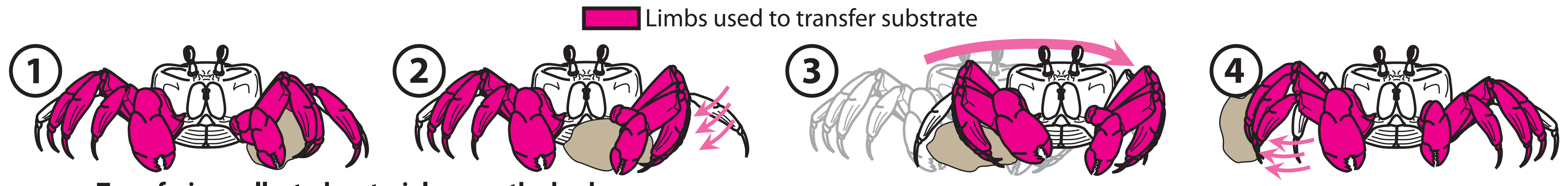
Manipulation

Limbs used to carry substrate



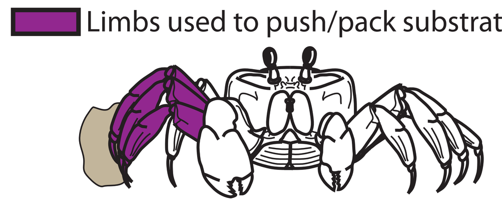
Carrying collected material:
Crabs can carry collected sand using the front two walking legs and the chela on the down-burrow side. The remaining limbs are free to enable climbing/walking, allowing the crab to remove the material from the burrow.

Limbs used to transfer substrate



Transfering collected material across the body:
While within their burrows (1), crabs can transfer collected material from one side of their body to the other. The down-burrow legs and chela push material towards the center of the body (2). Then, the crab shifts its body and up-burrow legs across the material (3). Finally, the up-burrow legs and chela push the material away from the body (4).

Limbs used to push/pack substrate



Pushing collected material:
After transferring material across their bodies, crabs can push material with the up-burrow legs. Crabs can use this strategy to push the material from their burrows or compact the material within their burrows, sealing the entrance.

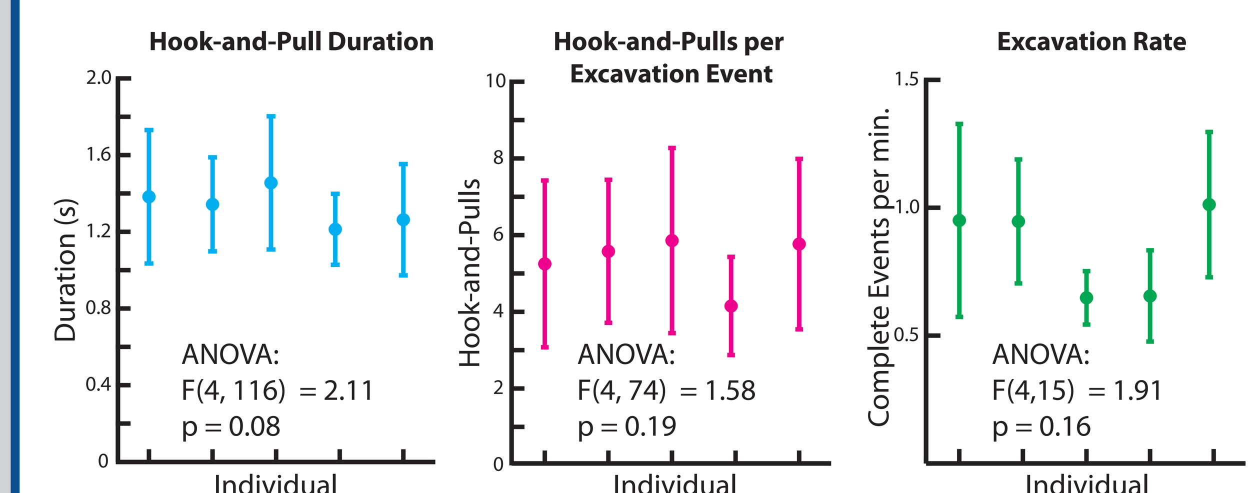
End of excavation event

Variability of Behaviors

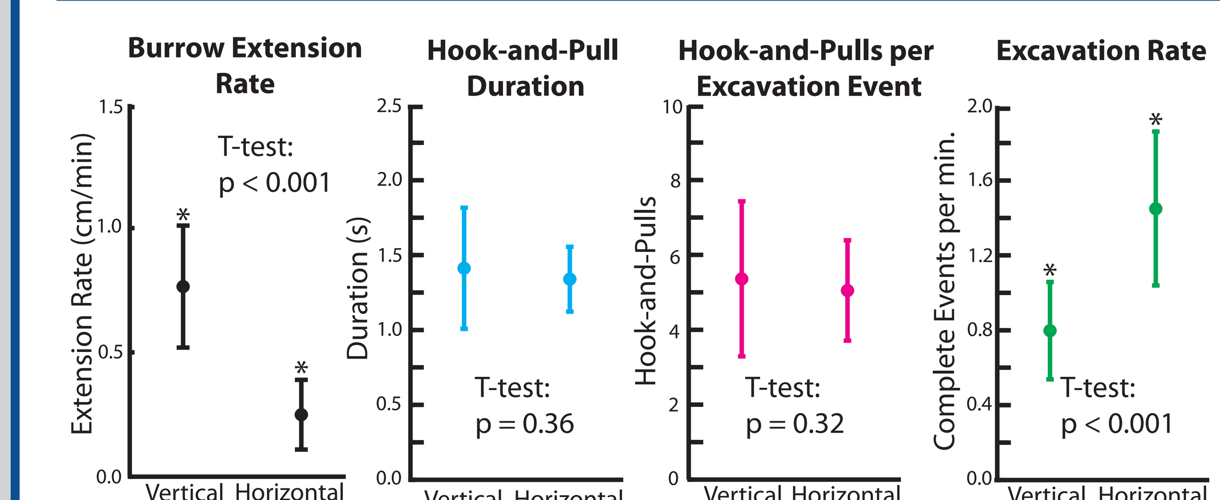
Definitions:

- **Hook-and-pull duration:** the duration of a single insertion/retraction hook-and-pull event. This represents faster substrate collection.
- **Hook-and-pulls per excavation event:** the number of hook/pull events per complete excavation event. This may represent increased substrate loads.
- **Excavations per minute:** the number of complete excavation events per minute. If the other parameters remain the same, this represents decreased resting intervals.

Comparisons:
Burrowing behavior does not vary significantly among the individuals tested. Behavioral metrics are shown below for vertical trials (data pooled individually).



Crabs can, however, vary their burrowing behavior in response to altered environmental conditions. Behavioral metrics below compare vertical and horizontal burrowing (data for all individuals pooled).



This difference in performance appears to be due only to an increased number of excavation events per minute, meaning the crabs burrow faster by reducing rest durations, rather than modifying the internal parameters of the excavation cycle.

Conclusions

Burrowing represents a complex suite of behaviors, representative of the overall multifunctionality demonstrated by ghost crabs. The parameters of this suite are consistent across individuals but can be adapted to variable burrowing environments. The observations presented here will enable more detailed future studies of burrowing in specific and multifunctionality in general.

Future Directions

Continued work, using crabs, physical models and robotic burrowers, will focus on quantifying burrowing behaviors, how substrate properties (including obstacles) affect burrowing. Robotic burrowers and physical models will be particularly useful when testing hypotheses.

Georgia Tech

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