On the Motility and Locomotive Organs of Beach Flea

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Abstract—Some semiterrestrial beach fleas are capable of swimming movement using their pleopods in water. Movements of swimming organ in beach flea were examined by high-speed video camera system. The structural properties of terrestrial beach flea pleopods were studied through the measurements of some morphological parameters. The swimming legs of the beach flea were examined with a color 3D laser scanning microscope. The relation between morphology of pleopod and motility of the beach flea was considered.

Index Terms—Bio-mechanics, Hydrodynamics, Beach flea, Swimming, Motility

I. INTRODUCTION

In the developments of biomimetics and bionics, the study of various functions of animals is of fundamental interest and importance with respect to a variety of technical developments. The motility is an important discriminate characteristic of animals. Therefore, extensive investigations on the motion of a great many animals have been conducted [1-3]. Authors also have been studying the insect flight [4-7], insect swimming [8-10], and insect jump [11-13] from the view point of dynamics. Through our previous studies, authors noticed the importance of the jump in animal evolution from the land to the sky. For example, the springtails jump, and can be carried away to strong wind in the sky.

Beach fleas are semiterrestrial, and they inhabit in coastal environments. In beach fleas, the usual way to move is by walking, but jumping is also used to escape from predators or disturbance. The jumping and swimming movements of beach fleas were analyzed by the high-speed video camera system in our previous report [11]. The report, however, presents the results within the limited analysis conditions. Research data on the structural properties and morphological parameters of swimming legs of the beach flea are insufficient and there still remains a large unexplored domain.

In this paper, the details of swimming movements of pleopod and morphological parameters in the beach flea are presented. The swimming mechanisms of the beach flea are also discussed. The results obtained here should provide useful clues for future research and the development of micro swimming robots.

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II. EXPERIMENTAL APPARATUS AND PROCEDURES

A. Swimming Analysis

The experiments of the beach flea swimming were conducted by use of a high-speed video camera system (Photron FASTCAM SA5). A block diagram of the experimental apparatus is shown in Fig.1. The experimental apparatus consists of the water container system and the high-speed video camera system. The rectangular container made of the transparent acrylic plastic with dimension 58 mm in height and 7 mm × 54 mm wide was used for free and tethered swimming analyses. The water container is to keep two-dimensional movements of beach flea swimming. The container was filled with water for swimming. Swimming movements of beach flea were analyzed in two dimensional coordinate system. A series of frames of free swimming of beach flea were analyzed by a personal computer. A series of frames of leg rowing of the tethered beach flea stuck on the needle with the adhesive, were also analyzed in the same manner. A 35 mm camera was also used to record the state of the beach flea. The experiment was performed in the laboratory under the condition of the room temperature.

B. Microscopic Observation

Microscopic observations of the beach flea pleopods (swimming organ) were conducted using a color 3D laser scanning microscope (KEYENCE VK-9700). This laser scanning microscope enables observations of color images with clarity rivaling scanning electron microscopes, and non-contact high precision 3D measurements. The test swimming legs was severed...
from the beach flea body before the observation. The cut swimming legs were observed carefully. Some height information in the joint parts of pleopod were examined in detail.

III. MOTION OF BEACH FLEA

A. Motility in Water

Usually, test beach fleas are terrestrial, but they can swim in the water [11]. Figure 2 shows the free swimming of test beach flea in the water container. Test beach flea swims at the velocity 0.11 m/s towards the right from the left in Fig.2. Beach fleas have three pairs of swimming legs (pleopods). Pleopods are the paired appendages, and are adapted for swimming. The beach flea rows pleopods in order of the hind-, middle-, and fore-pleopod in Fig.2. The beach flea swims forward by pressing the pleopods backwards against water. In this way, the beach flea uses oar-like device to produce thrust. A pair of antenna and the abdomen are horizontally extended, and the streamlined shape is maintained during the swimming.

