Proposal of a Water-repellency Model of Water Strider and Its Verification by Considering Directly Measured Strider Leg-rowing Force

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Nano- and micro-structures can be realized by using photofabrication, crystal growth, chemical deposition, etching and other methods. This variety of fabrication methods encourages the development of water-repellent surfaces from the viewpoint of biomimetics. Water striders have attracted interest in biomimetics because their water-repellency property makes it possible for them to live on water surfaces. Micro-hairs, which are present on the surface of the water strider’s legs, can maintain an air layer between the water surface and the legs, providing the repellency property. While there have been various studies which have considered a physical model of the water strider’s water-repellency property, no model has taken directly measured water strider leg-rowing force into account. Therefore, in this study, we proposed a physical model of a water strider using Laplace pressure, and then we considered directly measured leg-rowing force to verify the model. First, we considered the relationship between water pressure around the micro-hairs and the intersection of the surface of the micro-hairs and the water surface using our proposed model. We found that when the micro-hairs were in contact with the water surface and the air layer was maintained, the maximum Laplace pressure \( P_{\text{max}} \) was 35.2 kPa. This meant that if Laplace pressure exceeded 35.2 kPa, the water pressure caused by the rowing motion of the strider legs pushed water into the space between micro-hairs. Additionally, we calculated maximum water pressure \( P_L \) which was loaded around the surface of the water strider’s leg by rowing of the leg. \( P_L \) was 546 Pa, and this value was significantly smaller than \( P_{\text{max}} \). This meant that the water pressure did not push water into the space between the leg micro-hairs and the water strider’s legs maintained their water repellency when moving.

Keywords: Laplace pressure, Micro structure, Surface tension, Water repellency, Water strider

1. Introduction

Nano- and micro-structures that provide water-repellent (hydrophobic) surfaces have been realized by various fabrication methods such as photolithography (using photopolymers) [1-3], laser direct-writing [4,5], photoinduced crystal growth [6], chemical-base deposition [7-9], etching [10], electrospinning [11,12], and membrane casting [13]. Hence, the water-repellency properties exerted by microtextured hydrophobic surfaces of many living things have received considerable attention in the field of biomimetics. For example, lotus leaf surface structures show a self-cleaning ability due to their superhydrophobic property (this is called a lotus
effect) [14,15], and several studies have mimicked the superhydrophobic property of lotus leaf surfaces [16-19]. There have also been reports on the development of a surface which has mimicked a rose petal surface (petal effect) [20], a termite wing surface [6], and a porcupinefish skeleton material [21]. Additionally, self-cleaning by biomimetic hydrophobic surfaces has attracted interest in the fields of art and architecture [22]. Water striders can slide and jump on water surfaces, and many studies have developed hydrophobic surfaces mimicking the insect body surfaces [7-9,11-13] or they have developed water strider-like robots [23-30].

Water striders move on water surfaces freely because of their leg superhydrophobic surface which has many micro- or nano-structures (micro-hairs) (Fig. 1) and secretions of wax [31-33]. The superhydrophobic property of the micro-hairs arises from the Cassie-Baxter state [34] which forms a trapped air layer between the insect leg and the water surface [32,35,36]. Water striders can support their body using the surface tension which is created on the water surface by their leg superhydrophobic surface [31,37,38].

When water striders move on water surfaces, it is important that water is not pushed into the space between the micro-hairs by the water pressure caused by the leg-rowing motion. If the water pressure is large, the water surface becomes deformed and water is pushed between the micro-hairs. In this way, a water surface is formed on the leg shaft, and the air layer is lost. A similar argument has been made for lotus leaves [39]. When a water strider is moving on the water surface, its legs strike the water surface, and the water pressure loaded around the surface of the insect leg becomes a maximum value. If the water is not pushed between the micro-hairs at the maximum water pressure, the water-repellency property is maintained.

There have been several investigations of physical models which discussed the water repellency of the water strider’s micro-hairs. For example, depth and shape of a grooved water surface which was created by the water strider leg micro-hairs was discussed quasi-statically [32,40]. A physical model, which was explained by experimental observations (using lateral flow), was also reported [41].

