Plunge dynamics:

Compliance to reduce diving impact forces

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INTRODUCTION

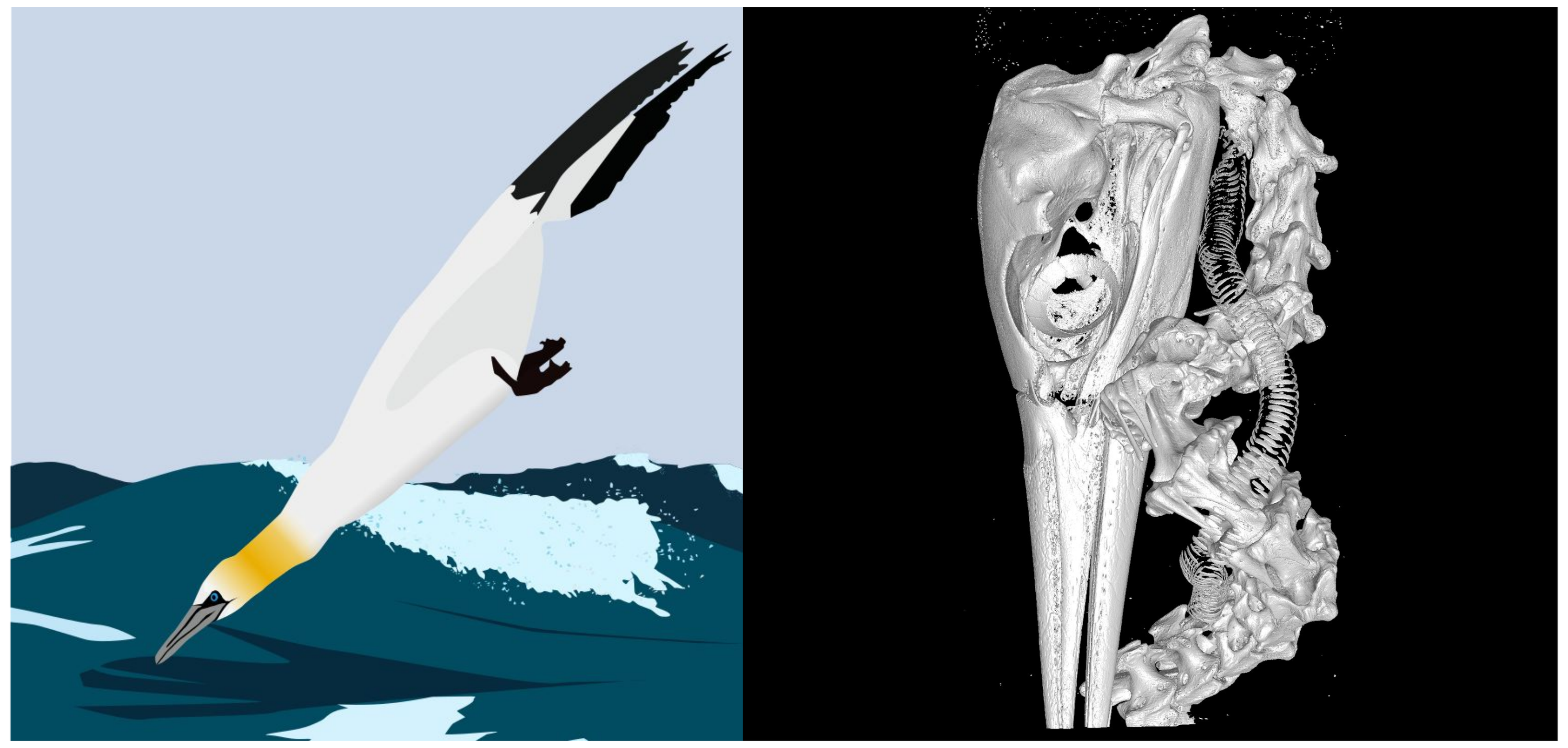

Fig. 1: Diagram of Northern gannet diving, CT-Scan of neck Northern Gannet

Northern Gannets dive at speeds exceeding highway speed limits, with speeds reported up to 120 mph (194 km/h) (Lee, 1982; Garthe, 2014). Despite entering the water at these speeds, their necks are long, highly segmented, and slender—quite the opposite of what you would expect to prevent the neck from buckling.