B. Movement of Pleopods

Pleopods are well developed to produce thrust for swimming of beach flea. Figure 3 shows a photograph of tethered beach flea. Pleopods (swimming legs) are shown in the photograph, that is, fore-pleopod (P11), middle-pleopod (P12), and hind-pleopod (P13). Beach fleas swim by rowing pleopods back and forth. Figure 4 shows high-speed frames of the power stroke and recovery stroke of tethered beach flea, viewed from outer lateral. First, the beach flea rows pleopod P13 (t = 0 ms – 32 ms). Following it, the beach flea rows pleopods in order of P12 and P11 (t = 24 ms – 56 ms). It is shown that the stroke angle is approximately 140 degree. The recovery stroke begins with motion of pleopod P13 (t = 48 ms). The recovery stroke with three pairs of pleopods is also observed in a moment (t = 72 ms). Nachtigall obtained the average thrust force arising from the acceleration reaction acting on a hindlimb of dytiscid beetle as follows [14];

Fig. 2. Selected frames from the high-speed movie of the free swimming of beach flea.

Fig. 3. Photograph of tethered beach flea.

Fig. 4. Pleopods movement of beach flea during tethered swimming.
where $c_1$ is the width of the limb, $c_2$ is its length, $\rho$ is the density of the fluid, $\omega$ is the frequency of oscillation, $\theta_1$ is the stroke angle, and $\theta_2$ is the midstroke positional angle. $J_1$ is a Bessel function of order 1. In this paper, Eq.(1) was applied for swimming of beach flea. There is a thrust maximum point at the halfway the power stroke. The thrust maximum point depends on the angle $\theta_2$. This result shows that beach flea swim unsteadily. They oscillate pleopods and produce periodical propulsive forces so that the swimming velocity of beach flea changes in time. This fact was reported in our previous paper [11].

C. Rowing Hairs

Pleopods of beach flea consist of biramous appendages with many articulated segments. Biramous appendages are clothed in minute hairs. These pleopods beat in swimming. Figure 5 shows two photographs in high-speed frames of beating movement of pleopods. Through a power stroke of pleopods movement, the surface of the rowing appendages is greatly enlarged (Fig.5 (a)). Rowing hairs of pleopods are opened out during the power stroke. Rowing hairs are closed during the recovery stroke (Fig.5 (b)). Therefore, the accessory area of pleopods vanishes in recovery stroke. There is a same mechanism such as rowing hairs of water beetles, that is, a kind of a snapping apparatus at the bases of the swimming hairs, keeping them in spread or folded position [14]. Figure 6 shows the opening and closing movement of rowing hairs during the power stroke of pleopods beating in tethered beach flea. These schematic are drawn from the under anterior view. During the power stroke they are stretched and move. Their frontal area $S$ is as large as possible to produce thrust. The flattened parts must be characterized by high values of the drag coefficient $C_D$;

$$C_D = \frac{2F_D}{\rho v^2 S}$$

(2)

where $F_D$ is the drag force, $v$ is the rowing velocity, and $S$ is the frontal area. The rowing hairs exhibit important function in the power stroke of pleopods for thrust generation. Through the power stroke, fluid resistance acts on the pleopods. Limb tips of pleopods are bent by the fluid resistance. Figure 7 shows the radius of curvature of limb tip bend, $R_p$. Curvature of Pl3 is the smallest, because Pl3 is the first rowing. The relative velocity of the Pl2 rowing decreases by the wake of Pl3 rowing. The relative velocity of the Pl1 rowing decreases in the same manner as Pl2. Therefore, the radius of curvature of Pl2 and Pl1 is larger. In the final stage of the power stroke, rowing hairs are laid against the limb, so that the accessory area vanishes.