However, there have been no studies which discussed water repellency of the water strider’s leg by using directly measured leg-rowing force. If we can use the directly measured leg-rowing force, the insect leg water repellency-property can be discussed in more detail. Then, this knowledge can contribute to development of stronger water-repellent materials. Therefore, to fill the information gap, we have measured the water strider’s middle leg-rowing force directly [42-44]. We measured the middle leg-rowing force because this leg force is mainly used for propulsion [45,46].

For the next stage, in this study, we proposed a model which explains the relationship between the water pressure around the water strider’s leg surface, loaded by the leg-rowing motion, and the
microtextured hydrophobic surface (micro-hairs) of the legs. By using its directly measured leg-rowing force, we can show the deformation condition of the water surface contacting with the micro-hairs when the water strider is rowing its legs.

2. Model

2.1. Relationship between the water pressure around the micro-hairs and the intersection of the surface of micro-hairs and the water surface

Figure 1 shows the scanning electron microscope (SEM) image of the tip of the middle leg (around the tarsus) of an adult water strider. For our proposed model, we were inspired by two classical studies [47,48]. The micro-hairs rise obliquely from the surface of the insect’s leg, and the tip of each micro-hair is bent like a hook (see the micro-hairs enclosed in the yellow dotted rectangle of Fig. 1). It can be presumed the tip of the insect’s micro-hairs are oriented parallel to the longitudinal direction of the leg. Thus, we considered a simple model in which the micro-hairs are cylindrical, and lie in parallel, deforming the water surface as shown in Fig. 2.

Figure 3 shows a cross-sectional image for the micro-hairs contacting with a deformed water surface. The micro-hairs (brown circles: center, O’; radius, r) and the water (blue area) surface are assumed to continuously exist in the depth direction without deformation. The distance between the center of two neighboring micro-hairs (O’-O’) is l. The water surface intersects at a point A, and the contact angle between the water surface and the surface of micro-hairs is θ at point A. The angle between the line O’-A and the horizontal line is β. It is considered that the shape of the water surface between the micro-hairs is part of a circle (center, O; radius, R). The distance between point A of each micro-hair L (A-A) is shown as Eq. 1.

\[ L = l - 2r \cos \beta \]  

(1)

The radius R is shown as Eq. 2 (by referring to the
\[ R = \frac{L}{2 \cos \varphi} \]  

(2)

The angle \( \varphi \) is shown as Eq. 3.

\[
\varphi = \cos(180 - \theta + \beta) \quad (\theta > 0) \\
\varphi = \cos(180 - \theta - \beta) \quad (\theta < 0) 
\]

(3)

By substituting Eq. 1 and Eq. 3 into Eq. 2, we get Eq. 4.

\[
R = \frac{\frac{L}{\cos(180 - \theta + \beta)}}{\cos(180 - \theta - \beta)} \quad (\theta > 0) \\
R = \frac{\frac{L}{\cos(180 - \theta - \beta)}}{\cos(180 - \theta - \beta)} \quad (\theta < 0) 
\]

(4)

The Laplace pressure \( \Delta P \) is shown as Eq. 5 (\( \gamma \), surface tension of water).

\[
\Delta P = \gamma \left( \frac{1}{R} + \frac{1}{R'} \right) 
\]

(5)

Here \( R \) and \( R' \) are the curvature of the water surface. Since the micro-hairs and the water surface continuously exist in the depth direction without deformation, it can be presumed \( R' \) become infinite. Then, we can get Eq. 6 [48].

\[
\Delta P = \frac{\gamma}{R} 
\]

(6)

By inserting Eq. 4 into Eq. 6, we get Eq. 7.

\[
\Delta P = \frac{\gamma \cos(180 - \theta + \beta)}{\left(\frac{L}{\cos(180 - \theta + \beta)}\right)} \quad (\theta > 0) \\
\Delta P = \frac{\gamma \cos(180 - \theta - \beta)}{\left(\frac{L}{\cos(180 - \theta - \beta)}\right)} \quad (\theta > 0) 
\]