Fig. 2: Plastic wrapped Northern gannet to show thickness of the neck under the feathers

An additional disadvantage of diving bird neck morphology is that their neck is built of articulating joints that cannot stretch out straight. This, in combination with the slenderness, leads to the hypothesis that diving birds use their neck as a passive shock absorber system. This inspired the research question: "*What is the effect of compliance on water entry dynamics?*"

METHODS

The diving bird is emulated with a two-body system, as shown in Figure 3. To validate our semi-analytical model, we experimentally explored a wide range of half cone angles (β) between 10° and 80° and multiple spring stiffnesses.

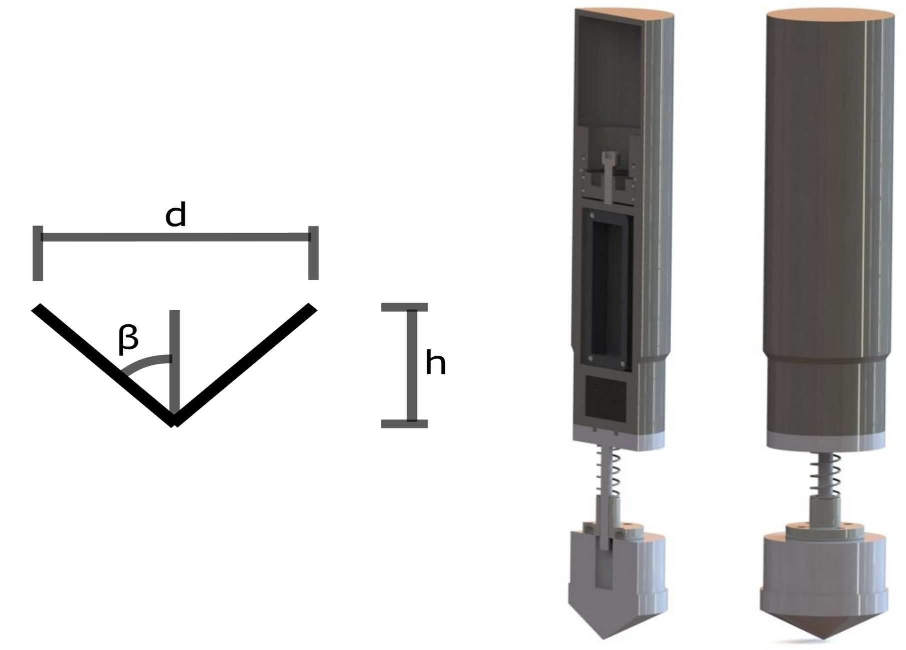

Fig. 3: a) Cone dimensions. b) Test objects have conical heads connected to a body using a compression spring. An IMU is placed inside the body to capture the impact accelerations.

The developed model, defined from impact to pinch-off (Figure 4a), is based on added mass, steady-state drag, and buoyancy. Figure 4b shows the effect of spring stiffness on water entry, with force on the body plotted over time for different spring stiffnesses: Rigid, Firm (7.8 N/mm), and Soft (1.7 N/mm). The extended impact duration and reduced peak force are visible, indicating that the impact energy is spread out over a longer period.