During the recovery stroke the mechanism of pleopods must be characterized by low values of the drag coefficient $C_D$ in Eq.(2). One of the mechanisms of that purpose is a hinge joint in pleopods. The rowing limb greatly bends in the recovery stroke. The radius of curvature, $R_p$ in the recovery stroke is also shown in Fig.7. The radius $R_p$ in the recovery stroke is smaller compared with the values of $R_p$. This fact shows anisotropy of pleopod structure in the swimming.
IV. MORPHOLOGY OF PLEOPOD

A. Morphological Parameters of Pleopod

Many animals in the ocean use appendages bearing arrays of hairs to move the fluid around them [11]. As shown in Fig.6, many hairs on the swimming legs (pleopods) of beach flea are opened during the power stroke. In this paper, some morphological parameters were measured with the color 3D laser scanning microscope. Figure 8 shows the laser scanning micrograph of the pleopod. Figure 8(a) shows the whole of biramous appendages, and (b) shows the enlarged photograph of some fine hairs. It can be seen from Fig.8 that the pleopods are V-shaped setae with fine bristles. Furthermore, many fine bristles are clothed in ultra fine hairs. This structure is very similar to bird flight feather. When a flying bird opens its wings, the bones are straightened and the flight feathers are automatically spread into the flying configuration. Bird feathers are a marvel of construction. They combine strength, flexibility and lightness.

Figure 9 shows the length of fine bristles, \( l_{f3} \), and their spacing, \( \varepsilon_{f3} \), to the limb shaft coordinate system defined in Fig.9. The length and spacing are not uniform, and they show certain distributions. These values must be related to the mechanism for spreading to produce the high drag coefficient in Eq.(2). Figure 10 shows the length of ultra-fine hairs, \( l_{u3} \), and their spacing, \( \varepsilon_{u3} \). In Fig.10, the coordinate origin is set at the root of the fine hairs. In general, the normal and tangential components of the drag of a fine circular cylinder in an oblique flow are respectively given by as follows [2];

\[
D_n = \frac{1}{2} \rho \nu U_n l / [0.9 / (0.87 - \log Re)]
\]

\[
D_t = \frac{1}{2} \rho \nu U_t l / [4 / (2.5 - 2.3 \log Re)]
\]

where \( \nu \) is the kinematic viscosity, \( U_n \) and \( U_t \) are normal and tangential components of the inflow velocity respectively, \( l \) is the length, and \( Re \) is the Reynolds number on the diameter of the fine cylinder. A large number of ultra fine hairs function as the effect to make longer length.

During the power stroke ultra fine hairs and fine bristles are spread to produce the effective area for rowing. The effective area produced by a fine bristle is described as follows;

\[
S_b = 2 \int_0^{\theta} l_{f3} \sin \theta d\theta
\]

where \( l_s \) is the length of the limb shaft, and \( \theta \) is the angle between the limb shaft and a fine bristle. At the stage of a maximum spread, the angle \( \theta \) is \( \theta = \pi / 4 \). The angle \( \theta \) is a function of the time during the power...
stroke. Therefore, the rowing effective area produced by one pair of pleopod is described as follows:

\[ S = 4S_b - S_d \]  

(6)

where \( S_d \) is the area decreased by the overlap of fine bristles. At the stage of a maximum spread, \( S_d \) can be neglected. In the case of the beach flea as shown in Fig.4, the maximum area was \( S \approx 3.5 \times 10^{-4} \text{m}^2 \). However, a number of ultra fine hairs on adjacent fine bristles overlap even at the stage of a maximum spread, because the average gap of each fine bristle is \( \varepsilon_{f1} = 55.7 \mu\text{m} \) and the average length of ultra-fine hair is \( l_{u1} = 57.9 \mu\text{m} \). Such microscopic overlap of ultra fine hairs generates the effective area for rowing.

**B. Shape of Limb Shaft**

As shown in Fig.8 limb shafts are clothed in fine bristles, and many fine bristles are clothed in ultra fine hairs. A large number of hairs are supported by a limb shaft. In this paragraph, the shape of the limb shaft was measured with the confocal laser scanning microscope. Figure 11 shows an example of such measurements. Figure 11(a) shows the optical image of part of limb shaft and some fine bristles, (b) shows the two-dimensional display of surface measurement, and (c) shows the three-dimensional display of measurement result for the pressure (rowing) side surface during a power stroke. It can be seen from Fig.11 (b) that the limb shaft surfaces form the concave shape. The both side parts clothed in fine bristles are fleshy. It can be seen from Fig.11 (b) that the pitch differences between mountain and valley are approximately 45.6 \( \mu\text{m} \) (left concave) and 28.1 \( \mu\text{m} \) (right concave) on the line 1 in the measurement limbs \( P_1-P_e \). It can be seen from the comparison of line 1 and line 2 that the concave area is enlarged towards the root of the shaft. Such three-dimensional shape of the shaft is clear in Fig.11(c). The concave shape is suitable to row water as water turbines. This configuration of pleopod raises the drag coefficient of Eq. (2).

