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► To cite this version:

C. Böhmer, M. Furet, B. Fasquelle, Damien Chablat, P. Wenger, et al.. Combining precision and power to maximize performance: a case study of the woodpecker's neck. *Computer Methods in Biomechanics and Biomedical Engineering*, 2019, 22 (sup1), pp.S20-S21. 10.1080/10255842.2020.1713463 . hal-03545754

HAL Id: hal-03545754

<https://hal.science/hal-03545754v1>

Submitted on 27 Jan 2022

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Combining precision and power to maximize performance: a case study of the woodpecker's neck

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1. Introduction

The neck in birds has been characterized as a highly complex system that positions the head during all kinds of behavior (Zweers et al. 1994; Böhmer et al. 2018). This involves a variety of highly demanding tasks such as feeding, manipulation, preening, sexual display, nest building, and combat behavior (Böhmer et al. 2019). This versatility is an opportunity for bioengineering, but prior to designing a technological model, the biological system must be understood; in particular regarding the form-function relationships. One behavioral pattern in birds that appears to be relatively constrained is pecking in woodpeckers. There is evidence that the drilling trajectory is essentially planar (Spring 1965). From a morphofunctional point of view, woodpeckers are highly interesting because they are very lightweight (mean body mass $\frac{1}{4}$ 300 g), but are capable to dig into dense tree trunks (Puverel et al. 2019). They strike their beak against a tree repeatedly with high accelerations, high velocity and large force transmissions (May et al. 1979; Wang et al. 2011). We took this bird species as a first example for a biologically inspired robot arm that combines precision and power to maximize performance. Adding biological knowledge into the design process requires a simplification of the complexity of the biological entity (Whitesides 2015). In this context, we (1) analyzed the neck musculature which supplies force for movement; (2) established a planar robotic model using several stacked tensegrity crossed bar mechanisms and (3) integrated all data into an actuated model of the bird neck.

2. Methods

2.1. Dissection

The neck musculature of one generalist bird (*Corvus monedula*) and three species of woodpeckers was comparatively investigated by quantitative dissection: the green woodpecker (*Picus viridis*), the great spotted woodpecker (*Dendrocopos major*) and the black woodpecker (*Dryocopus martius*). They differ in pecking performance (Jenni 1981) which allows identification of muscular adaptations specific for high power. After removing the skin and fascia, each muscle was identified and systematically detached from both the origin and insertion. Muscles were assigned to main functional categories indicating the direction and vertebral region of action. The craniocervical muscular system was illustrated in a schematic diagram.

2.2. Kinematic and dynamic modelling

The woodpecker neck is modelled in the sagittal plane with a serial stack of Snelson's X-shape tensegrity mechanisms (Wenger and Chablat 2017), which is a class 2 tensegrity mechanism composed of an antiparallelogram made of 4 rigid links. The sides of the mechanism are attached with two springs that ensure a stable rest position, and cables run through the springs. By modifying the cable tension with motors, different positions can be reached. The kinematic model links the output of the modelled stacked modules (i.e. the position and orientation of the tip of the beak) to the input of the robot (the orientation of each X-shape mechanism). The dynamic modelling takes into account the influence of the rigid links masses and inertia, spring stiffnesses and cable tensions and links the motion of the model (position, velocity, acceleration) to the forces needed to move it (Furet et al. 2018).

3. Results and discussion

3.1. Muscular adaptations

The overall muscular system of the neck in the analyzed woodpeckers corresponds to an earlier anatomical description of *Dendrocopos* provided by Jenni (1981). Our quantitative analysis revealed that the adaptation to pecking is particularly evident in the craniocervical and ventral muscle system.

As opposed to generalist birds, the muscles of the craniocervical system in woodpeckers show adaptations specific for precision of force control. The highly specialized tendinous architecture of the ventral muscle system in woodpeckers enables forceful and rapid movements. Compared to the other species of woodpeckers, the tendons are most prominently developed in the black woodpecker.

In summary, the anatomical arrangement of muscle and tendon in the neck of woodpeckers facilitates efficient pecking by combining precision and power.

3.2. Neck movement

Videos of alive woodpeckers do not allow us to precisely detect the neck movement because of the feathers. As a consequence, a film of the corpse of a green woodpecker without its feathers and moved by hand was recorded and used to capture a neck movement, with the aim of reproducing it with our robot in simulation.

To convert the video into a robot movement, the frames are analyzed independently. For each of them, the middle line of the neck is detected, then the mechanisms of the robots are placed one by one from the bottom of the neck. The obtained positions give us the trajectory.

3.3. Simulation

The manipulator is made of 11 identical mechanisms that is the number of vertebrae in the green woodpecker. The dimensions were chosen to have a manipulator with the same proportions than the woodpecker neck.

Simulations are performed with Matlab Simulink and Simscape Multibody. The use of the dynamic model in the control law allows obtaining an accurate tracking with a full-actuated robot. In this case, the forces applied have similar shapes for each mechanism, which is promising for under-actuation. Simple under-actuation strategies also succeed at tracking the movement with a good precision, and the neck musculature of the woodpeckers will be used to create related under-actuation strategies.

4. Conclusions

The aim of the present work was to extract the anatomical parameters that are essential to perform precise and powerful movements. The conceptualization of the extremely complex musculature of the neck in birds revealed such a specialization. Eventually, the prototype of the woodpecker's neck will serve as a starting point for future invention and application such as industrial soft-robots that execute their task in collaboration with humans in an efficient and safe way.

Acknowledgements

We thank the Chene Association and the Goupil Association for providing bird specimens for dissection.

Funding

This study was financially supported by the Agence National de la Recherche (ANR): Project ID #ANR-16-CE33-0025 (AVINECK), Project coordinator: A. Abourachid.

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KEYWORDS Neck; bird; tensegrity; bio-inspired; robotics

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