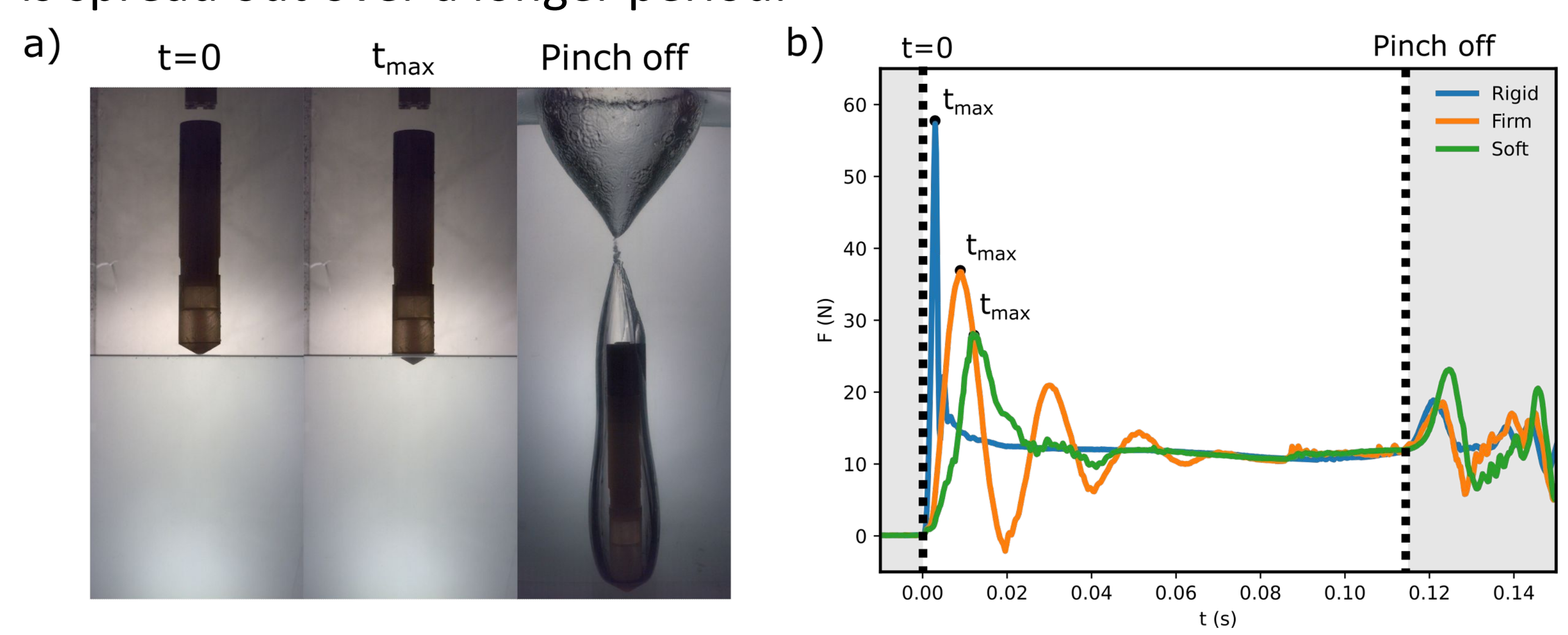

Fig. 4: a) Important time point during water entry. b) Force evolution to the body of the projectile.

RESULTS

The resulting model accurately describes both rigid and compliant water impacts, as demonstrated in Figure 5, for a half cone angle of 60° with a Firm spring (7.8 N/mm).

