A Study on the Locomotive Functions of Excirolana chiltoni Richardson

Kyohei HOSHIKA¹ and Seiichi SUDO²

¹ Graduate School of Systems Science and Technology, Akita Prefectural University, Yurihonjo 015-0055, Japan
² Faculty of Systems Science and Technology, Akita Prefectural University, Yurihonjo 015-0055, Japan

(Received 28 December 2010; received in revised form 12 May 2011; accepted 5 June 2011)

Abstract
This paper describes the locomotive functions of a cirolanid isopod, Excirolana chiltoni Richardson, from the viewpoint of mechanics. The behavior of isopods in the laboratory was analyzed with the high speed video camera system. Both free swimming and tethered swimming of cirolanid isopods were analyzed quantitatively. Some locomotive modes of cirolanid isopods were found out, that is, swimming in water, walking in air, and burrowing into the sediment were observed. The results of a series of observation and analysis revealed the locomotive characteristics of cirolanid isopods, such as the swimming velocity, swimming leg tip path, walking vertical walls and climbing velocities in air, and burrowing velocity into sand, and so forth.

Key words
Cirolanid Isopod, Aquabiomechanism, Locomotive Function, Swimming, Hydrodynamics, Thrust

1. Introduction
All living things are sensitive to certain changes in their surroundings. Animals are members of the kingdom Animalia. They obtain energy by acquiring and ingesting their food. Most animals move about using legs, wings, or fins. Generally almost all swimming animals, both fish and mammals, are considerably longer in the direction in which they swim than in the directions at right angle to it. They have reasonable body figures for their movement. They have their original locomotive organs and locomotive functions. Extensive investigations on the locomotive mechanisms and the locomotive functions of swimming animals have been conducted and reported [1]. For example, the measurements of morphological parameters and the drag coefficient on various individuals of nine species of the family Dytiscidae were carried out by Nachtigall [2]. He also referred to his own investigations [3]. Daniel developed simple methods for dealing with the acceleration reaction and explored applications of the acceleration reaction in animals that swim unsteady or move appendages in an unsteady fashion [4]. Alcaraz and Strickler studied the swimming mechanisms of cyclopoid copepods and attempted to estimate the work done and the contribution of locomotion to total energy consumption [5]. Authors also analyzed the swimming behavior of small shrimp-like creature and small planktonic copepods in our previous paper [6]. However, there still remains a wide unexplored domain. Especially, the synthetic locomotive functions of small aquatic creatures have never been studied. The behavior of the cirolanid isopods is to a great degree governed by the tides [7]. They show highly mobile locomotive methods.

This paper is the first step study for the purpose of clarifying the whole aspect of isopod locomotive functions from the viewpoint of aquabiomechanism. The behavior of the cirolanid isopod, Excirolana chiltoni Richardson, was analyzed with the high-speed video camera system. Three locomotive modes of the cirolanid isopod were found out. The characteristics of swimming, walking, and sand burrowing were revealed.

2. Experimental Apparatus and Procedures
In the experiments, the locomotive functions of the cirolanid isopod were examined. A schematic diagram of the experimental apparatus to study characteristics of swimming, walking, and burrowing into sand is shown in Fig. 1. The experimental apparatus consist of the water container system and the optical measurement system. The rectangular container made of the clear glass with dimension 30 mm in height and 22 mm x 4 mm wide was used for free swimming and tethered swimming analysis. In the experiment, container was filled with seawater. The cirolanid isopods were released on the tethered cirolanid isopod was set in the water container. In the experiment on swimming, the container was partially filled with the coastal sand with 12 mm in depth. In the experiment on walking, the container was partially filled with seawater 14 mm in depth. In this case, the wall climbing speed were measured.

The motions of swimming, walking, and burrowing sand were recorded by the high-speed video camera. A series of frames of the locomotive behavior of the cirolanid isopod were analyzed by the personal computer. The experiments were performed under the condition of the room temperature (water temperature 15-20°C).

3. Test Cirolanid Isopod
In this study, test cirolanid isopod is Excirolana chiltoni Richardson. Figure 2 shows the photograph of the cirolanid isopod used in the experiment. The cirolanid isopod, Excirolana chiltoni Richardson, occurs in the intertidal zone of sandy beaches in northern Japan [8]. The behavior of the isopod, Excirolana chiltoni, is to a great degree governed by the tides [7]. When the advancing wave wash of the incoming tide reaches the level on the high intertidal beach where isopods are buried, they leave the sand to swim and forage in the wash zone. This period of swimming activity continues for approximately 2 hours past tide crest, after which the isopods once again burrow into the sand, which allows them to escape the ebbing tide and reestablish their position on the exposed beach until the next period of high water [7].

