Understanding the relation between morpho-functional patterns and burrowing performance in moles: a bio-inspired approach

Background

As they are all strictly fossorial, *Talpa* species are of particular interest when focusing on burrowing performance. Among many other specializations, the morphology of the forelimb has been suggested to be a good indicator of locomotor ecology in quadrupedal animals (Fabre et al., 2014) and in moles it corresponds to the main locomotor structure used for digging. Thus, their forelimb specializations have been described by several authors (e.g. Castiella et al., 1992). This limb is composed of three long bones (humerus, ulna and radius), described as shorter but more robust than in other mammals, and displaying supplementary prominent surfaces allowing a greater attachment of the muscles (Fig. 1). The bones of the wrist and the hand are also specific and the development of an accessory bone in the manus, the falciform bone, is noticeable. An important part of the shape of these bones is thought to be driven by functional constraints. Cornette et al. (2015) showed that bone shape is influenced by muscle volume and strength, thus creating various morpho-functional patterns. These patterns, which drive diverse abilities according to the environment, are likely targets of natural selection.

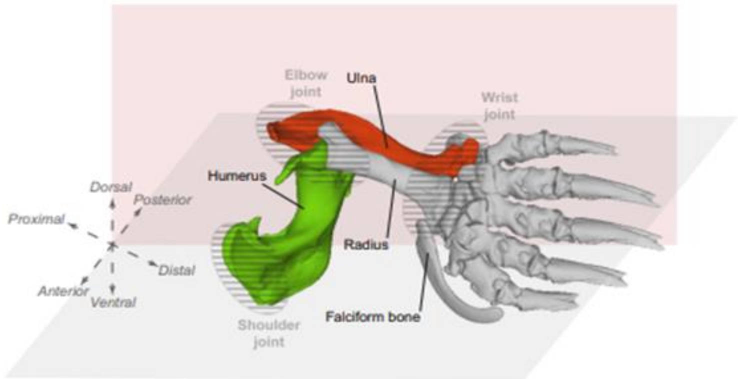

Figure 1 : Illustration of the anatomy of the left forelimb of a mole specimen

However we know little about how the forelimb of the mole is used during digging as very few studies have focused on its kinematics. Using the marker-based XROMM workflow[1], Lin et al. (2019) recently showed that *Scalopus aquaticus* (another fossorial Talpidae) burrows using different forelimb kinematics in loose and compact substrates, demonstrating a clear link between the burrowing motions and the substrate compactness. To go deeper in the understanding, a bio-inspired approach could be especially relevant. For two decades, the bio-inspiration led to the emergence of technical solutions reproducing principles or structures initially described in animals or plants. In a robotics context, studying animal movement and the related morphological adaptations, have provided insights to make efficient autonomous machines (e.g. Chablat et al., 2005). In addition, by using tensegrity mechanisms[2] (e.g. Furet et al., 2019), it is possible to mimic closely the musculoskeletal system of the studied animal and take advantage of these performances (lightness, stiffness…). Conversely, robots are also used as scientific tools to investigate animal locomotion by emulating the kinematic and dynamic properties of animals (e.g. Porez et al. 2014). Thus, in combining the accurate three-dimensional scans of bones, and 3D motions catched by the XROMM technology with a mole robot, we would be able to access key performance values which are today untapped in the morpho-functional studies and highlight the burrowing capabilities of the mole. This robot could find

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[1] The XROMM (X-ray Reconstruction of Moving Morphology) technology combines 3D models of bone morphology with movement data from *in vivo* biplanar x-ray video (Brainerd et al., 2010 ; Gatesy et al. 2010).

[2] They consist of a set of beams (in compression) copying bones in balancing (in the sense of the mechanics) with cables and springs (in tension) reproducing tendons and muscles.

applications in the agro-industry field to sample in the heart of grain bins, but also in underground exploration for raw materials or seeking for victims after an earthquake.

