Physical and Biomechanical Modeling of Underwater Locomotion in Sea Stars

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Extensive research has been conducted on terrestrial walking—humans and other bipeds use an inverted pendulum gait that employs an efficient trade-off between kinetic energy (from the velocity of motion) and potential energy (from up and down movement) to propel forward motion (Kuo et al., 2005). Recent research in the Johnson lab has identified a bouncy gait in underwater walkers (Ellers, Johnson et al., 2014), however, modeling and analysis of walking underwater remains understudied. Because water is denser than air, an object's underwater buoyancy counteracts the force of gravity—in this respect, walking underwater resembles a reduced gravity environment. As forces that depend on the density of the fluid in which motion occurs, drag and lift grow by a factor of one thousand underwater. In other words, humans walking underwater would feel like they were fighting to move against a strong wind. Underwater walkers must also account for the acceleration reaction (a fluid's resistance to changes in inertia, i.e.: the force one feels while speeding up and slowing down one's hand in water) and the ground effect (the increase in lift and decrease in drag close to a surface due to flow patterns around the object). In air these factors are mostly negligible, however, underwater they feature strongly in gait analyses.

Approximating the sea star as a flat disc and excluding only the ground effect and any biological catching mechanism employed by sea star podia, I input sea star specific parameters into a force balance equation to model the fall stage within the sea star bouncy gait. Comparisons of this model to experimental data showed the model's estimate of fall distance over an experimentally determined fall time of two seconds to be an overestimate by an order of magnitude. In comparison, my experimental data from controlled drops of varying size and material flat disks and spheres matched nicely the theoretical trajectory obtained through my model (Fig. 1 for a clay disk). This allegiance suggests that the sea star model's divergence from the theoretical originates from the role of the ground effect and leg-catching mechanisms.

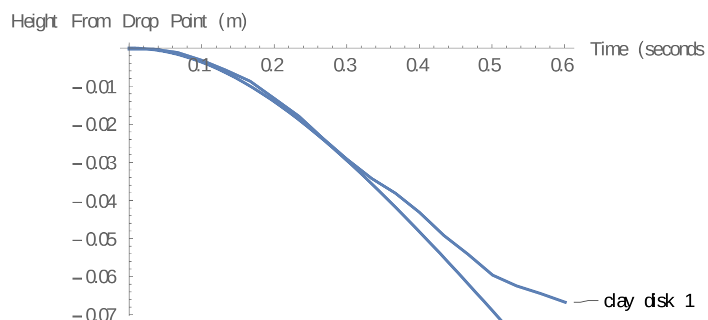

Fig. 1: Drop distance as a function of time. Data for clay disk (top line) vs. theoretical (bottom line)

Quantifying the role of the ground effect depends on certain shape-dependent coefficients that are unknown for sea star shapes. To find these coefficients, I modeled a simple damped pendulum motion in water with objects such that the desired force coefficients were the only unknown influence in the system. I also constructed a force platform to measure the force of impact of sea star falls underwater. Although more work remains to connect force profile data with video analysis, preliminary attempts to measure the sea star's gait appear to coincide well with known values for step frequency (Figure 2).

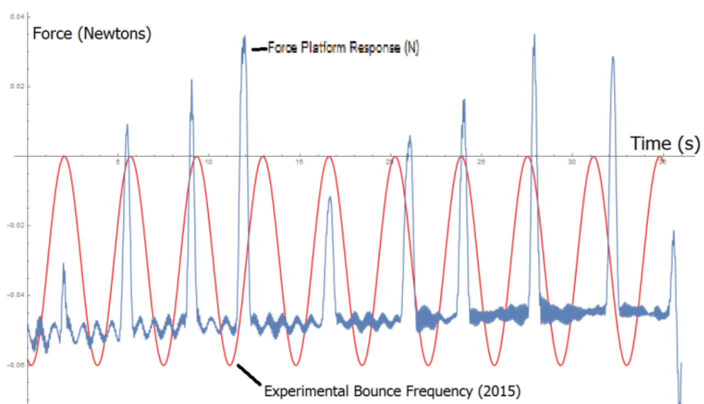

Fig. 2: Force over time. The blue line is the force platform data (with finger taps on the platform as markers of sea star bounces for reference); the red line shows an experimentally determined bounce frequency from Johnson lab (2015).

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References:

Ellers O, Johnson AS, Guttenplan K*, Motokawa T. (2014). The bounce in a sea star's step: classifying gaits in underwater legged locomotion *Integr. Comp. Biol. 54 (suppl 1): e59 doi:10.1093/icb/icu008*

Kuo, A. D., Donelan, J. M., Ruina, A. (2005). Energetic consequences of walking like an inverted pendulum: step-to-step transitions. *Exercise and sport sciences reviews*, *33*, 88-97.