(7)

2.2. Water pressure around micro-hairs when rowing the middle leg

When a water strider is rowing its legs, water pressure around the micro-hairs is increased because the pressure due to this rowing is loaded on the water surface. We denote the pressure which is loaded by leg rowing as \( P_L \) (Fig. 4). We assume reactive force \( F_L \) is generated on the water surface by leg rowing. If the water surface covers half of the interface area between the water and micro-hairs when the strider is rowing its legs, \( P_L \) which is generated by \( F_L \) is shown as Eq. 8.

\[
P_L = \frac{2F_L}{\pi D l} 
\]

(8)

Here \( D \) is the diameter of the interface area between the water and micro-hairs and \( l \) is length of the contact area between the leg and water surface.

3. Materials and methods

3.1. Insects

Water striders (\textit{Aquarius paludum paludum}) used were collected from a pond on the Suita campus of Osaka University (Suita, Osaka, Japan). After the initial collection, they were fed and propagated in an aquarium at room temperature (from 20 to 25 °C).

3.2. SEM morphological observation of water strider’s middle leg

Adult water striders (sixth instar) were observed with an SEM (VE-8800, Keyence Corp., Osaka, Japan). When a water strider is rowing its legs, the tip of the middle leg (around the tarsus) is in contact with the water surface; therefore, the tip of the middle leg was observed.

3.3. Observation of contact length between water strider’s middle leg and the water surface

The contact length \( l \) (Fig. 5) between the water strider’s middle leg and the water surface when rowing its legs on the water surface was observed with a high-speed camera (IDP, Photron Ltd., Tokyo, Japan). The water strider was in a water-filled aquarium and the rowing motion was recorded from above. The high-speed video images were analyzed with image processing software (ImageJ 1.51j8). Because the maximum leg-rowing force is generated when the angle between the body and leg becomes about 90 ° [44], the contact length was measured when the angle between body and leg became about 90 °.
4. Results

4.1. Morphology scales of water strider’s middle leg

Figure 1 has a representative SEM image showing the tip of an adult water strider’s leg; a magnified image of one area is also included. According to the SEM images, the diameter of the micro-hairs around the apex of the curve \( r \) (white arrow) was \( 0.49 \pm 0.03 \) µm, and the distance between the apices of the curve \( l \) (yellow arrow) was \( 4.76 \) µm. The \( l \) was calculated using the number of micro-hairs that the apices of the curve enclosed by the \( 20 \mu m \times 10 \mu m \) rectangle on the center of the leg shaft (white dotted rectangle). The \( l \) was obtained by dividing \( 20 \mu m \) by the number of micro-hairs. The diameter of the water-micro-hairs interface \( D \) was assumed to be \( 104 \pm 10 \mu m \) (red arrow).

4.2. Contact length

Figure 5 shows a photo of the water strider’s rowing motion which was recorded with a high-speed camera. The maximum contact length between the middle leg and water surface \( l \) was \( 11.0 \pm 0.5 \) mm (black arrow).

4.3. Relationship between the water pressure around the micro-hairs and the intersection of the surface of micro-hairs and the water surface

By using Eq. 7, we can get the relationship between the water pressure around the micro-hairs and the intersection of the surface of the micro-hairs and the water surface. The \( r \) was \( 0.49 \mu m \), and \( l \) was \( 4.76 \mu m \) (Sec. 4.1). By assuming the surface tension of water as \( 72.75 \) mN/m and the contact angle between water and micro-hair \( \theta \) as \( 124.8 ^\circ \) [49], Fig. 6 is gotten by Eq. 7. According to Fig. 6, the

**Fig. 6.** The relationship between the water pressure around the micro-hairs and the intersection of the surface of the micro-hairs and the water surface. The maximum Laplace pressure was \( 35.2 \) kPa \((\beta = -45.5 ^\circ)\).
maximum $\Delta P$ ($P_{\text{max}}$) was 35.2 kPa ($\beta = -45.5^\circ$).

