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Measurement on Morphology and Kinematics of Crucian Vertebral Joints

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Abstract

In order to provide data for joints control of our recently designed crucian like biomimetic robot fish, an X-ray photograph technology was adopted to determine the number and length of vertebral joints. A frame-by-frame analysis of high-speed videotapes was conducted to quantify the kinematics of crucian at four speeds (12.651 cm·s^{-1}, 18.201 cm·s^{-1}, 21.901 cm·s^{-1}, 24.368 cm·s^{-1}) during cruising. In addition to a brief introduction to experimental conditions and methods, we analyzed the influence of individual diversity on the absolute length as well as the non-dimensional length of vertebral joints. We also presented the maximal angular velocity and acceleration of vertebral joints under four swimming speeds, and provided the change of relative rotation angle, angular difference, angular velocity and angular acceleration of the rear vertebral joints with time at a certain swimming speed of 12.651 cm·s^{-1}. At last, we presented the maximal lateral displacement of each mark at that speed. The study found that the influence of individual diversity on the non-dimensional length of vertebral joints is not significant; the maximal angular velocity and acceleration of vertebral joints increase with swimming speed; angular difference, angular velocity and angular acceleration exhibit two maximal values over one period at a certain swimming speed.

Keywords: crucian, high-speed-video technique, morphology, kinematics, vertebral joint

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1 Introduction

The process of evolution has produced a diversity of nearly 25000 species of fish during the last 520 million years[1]. Natural selection proposes that each species has its own unique and optimum way of interacting with its environment. This gives each fish uniqueness in its body shape, size and propelling style[2]. Although not optimal but highly efficient swimming mechanisms of fish should guide the design of the propulsion systems of swimming robots[3]. Whilst the fish body and fin are the major aids in providing maneuvering control, different combinations in the movement of these aids actuate a maneuver and make the task of mimicking fish movement complicated[4]. In the field of underwater research, carangiform robot offers exceptional advantage over propeller in preserving an undisturbed condition of its surroundings for data acquisition.

The majority of fishes use Body/Caudal Fin (BCF) undulations for propulsion. Only about 12% of 450 extant fish families use undulations of Median or Pectoral Fins (MPF) as their routine propulsive mode[5]. However, many more species use MPF for stability and maneuverability, especially at low speeds, while some MPF swimmers apply BCF mode to reach high speeds during escape reactions[5]. Fish that mainly use BCF undulations for locomotion are classified into five different types, depending on the manner they swim: anguilliform, sub-carangiform, carangiform, thunniform and ostraciform[2,5–8]. Carangiform swimming is a mode of BCF propulsion in which the large amplitude of the undulations is mostly restricted to the one-half or even one-third posterior part of the body and increases sharply in the caudal area[7]. This mode of swimming is used by many fishes, such as crucian.

Two fundamentally different conditions are usually adopted to measure fish: one is the spontaneous movement of a fish swimming in static water[8–11]; the other is the movement of a fish in a controllable water current, such as flow tank[12,13]. Numerous recent experiments with the state-of-the-art Particle Image Velocimetry (PIV) technique have provided a wealth of data in terms of wake flow field[14–21]. Most attempts to relate these attributes of undulating organisms to fish anatomy have

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concentrated on the distribution of external surface area[22,23]. However, to clarify the functional basis of undulatory swimming performance, it is desirable to determine how internal morphology is related to externally visible movement[14–18]. Moreover, few reports involve the vertebral joint kinematics of carangiform fishes. Particularly, most of these studies are not for the purpose of the bionic robotic fish applications.

The present research aims to tackle several confused issues, such as what is the influence of individuals on vertebral joint length? How do kinematic parameters like rotation angle, angular difference, angular velocity and angular acceleration of the rear vertebral joints change with propulsion speed? What is the relationship between the maximal lateral displacement of vertebrae and propulsion speed? The answers to these questions help in providing data for joints control of our recently designed crucian like biomimetic robot fish.

