KINEMATIC MODELING OF THE SEAHORSE TAIL

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INTRODUCTION

Through billions of years of natural selection, nature has produced elegant and efficient solutions to a whole range of real-world problems. The evolutionary adaptation of an organism to its environment is in a lot of ways comparable to the design cycle in engineering: changes in functionality are tested on their fitness and are thereafter reinforced or rejected.

A seahorse (belonging to the genus *Hippocampus*) is one example of an animal that underwent remarkable adaptations to its environment. Due to a relatively weak caudal fin, the seahorse is hardly able to escape from predatory fish. For defensive purposes, the seahorse is covered by bony plates instead of scales, acting like a sort of armor against bites of predators. Despite the 'armor plating', this fish has still a remarkable tail bending flexibility. The seahorse can use its tail as a prehensile organ, grasping onto plants and other object on the seafloor.

The unique combination of strength and flexibility of the seahorse tail structure is very interesting from an engineering point of view. The tail bending mechanism has been studied in vivo [1], but details of the mechanics and kinematics involved remain largely unknown. Modeling the seahorse tail will hopefully provide a profound insight in the mechanics and kinematics of the different chains of the tail skeleton.

METHODS

A micro-CT scan (spatial resolution 21 μm) of a seahorse (species *Hippocampus reidi*) with curled tail was performed by the Centre for X-ray Tomography of Ghent University. Segmentation and 3D-mesh generation was carried out using Amira 5.2 (Visage Imaging, Inc.) (Fig.1, left). For two tail segments, the five skeletal elements (a central vertebral element, surrounded by four dermal plates) were exported as individual triangular surface meshes (Fig.1, right). Two other segments were combined into a single surface mesh in order to act as a constraining structure during the kinematic analyses.

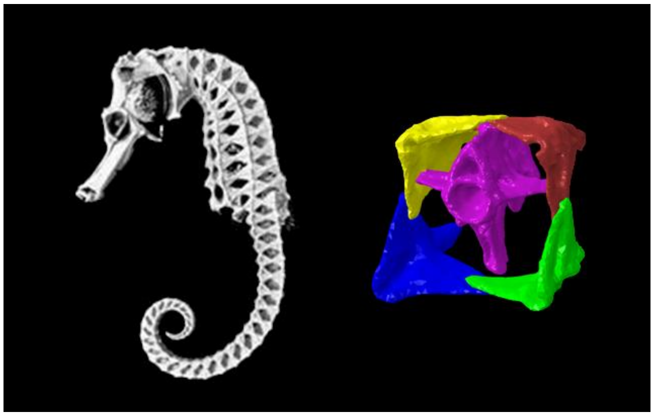

Figure 1: Micro-CT scan of a seahorse (left) and a single tail segment (right)

The musculoskeletal system of the seahorse tail was modeled with Abaqus/CAE 6.9-EF1. The geometry was simplified by replacing the different elements with rigid beam connections between the centre of mass of each element and the attachment points (Fig.2). The mass of each part was approximated by multiplying its volume with 1800 kg/m³ [2]. Muscles and joints between the elements were modeled by creating connectors. The joints were given constraints according to their physiology and stability considerations. They included sliding joints and ball and socket joints. The entire model is demonstrated in Fig.3.

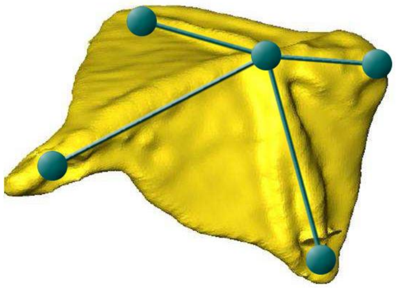

Figure 2: Beam connections on a dermal plate

The attachment points of the muscles were determined with pyFormex, an open-source software package intended for generating, manipulating and operating on large geometrical models of 3D structures (www.pyformex.org). As the different segments of the tail skeleton appear to have a highly uniform shape, the determination of the attachment points was automated within pyFormex, which has proven to be well suited as a dedicated pre-processor for finite element modeling.

Figure 3: Tail model with the different skeletal segments

RESULTS AND DISCUSSION

The main muscles that seem to be involved in the ventral curving of the caudal system are the myomere muscles and the median ventral muscles (Fig.4). The myomere muscles are biarticulate, spanning three vertebrae. They can bend the tail both ventrally (bilateral contraction) and laterally (unilateral contraction). The median ventral muscles are uniarticulate and connect the ventral processes of two consecutive vertebrae. Contraction of these muscles causes a ventral bending of the system.

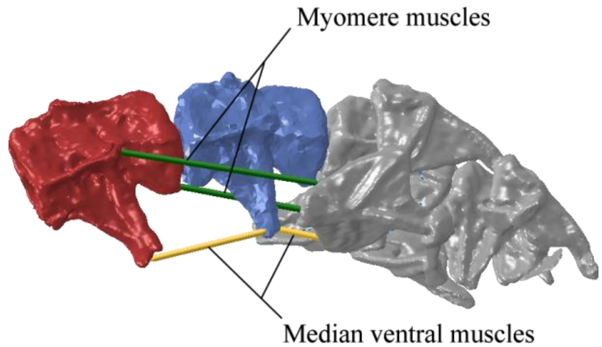

Figure 4: Modeled tail bending muscles

Two different sets of kinematic constraints were applied to the model. In the first simulation, the caudal segments were stretched, while measuring the connector motions. The second analysis used the connector motions of the median ventral muscles. As the tail stretches, the different elements of the tail segments enlarge while the overlapping joints between the dorsal and ventral plates become shorter.

CONCLUSIONS

Some segments of the musculoskeletal system of the tail of a seahorse were modeled. As the tail stretches the joints between the vertebrae, dorsal and ventral plates move in a complex way to allow the motion. The model holds promise to provide a keen insight in the kinematics involved.

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