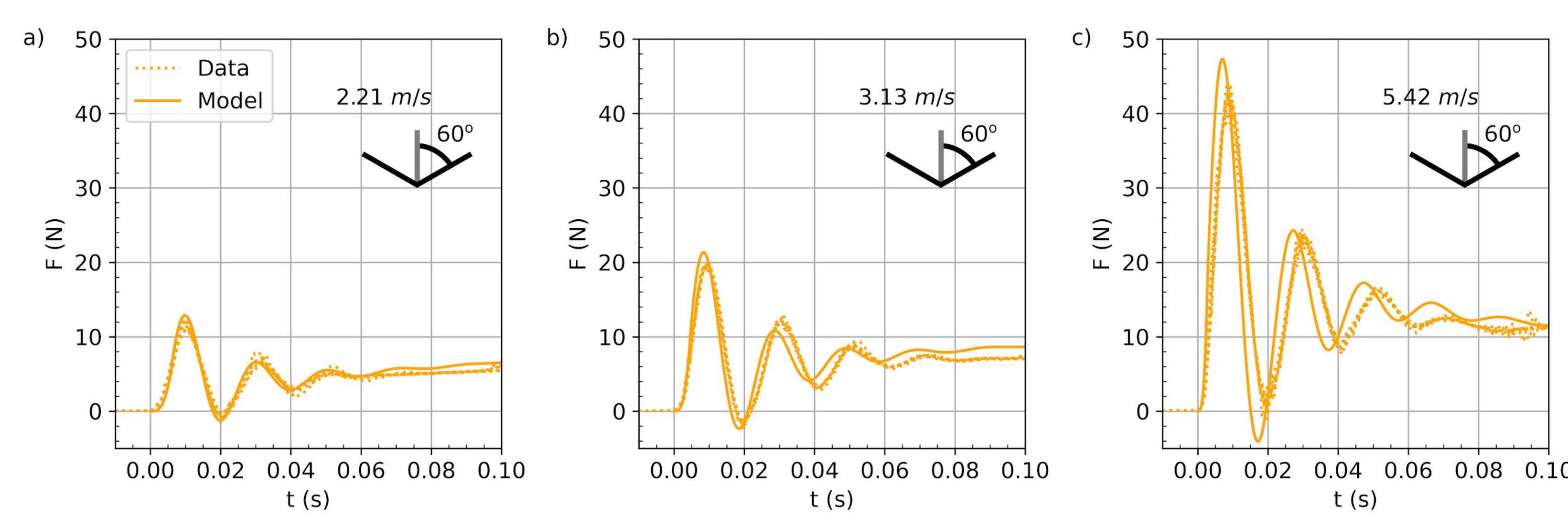

Fig. 5: Impact forces on the body for a half cone angle of 60° at different velocities, comparing the model (solid line) and the experiment (dotted line).

Reducing spring stiffness can decrease body impact force by up to 90%, as shown in Figure 6. Here, C represents the force coefficient, normalized by inertia effects, and ω0h/U0 is the eigenfrequency over the impact frequency. Additionally, a soft spring can lower head force by up to 20%. Figure 6 illustrates how the spring's effect varies with half cone angle and eigenfrequency.