4.4. Water pressure around micro-hairs when rowing the water strider middle leg

The middle leg-rowing force of water strider was measured directly, and the maximum rowing force was 980 μN [44]. Therefore, $F_L$ was assumed to be 980 μm. The $D$ was 109 μm, and $l$ was 11.0 mm (Sec. 4.1 and 4.2). Then, we get $P_L$ as 546 Pa by inserting these values into Eq. 8.

5. Discussion

Figure 6 shows the relationship between the Laplace pressure $\Delta P$ and angle $\beta$. When $\beta$ becomes over 34.8 °, $\Delta P$ becomes negative. This means that the shape of the water surface becomes a concave curve. On the other hand, when $\Delta P$ becomes positive, the shape of the water surface becomes a convex curve, and the $P_{\text{max}}$ was 35.2 kPa ($\beta = -45.5^\circ$).

Figure 7 shows the condition of the water surface when $\Delta P$ is changed. If $\Delta P$ is significantly small (it becomes negative), $\beta$ becomes larger than 34.8 °, and the shape of the water surface is the concave curve (Fig. 7-a). As the water pressure increases (it becomes positive), $\beta$ decreases (it becomes smaller than 34.8 °). This means that the water surface is propelled or pushed in the downward direction. The water surface deforms to a convex curve (Fig. 7-b). If $\Delta P$ exceeds $P_{\text{max}}$, $\beta$ is decreased, and the water surface is pushed to the lower micro-hairs at once. Finally, the water surface covers the micro-hairs and they are submerged in the water (Fig. 7-c). This means that the water-repellency property is lost.

Lastly, we discuss the proposed model by using the maximum water pressure $P_L$ which is caused by the rowing motion of the water strider’s middle leg. The $P_L$ was 546 Pa, and this value was much smaller than the maximum Laplace pressure $P_{\text{max}}$. This means there is no probability that the pressure $P_L$ pushes water into the space between the micro-hairs. In this study, our model is a two-dimensional model. As a matter of fact, all micro-hairs are not continuously parallel with the longitudinal direction of the insect’s leg. The micro-hairs are discontinuous and curving. Therefore, our calculated $P_{\text{max}}$ may differ slightly from the actual pressure. However, because the micro-hairs are multi-layered, we consider that the water repellency property of the water strider is stronger than the assumption of our model. Therefore, the water strider does not lose its water repellency by the rowing motion.

6. Conclusion

Nano- and micro-structures-based water-repellent surfaces have been fabricated by photofabrication, crystal growth, chemical deposition, etching and other methods. When developing a water-repellent surface, some studies have referred to or mimicked micro-hair surface structures of water striders. However, understanding of the water-repellency mechanism of water striders is insufficient.

In this study, we proposed the model which explains the water repellency property of water strider legs, and we confirmed the water-repellency capability using the directly measured water strider’s leg-rowing force. There have been many studies which discuss the water-repellency property of the water strider due to micro-hairs present on its legs. On the other hand, there have no studies which
have discussed the effect on water repellency by leg-rowing of the water strider. When rowing the legs, water pressure around them is increased. If the water pressure becomes larger than necessary to keep the insect afloat, water may push into the space between the micro-hairs. This means the loss of water repellency. Therefore, we confirmed the robustness of the water-repellency property of the water strider by the proposed model.

By using the proposed model which considered the Laplace pressure, we got the relationship between the water pressure around the micro-hairs and the water surface. When the angle between the surface of a micro-hair and water $\beta$ exceeded 34.8°, the Laplace pressure $\Delta P$ became negative. When $\beta$ became less than 34.8°, $\Delta P$ became positive. The maximum Laplace pressure $P_{max}$ was 35.2 kPa ($\beta = -45.5$°).

Additionally, we estimated the maximum water pressure around the surface of water strider’s leg ($P_L = 546$ Pa). We considered that the water did not push into the space between micro-hairs because $P_L$ was sufficiently smaller than $P_{max}$. Therefore, the water-repellency property of the water strider’s legs is not lost by their rowing motion.

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