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Evolution & Behaviour

The body-language of the elephant trunk

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ABSTRACT

The elephant trunk functions as a muscular hydrostat: it can achieve elaborate movements without the support of any bone. Elephants have evolved unique biomechanical strategies to manage the complexity of this organ. The 3D trajectories of the trunk are composed of basic elements of torsion, curvature and elongation (motion primitives), emerging from the orchestrated actions of antagonist muscle groups.

Illustration by Nadia Freymond realized in the framework of a collaboration between the Image/Recit option of the HEAD (Haute École d'Art et de Design) and the Faculty of Sciences of the University of Geneva.

Articulated bodies like the human skeleton are made of serial joints, restraining the number of possible movements they can accomplish. Conversely, the elephant trunk, the tongues of reptiles and mammals, the arms and tentacles of octopi and squids are all continuously flexible muscular hydrostats. In other words, these arrays of muscles can move with a virtually infinite number of degrees of freedom. They are capable of torsion, bending, elongation, shortening, and stiffening, all without the support of any bone.

Equally delicate and robust, the elephant trunk (also called a 'proboscis'), originates in the embryo as the fusion of the nose and upper lip. It displays an incredible versatility: it can manipulate fine objects, as small as a single blade of grass, or carry heavy loads weighing over 250 kg. Understanding how the elephant deals with the complexity of its trunk and succeeds in controlling its motion is a challenging problem. Research in this domain offers excellent perspectives to engineers trying to develop new paradigms in soft robotics.

To investigate the biomechanical functions of the elephant proboscis, we combined behavioural and motion capture experiments with state-of-the art anatomical analyses. We travelled to South Africa to record the trunk in action. Two adult elephants participated in the study: Chishuru, a 21-year-old fast learner, and Chova, a 23-year-old bull whose trunk is missing the tip 'fingers' and therefore had to develop new prehension strategies. We placed reflective markers along the trunk to measure its trajectories in 3D. Then we set up infrared cameras around the scene to track the markers with very high accuracy.

Meanwhile, in Switzerland, we used medical 3D scanning technologies (magnetic resonance imaging and CT scans) to investigate the functional anatomy of the trunk. Finally, we serially sectioned frozen trunks of African and Asian elephants in 180 slices of 1 cm thickness. Each slice, photographed at very high resolution, provided unprecedented insights into the fine trunk anatomy.

We discovered a fundamental simplification mechanism in the trunk biomechanics. Elephants compose sophisticated trajectories with their trunks similarly to a language. Within this particular language, the combination of kinematic building blocks (instead of words) produce various behaviours (instead of sentences). Indeed, behind the apparent complexity of the trunk motion, we unveiled a finite set of about 20 basic trunk behaviours used to grab and transport objects of various shapes, sizes and weights. Varying the objects attributes induced continuous transitions in the prehension strategies corresponding to different combinations of the 20 building blocks. We found that basic trunk movements can be represented by signature patterns in the time maps of curvature, torsion and elongation. For example, when an elephant grabs and transports an object, the bending of the trunk travels from the tip to more basal portions of the trunk. When reaching for a target in front, it elongates and retracts specific trunk portions in a modular fashion. When the target is placed more to the side, the continuous proboscis can form virtual joints, momentarily giving the impression of an elbow and a wrist, with rigid segments in between. We also uncovered a mathematical relation between the speed of the trunk tip and the curvature of its path: how much the appendage slows down when following a curve can be predicted precisely on the basis of the local curvature of that path. Remarkably, such a scaling law also exists for the human hand when drawing.

In brief, movements of the proboscis are composed of piece-wise patterns in curvature, torsion and elongation, so-called "motion primitives". To understand how the coordinated action of antagonist muscle groups is generating these primitives, we analysed the arrangement of muscle and connective fibres in high-resolution images across the whole trunk. We then reconstructed the morphology of the six main muscle groups in 3D. By combining the anatomical and kinematic data, we were able to draw strong connections between the muscular synergies of the trunk and its basic mechanical functions. We created an interactive online tool allowing the user to explore these principles by observing how specific kinematic variables vary along the 3D-reconstructed trunk when it manipulates objects (https://www.lanevol.org/projects/proboscis).

Using a biomimetic approach, our biomechanical study of the elephant proboscis will assist the development of new so-called ‘soft-robotic’ manipulators (www.proboscis.eu). Indeed, traditional robots, made of serial discrete joints, are very efficient when performing a single pre-defined operation but fail to perform versatile tasks. In that framework, decomposing the motion of a soft and continuous appendage into a small set of basic primitives reduces the complexity of control.

Hence, solutions derived from the natural proboscis can inspire engineers to select the proper design to mimic the high compliance, flexibility and strength of muscular hydrostats.