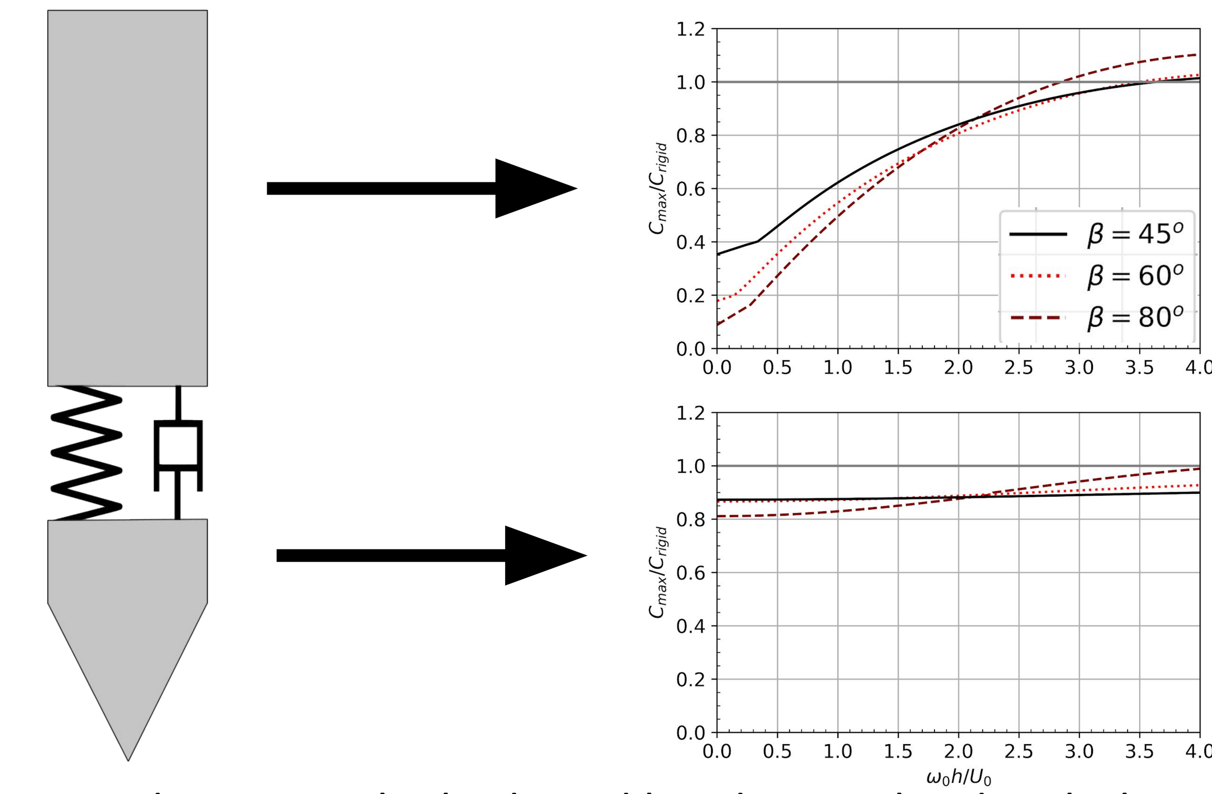

Fig. 6: Force reduction to the body and head normalized with the rigid impact.

With the introduction of the spring, the energy that would normally be immediately lost due to drag is now first absorbed by the spring and later released. Figure 7a illustrates the energy at time t relative to the initial energy. It shows that the energy fluctuates around the rigid case. Additionally, Figure 7b displays the difference between rigid and sprung cases, demonstrating a delayed energy transfer. It was found that the energy losses at pinch-off are the same for rigid and sprung cases, indicating that no significant efficiency was sacrificed for the improvements in force reduction.

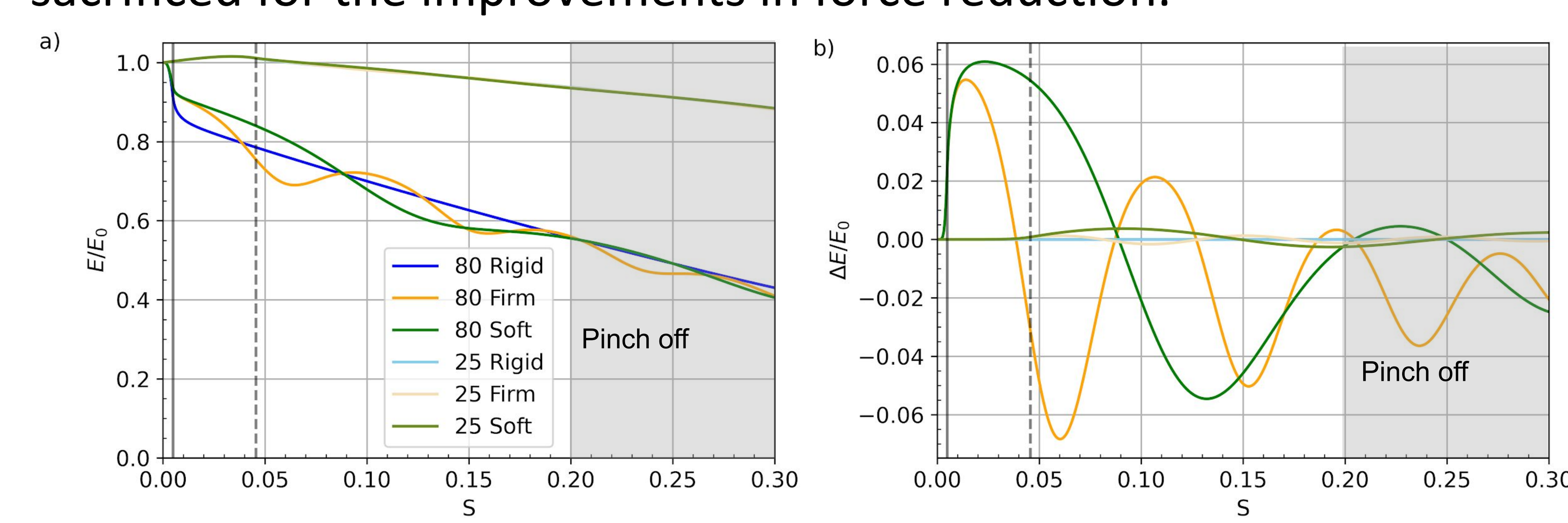

Fig. 7: Energy modulation during impact where E0=initial energy, ΔE=rigid-spring.

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LITERATURE

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