**C. Joint System of Pleopod**

In general, joint structures are linked in such a way that skeletal movement is possible. In the human skeleton, three types of joints are recognized. A pivot joint allows one bone to twist against another. A hinge joint moves in only one direction. A ball-and-socket joint consists of a rounded head on one bone which fits into a cup-shaped socket on another. The ball-and-socket joint allows twisting and bending.

The small radius of curvature \( R_b \) (large bending) of pleopods in beach flea swimming during the recovery stroke suggested the existence of the hinge joint. Such bending part of pleopod was observed with the confocal laser scanning microscope. Figure 12 shows the optical image of bending part of pleopod in outer lateral view. It can be seen from Fig.12 that the bending part shows a hinge joint structure. This hinge joint structure enables the large bending of pleopods during the recovery.
stroke. More detailed observation was accomplished for morphological characteristics. Figure 13 shows the joint part of pleopod. Figure 13 (a) shows the optical image in frontal view, (b) shows the three-dimensional display of measurement result for the wake side surface during a power stroke, and (c) shows the shapes on two lines. It can be seen from Fig.13 that the joint part is hollow. During the recovery stroke points \( P_1_s \) and \( P_2_s \) bend downward for points \( P_1_e \) and \( P_2_e \), respectively. The hollow in joint structure extends and gives the pleopod bending flexibility. Some movements were observed in outer limb (right limb in Fig.13 (a)). Arrows A, B, C, and D in Fig.13 (b) show the direction of such movements of the limb. The movement of arrow A is limb bending at the recovery stroke for rowing motion of pleopod. The movement of arrow B is limb closing at the recovery stroke. During the closing movement the outer limb overlaps with the hollow part of inner limb (left limb in Fig.13 (b)). The movement of arrow C is limb open at the power stroke. The movement of arrow D is limb twist. The inner limb bends backward at the recovery stroke, but opening, closing and twisting movements were not observed.

Figure 14 shows the joint part that is backside surface of the pleopod shown in Fig.13. During the power stroke, a situation is created whereby the
pressure acting on this surface is in excess of that acting on another surface. A resultant force acting on the surface of limbs in the direction of the relative fluid motion exists, that is, pressure drag. At this stage, the rowing velocity must be larger than the body velocity. The reciprocal motion of pleopods such as paddling is effective for propulsion. Therefore, the surface shape of the limbs has a concave as shown in Fig.14 (b) and Fig.11. The concave shape of the limb surface improves the drag coefficient. It can be seen from Fig.14 that the limb is connected to the basic root on line1. Line 2 shows the concave surface shape of limbs. These shapes of the swimming organ of beach flea suggest a process of evolution from the sea to the land in this insect.

V. CONCLUSIONS

The swimming behavior in water of a beach flea was analyzed by the high-speed video camera system, and morphological parameters of swimming organ were measured with the color 3D laser scanning microscope. The results obtained are summarized as follows:

(1) The beach flea can swim by rowing their pleopods from front to back. Through the power stroke of pleopods movement, the surface of the rowing appendages is greatly enlarged. At the recovery stroke, the surface of the rowing appendages is closed, and pleopods bend greatly.

(2) Pleopods of beach flea are clothed in many fine bristles, and many fine bristles are clothed in many ultra fine hairs. The length and spacing of fine bristles are not uniform. Furthermore, the length and spacing of ultra fine hairs are also not uniform.

(3) Pleopods of beach flea have their joint structures with several degrees of freedom. The pleopod surface forms concave shape in the pressure side.

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References