The isopod body is divided into three distinct regions; head (cephalon), thorax, and abdomen (pleon) [9]. The first
5th International Symposium on Advanced Science and Technology in Experimental Mechanics, 4-7 November, 2010, Kyoto, Japan

Segment of the thorax is fused to the compact head with two pairs of antennae and a compound eye. The first antennae are typically chemosensory, and the second antennae are typically tactile structures. The remaining seven free segments (pereonites) of the thorax comprise the pereon. Each segment bears a pair of pereopods (walking legs). The pereopods are modified for locomotion and for latching onto prey. The short abdomen consists of five free segments (pleonites) and pleotelson (fusion of last pleonite to telson). Each pleonite bears a pair of biramous pleopods which are used for swimming and for respiration.

4. Experimental Results and Discussion

4.1 Swimming behavior

4.1.1 Free swimming

Figure 3 shows a sequence of photographs showing the free swimming behavior of cirolanid isopod. The thrust-generating mechanism is related to the motion of the swimming legs. Figure 4 shows the swimming trajectory of the cirolanid isopod. In Fig. 4, the head point of the cirolanid isopod is plotted in a fixed coordinate system located on the container. The length of the cirolanid isopod is \( L = 7.1 \text{ mm} \). The cirolanid isopod is swimming in the direction as shown by the arrows. The time interval during each plot is \( \delta t = 2.22 \text{ ms} \). Swimming speed can be obtained from the time change of displacement in Fig. 4. Figure 5 shows the velocity variations of the cirolanid isopod during free swimming. It can be seen from Fig. 5 that cirolanid isopod swimming is unsteady motion. Whenever animals move relative to a fluid environment, forces are generated. There are some studies in which the hydrodynamics for acceleration locomotion have been analyzed [10-13]. In all these cases, accelerations of a body lead to large hydrodynamic reactions known as add-mass force, as well as the drag force [14]. Based on these studies, the thrust is described as follows:

\[
T = \frac{1}{2} \rho S C_D U^2 + \alpha \rho V \frac{dU}{dt} + m \frac{dU}{dt}
\]

where \( \rho \) is the density of fluid, \( C_D \) is the drag coefficient for motion, \( U \) is the instantaneous velocity of the body, \( \alpha \) is the add-mass coefficient that depends upon the orientation of the body, \( S, V, \) and \( m \) are respectively, the surface area, volume and mass of the body, and \( t \) is the time. In free swimming shown in Fig. 3, Fig. 4, and Fig. 5, the acceleration of the cirolanid isopod in the speed increase region is

\[
\frac{dU}{dt} \approx 7.6 \text{m/s}^2
\]
Cirolanid isopods resemble the family Dytiscidae in body shape. We can see the data of the drag coefficients of water beetles, $C_D$, obtained by Nachtigall [2,3]. Because their frontal areas are similar, thus $C_D$ is 0.5 for the isopod with body length $L=5\text{ to }7\text{mm}$ as well as water beetles. The added mass for usual aquatic animals is expressed by

$$m \approx \alpha \rho V$$  \hspace{1cm} (3)$$

Substituting these values into Eq.(1), the maximum net thrust was $T=4.3 \times 10^{-4} \text{N}$.

4.1.2 Motion of pleopods

In free swimming of the cirolanid isopod, unsteady motion was observed as shown in Fig. 3, Fig. 4, and Fig. 5. In a general way, aquatic animals and their appendages do not move in a steady manner. In this experiment, tethered swimming was tested to examine the movement of pleopods (swimming legs). Figure 6 shows a sequence of photographs showing the movement of pleopods. Photographs were taken from the belly side of the isopod. It can be seen from Fig. 6 that seven pairs of pereopods hardly move. The isopod is rowing the film-like pleopods. The lateral view in tethered swimming was analyzed to examine the movement of pleopods. Figure 7 shows a sequence of photographs showing the movement of pleopods in the lateral view. The isopod is rowing pleopods backward. Figure 8 shows the legtip orbit of second pleopod during rowing of the isopod. The right arrows show the recovery stroke, and the left arrows show the power stroke. During the power stroke, the pleopods are stretched and move backward. In the recovery stroke, they are folded and narrowed. Figure 9 shows speed variation in the legtip motion of the isopod shown in Fig. 8. In Fig. 9, the first mountain corresponds to the recovery
stroke, (0 < t < 0.1 s), and the second mountain corresponds to the power stroke (0.1 s < t < 0.2 s). In the power stroke, pleopods move at a faster rate. To simplify the calculation, the pleopod is assumed to move backward along a straight line with a constant velocity \( U \). The steady driving force \( T_D \) generated by the hydrodynamic drag, which is proportional to the dynamic pressure of the relative speed \( U - U \), can be described as follows [1]:

\[
T_D = \frac{1}{2} \rho \left( U - U \right) \left| U - U \right| S \eta \eta
\]

where \( U \) is the constant velocity of the isopod body, \( S \) is the frontal area, and \( \eta \) is the drag coefficient of the pleopod. In actual swimming of the isopod, the motion of pleopods generates the squeeze flow between pleopods and pleotelson in the final phase of the power stroke. The squeeze flow grows up to be a backward jet. In this case, thrust force can be expressed as follows:

\[
T_j = m_j \left( v_j - U \right)
\]

where \( m_j \) is the mass flow rate, and \( v_j \) is the jet velocity. Figure 10 shows the photographic visualization of flow field of jet generated by the motion of pleopods. In Fig. 10, the maximum velocity of jet flow is 30 mm/s.

