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# Penetration of fox and human skulls into granular matter: Oversimplifying a complex phenomenon?

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The penetration of "perfect" objects such as spheres and cylinders in granular beds has been systematically investigated over the last decades. Given the complex interplay between fluid and jammed states in granular matter, it is already a challenging task (1–6). The study of granular penetration of realistic—"imperfect"—objects is even more difficult and scarce (7, 8).

Recently, Yuk et al. (9) have approached that problem in order to shed light on "mousing": the plunge of the artic fox (*Vulpes lagopus*) into snow to catch prey. The authors dropped a 3D-printed model of the artic fox's skull in order to measure the upward resistance force exerted on it by snow, assuming it as a granular material. They concluded that the curvature of the snout critically determines the impact force: A sharper snout means a lower average impact force (9).

Previous to the work of Yuk et al. (9), we had performed a quantitative study of the penetration of a skull into granular matter—but a human one (7). It was shown that nonsymmetric penetrating objects tend to rotate and to depart from the vertical plunge. Furthermore, it was concluded that subtle imperfections in a sinking object may provoke large tilting angles. Consistently, in the case of a human skull sinking in the head-up position, the rotation occurs toward its smoother part, i.e., the occipital region (see supplemental material in ref. 7).

Since in ref. 9 the authors restrict the fox skull to a purely vertical penetration by attaching it to a load cell by a rigid rod, the possibility of tilting during "free diving" was suppressed. In this letter, we have tackled the problem: We examined the unrestricted penetration of 3D fox skull models penetrating light granular material (expanded polystyrene particles), to detect the possible presence of rotation. A skull model similar to that reported in ref. 9 showed negligible rotation, which seems to offer further support to Yuk et al.'s conclusion that the artic fox is well adapted for mousing (9). However, similar experiments with a different fox skull model (10) did reveal rotation. Fig. 1 shows a snapshot sequence showing the penetration of the latter as it enters the free granular surface at a speed of 2 m/s (see ref. 7 for details of the preparation of the granular bed). Thanks to a light rod attached to the back of the skull, a systematic rotation with a final average angle of nearly 17 degrees is revealed, always in the direction of the "smoother" half of the skull.

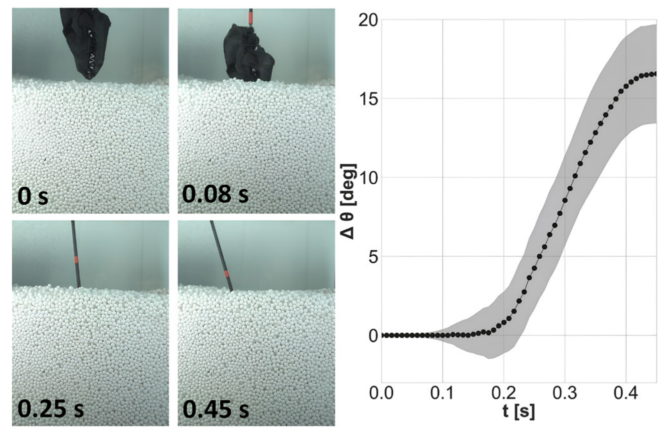


**Fig. 1.** Diving of a 3D-printed model of a fox's skull (10) into granular matter. *Left*: Snapshots of the penetration process at different moments. *Right*: Rotation of the skull relative to the vertical direction. The black line is the average over 10 repetitions of the experiment, and the gray zone represents the SD from the mean.

However, both the experiments reported in ref. 9 and the ones presented here seem too simplified to support a full biomechanical picture of mousing in real life. For example, the surprising increase in the acceleration around 0.8 s shown in Fig. 1*B* of ref. 9, probably means that the artic fox propels itself into the snow using the anterior legs. Further experiments allowing the possibility of skull rotation, leg activity, and perhaps mouth opening are mandatory to get a more realistic biomechanical characterization of fox mousing.

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1. H. M. Jaeger, T. Shinbrot, P. B. Umbanhowar, Does the granular matter? *Proc. Natl. Acad. Sci. U.S.A.* **97**, 12959 (2000).
2. T. Shinbrot, N.-H. Duong, L. Kwan, M. M. Alvarez, Dry granular flows can generate surface features resembling those seen in Martian gullies. *Proc. Natl. Acad. Sci. U.S.A.* **101**, 8542 (2004).
3. H. Katsuragi, D. J. Durian, Unified force law for granular impact cratering. *Nat. Phys.* **3**, 420 (2007).
4. G. Sánchez-Colina *et al.*, "Lock-in" accelerometry to follow sink dynamics in shaken granular matter. *Rev. Sci. Instrum.* **85**, 126101 (2014).
5. N. Algarra, P. G. Karagiannopoulos, A. Lazarus, D. Vandembroucq, E. Kolb, Bending transition in the penetration of a flexible intruder in a two-dimensional dense granular medium. *Phys. Rev. E* **97**, 022901 (2018).
6. V. Díaz-Melián *et al.*, Rolling away from the wall into granular matter. *Phys. Rev. Lett.* **125**, 078002 (2020).
7. M. Espinosa *et al.*, Imperfect bodies sink imperfectly when settling in granular matter. *Sci. Adv.* **9**, eadf6243 (2023).
8. L. Martínez-Ortíz, A. Rivera-Rivera, E. Altshuler, A smart granular intruder. *Phys. Fluids* **36**, 033345 (2024).
9. J. Yuk, A. Pandey, L. Park, W. E. Bemis, S. Jung, Effect of skull morphology on fox snow diving. *Proc. Natl. Acad. Sci. U.S.A.* **121**, e2321179121 (2024).
10. K. Matthieu, Fox skull. *Zenodo* (2018). https://doi.org/10.5281/zenodo.11270132.