The rest of this paper is organized as follows. In section **2**, we give a brief description of the experiment condition and method. Section **3** is the results and discussion. The last section draws conclusions and suggests future work.

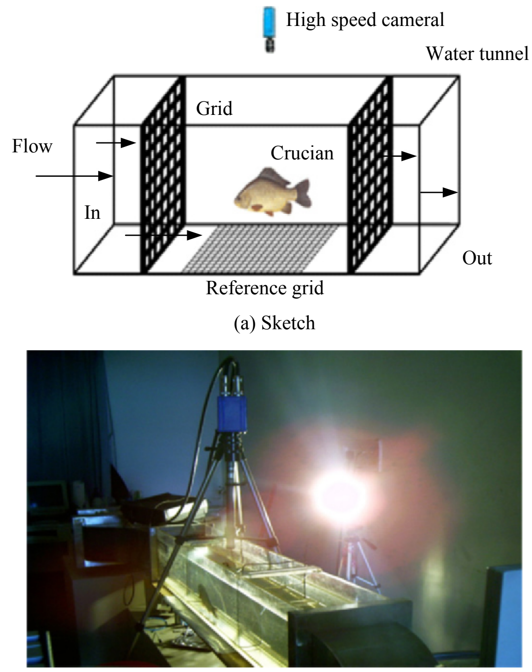
2 Materials and methods

2.1 Experimental subjects and protocol

We obtained six crucian from supermarket which were divided into two groups. For three large individuals, the average values (and range) of total length (*TL*) and mass were 32.8 cm (31.3 cm – 34.3 cm) and 538 g (516 g – 560 g), respectively, and for three small individuals, these quantities were 19.2 cm (18.2 cm – 20.2 cm) and 296 g (284 g – 308 g). The crucian were fed a maintenance diet of earthworms, and their average time in captivity after marking on them was approximately 3 days. All fish were maintained at a constant temperature of 19±2 ˚C, which was the same as the mean value of water temperature used during experiments (19±1 ˚C). The larger individuals were housed individually in 35 L tanks, whereas the smaller individuals were kept in a 20 L tank. The average exposure time is 12 hours/day.

After some additional experiments, the fish were preserved and X-ray photographs were taken to determine the number and length of vertebral joints. We used a calibrated flow tank to obtain steady swimming from each crucian at average forward speeds of 12.651 cm·s^{-1}, 18.201 cm·s^{-1}, 21.901 cm·s^{-1}, 24.368 cm·s^{-1}, respectively. The working section of the flow tank was 40 cm × 20 cm × 25 cm, with the long dimension being parallel to the flow. Prior to the experiments, flow speeds were determined by videotaping dense clouds of methylene blue dye, which was injected at 2 cm – 3 cm intervals along the height and width of the working section, and we then generated calibration curves relating flow to the digital display of a tachometer that indicated the rotation speed of the propeller in the flow tank. We only analyzed sequences of fish that were swimming more than 5 cm away from the sides and bottom of the tank and below the surface of the water. Strict criteria were used for selecting steady swimming. Sequences were only analyzed if the change in the upstream–downstream position of the fish was less than 5 mm per tail beat. With the exception of the two fastest speeds, the change in upstream–downstream position was usually less than 5 mm over the entire time interval analyzed.

Fig. 1 shows the experimental set-up for measuring the morphology and kinematic parameters of crucian vertebral joints. The set-up consists of water tunnel, high-speed camera system, an indication of grid and reference grid coordinates. The water tunnel space dimension is 145 cm × 20 cm× 25 cm, with continuously adjustable flow speed range of 0 cm·s^{-1} – 50 cm·s^{-1}, the acceleration or deceleration of the flow is 0.2 cm·s^{-2}.



(a) Sketch

(b) Laboratory set-up

Fig. 1 Experimental device for measuring the morphology and kinematic parameters of crucian vertebral joints.