Objectives

In this context, this PhD project will focus on the newly described species *Talpa aquitania* and its two sister-species *Talpa europaea* and *Talpa occidentalis*. Previous study on the humerus and the ulna of these species (Costes et al., 2023), already highlighted morphological variation, especially in muscle attachments area, for these two bones between the three species and between two populations of *T. aquitania,* possibly related to different burrowing performance. Our objectives are to describe and compare (1) morphological variation, and (2) forelimb kinematics during burrowing between these three species, co-occuring in south-western Europe, and between different populations. We expect to describe morpho-functional patterns and to understand the relation between them, locomotor performance and an environmental factor, soil compactness. Data will feed the modeling and the design of an efficient burrowing robot. In fact, we plan to synthesize a forelimb tensegrity structure (3) and define geometric and kinematic configurations (4) classified according to identified efficiency criteria. Once done, we will build a mechatronic mockup (5) based on the most promising configuration in terms of its applicative potential. Finally, we will use in return (5) to evaluate (3) and to confirm assumptions on the mole locomotion expressed in (2).

Assumptions

a) We expect more robust muscles and bones in species and populations living in harder soil, related to more efficient burrowing performance b) we expect inter and intra specific variation in forelimb kinematic during digging and c) we also expect, thanks to the robotic modeling and the mechatronic mockup, to observe, according to the identified morpho-functional patterns variations in burying forces and power consumption.

Methods

Forelimb morphological variation*:* To analyze shape variation and co-variation of the bones 3D geometric morphometrics will be used (Zelditch et al., 2012). The candidate will have to design new templates for the radius, the falciform bone and the phalanges of the thumb. Templates have already been designed by Costes et al. (2023) for the humerus and the ulna. Anatomical dissections will allow us to describe muscle and tendon attachments. Physiological Cross Section Area will also be used to quantify muscles in order to quantify covariation with bones.

3D skeletal kinematic*:* Description of 3D bones movement and skeletal kinematic will be performed following the XROMM analysis method. XROMM animation makes it possible to study skeletal kinematics in the context of detailed bone morphology as it relies on sets of marker positions and quantification of their movements from frame to frame (Brainerd et al., 2010). 2-3 specimens by species or populations (for *T. aquitania*) will be captured in various localities. Each specimen will be filmed burrowing in a radio-translucent enclosure filled with semolina mixed with more or less water to recreate substrate compactness variation.

Pedology data: Serial soil hardness data (kg/cm^2) will be taken in each sampling locality during field work and analyzed along with morpho-functional data. Soil study will be carried out in collaboration with a specialist in granular media, Baptiste Darbois Texier, from the university Paris Saclay in Orsay.

Design of a burrowing robot: The first step will be to define the geometry of the robot as a tensegrity mechanism according to a multibody system framework (e.g. Boyer et al., 2015). It corresponds to a set of solid bodies bound together by joints, and to the earth by contacts. To do so, the main geometric parameters of each body, the nature of each joint and the connection points on bodies of cables and springs will be identified from the morphological data[3]. In a locomotion context (C. Chevallereau et al., 2017), and according to skeletal kinematic data, the second step will be to

[3] The MNHN owns an important moles fluid collection available for the morphology study (bones and muscles). CT scans data are also already available.

define parametric functions of time (cyclic or not) which will control the evolution of the internal shape of the system but also its absolute positions and orientations in space. Once done, a mockup of a mole-like burrowing robot will be produced. As a complement to animal experiments, the locomotor performance of the prototype will be investigated while burrowing in more or less compacted semolina. Kinematic (trajectories, speeds) and dynamic data (torques, power consumption) will be compared with those obtained from the moles in the same conditions.

Feasibility

Material and CT scans data are already available for geometric morphometrics and muscle dissections in MNHN collections. Concerning the kinematic study, PhD supervisors already have a great knowledge of mole trapping and locality of capture. Moreover, the protocol for 3D cineradiography was already established in collaboration with Anvers University. 3D X-ray motion analysis will be performed on the technical platform of motion analysis of the MNHN (MECADEV). Access to this technical platform was granted by the platform managers. Collaborations between MNHN and LS2N already led to the design of bio-inspired robots with tensegrity type mechanisms.

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