Thus, a series of paddling of pleopods generate thrust force of a cirolanid isopod. Therefore, swimming of isopod is unsteady, and swimming speed synchronizes with the pleopod movement.

### 4.2 Walking of cirolanid isopod

As shown in Fig. 2, isopods have seven pairs of pereopods. The pereopods are used for locomotion (walking) and for latching onto prey. Figure 11 shows a sequence of photographs showing the locomotion of two cirolanid isopods in the test container. The container is partially filled with seawater and the upper layer is filled with air. It can be seen from Fig. 11 that two isopods can swim and...
climb the wall. They swim using their pleopods, and walk with their pereopods. They move by collaborate motion of their pereopods and pleopods for early stage of water surface breaking. Their pleopods generate a thrust force only in the water. In this wall climbing of isopod, the adhesion of water plays an important role. Pereopods are clothed in minute hairs. A lot of minute hairs might be advantageous for holding water in pereopods.

Figure 12 shows the locomotion trajectory of one cirolanid isopod. The cirolanid isopod breaks through the water surface, climbs, walks the wall, and swims to former position again. Figure 13 shows the variations of locomotive speed corresponding to Fig. 12. The coloring zone in Fig 13 corresponds to swimming locomotion. It can be seen from Fig. 13 that the swimming speed is greatly higher compared with the walking speed. In this case, the adhesive properties of water play an important role for climbing of isopod. In Fig. 13, the average climbing speed is $U_{climb} \approx 21\text{mm/s}$. In general, it is difficult for minute aquatic organisms to break through the water surface. However, cirolanid isopods break through the water surface from the water easily. Figure 14 shows such a fact.
It can be seen from Fig. 14 that the isopod is sticking out from the water in the air smoothly.

4.3 Sand burrowing
The cirolanid isopods are one of the crustacean groups. They live in coastal and shelf waters, moving around on the sea floor. As previously stated, they can swim in water, and can climb the wall. In this paragraph, another locomotion ability of the cirolanid isopod is shown. Figure 15 shows a sequence of photographs showing sand burrowing behavior of the cirolanid isopod. It can be seen from Fig. 15 that the isopod digs sand and burrows. Many sand grains are thrown up backward. In this case, the isopod sinks into sand almost horizontally. Figure 16 shows position change of the peak of isopod pereon. The isopod is burrowing sand with shaking body back and forth. The pereon, which is the middle section of the isopod body, bears pereopods. Generally, locomotory behaviors of isopods are affected by the surrounding environment such as sediment grain size, water content, water flow, etc. In this experiment, approximately two dimensional container was used, that is, depth thickness of the container shown in Fig.1 was restricted. In burrowing of isopod, pereopods from the first pair to the third pair did the digging, pairs from the fourth to the sixth compacted the excavated sand, and the seventh pair pushed the bolus behind the isopod. It seems that isopod goes back and forth to make space in sand during the digging. In addition, the vertical diving of isopod was also observed. The sand burrowing velocity of isopod was calculated from Fig. 16. Figure 17 shows variation of the sand burrowing velocity corresponding to Fig. 15 and Fig. 16. At first, it dives sand faster, and then the average burrowing velocity decreases to \( U = 3.6 \text{ mm/s} \). The sand digging is a cooperation working of pereopods and pleopods. The vertical burrowing behavior of the isopod was also observed.

5. Conclusions
The locomotive characteristics of small crustaceans were studied experimentally. The swimming, walking, and sand burrowing behavior was analyzed by the digital high-speed video camera system. The results obtained are summarized as follows:

1. Cirolanid isopods usually swim using pleopods. The beat of the pleopods propels the isopod forward. The swimming pleopods move to increase hydrodynamic drag and inertial force during the power stroke, and they move in the retracted state during the recovery stroke.

2. Cirolanid isopods have seven pairs of pereopods for walking on the sea-bed. They can climb a vertical wall by using pereopods in air.

3. Cirolanid isopods can burrow into sand by using pereopods and pleopods in water. Their sand burrowing velocities are 3.6 mm/s on the average.

Acknowledgement
This work was supported by Grant-in-Aid for Scientific Research (C)(22560173).

References