

Metallic-peristome surface inspired by *Nepenthes alata* for anti-sticking of electrosurgical electrodes

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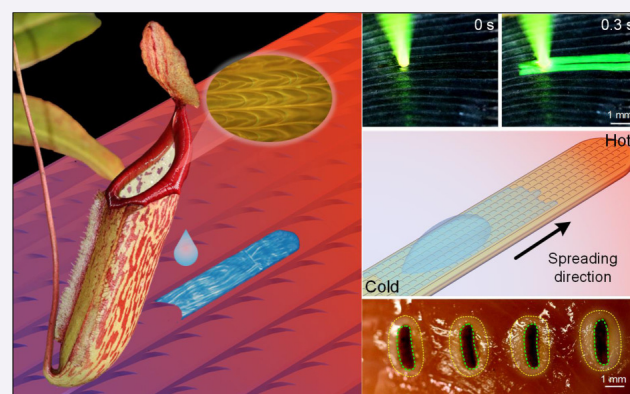
ABSTRACT: Soft tissue sticking to electrosurgical electrodes in minimally invasive surgery can cause tissue trauma, laceration, and bleeding and can easily lead to medical accidents. The multilevel structure on the peristome surface of *Nepenthes alata* creates a stable liquid film and long-term slippery phenomena, providing excellent antisticking performance. However, transferring the multilevel structure to metallic substrates is a critical challenge. Herein, a facile method using a bionic replication process combined with an electroforming process was reported to successfully prepare a realistic metallic-peristome surface (MPS) from the peristome surface of *Nepenthes alata* to a copper-based substrate. The long-term lubrication theory of MPS was analyzed, which demonstrated the high wettability and robustness of the surface. The unidirectional transport behavior and long-term lubrication performance of dimethyl silicone oil on the MPS under the action of a thermal field gradient were analyzed. The results show that the as-prepared metallic-peristome surface has liquid transport capability in the opposite direction of the thermal field gradient. In addition, the introduction of microstructures on the surface of the MPS electrode can promote the occurrence of spark effects and improve the cutting effect. An electrocution test of isolated pig liver tissue was conducted to test the tissue antisticking properties, thermal damage, and antibacterial effects of self-lubricating slippery surface bionic electrosurgery. MPS exhibits excellent antistick properties, low thermal damage, and significant antibacterial properties, laying the foundation for its application in other fields.

KEYWORDS: *Nepenthes alata*; metallic-peristome; multilevel microstructure; electrosurgical scalpels; TiO₂ coatings; antisticking surface

1 Introduction

Minimally invasive surgery has received increasing attention because it is less invasive and allows faster patient recovery [1–4]. However, owing to the instantaneous high temperature during surgery, soft tissues are carbonized and stuck to the surface of electrosurgical instruments, causing tissue trauma, bleeding, and burns [5–8]. Therefore, there is an urgent need to solve the problem of soft tissue adhesions. There are two main methods used to alleviate tissue adhesion: the normal-temperature anti adhesion method and the high-temperature anti adhesion method. The normal-temperature anti adhesion method reduces soft tissue adhesion by adding antiadhesive media between tissues [9–16]. High-temperature antisticking technology can be divided into two types according to its form: dry surface antisticking

technology and lubricated surface antisticking technology. Dry surface antiadhesion technology involves coating the device surface with low-surface energy alloy coatings or polymer coatings or processes micro/nanostructures, such as TiO₂ [17], CrN [18], copper doping, diamond-like carbon [19–21], and bionic corn leaf microstructures [22]. Lubricated surface anti adhesion technology reduces soft tissue adhesion through surface modification and the addition of lubricating media. Notably, Xue et al. [23] prepared copper-doped hydroxyapatite “nanorods” whose degradation caused an increase in local pH, weakened the proton motive force of *Staphylococcus aureus*, and showed good antibacterial properties and biocompatibility. Li et al. [24] deposited nanometers on bionic microstructures through laser texturing, pickling, and atomic layer deposition (ALD) technology. A coupling surface made of a high-grade hafnium oxide (HfO₂)



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coating has excellent anti adhesion properties for blood, providing new insights into anti adhesion under high-temperature conditions. In addition, the use of new polymer nanofilms and chemical interface reaction methods to achieve excellent self-lubrication and wear resistance has also received widespread attention from researchers [25–27].

Anti-stick biological prototypes in nature, such as lotus leaves that are not contaminated by silt [28], desert beetles [29], the peristome surface of *Nepenthes alata* [30], the compound eyes of mosquitoes [31], and the wings of butterflies [32], provide a rich sample library for bionic design and manufacturing. The long-lasting lubrication mechanism on the peristome surface of *Nepenthes alata* is based mainly on the one-way transport characteristics of the liquid, which results in the formation of a liquid film on its surface. The liquid film consists of large grooves in the first-order array on the peristome surface of *Nepenthes alata* and a wedge-shaped blind hole structure on its surface. Therefore, the formation mechanism of liquid films and the friction antisticking mechanism have received widespread attention [6, 33–38]. In particular, the liquid-infused surface (LIS) is inspired by the oral surface of the pitcher plant. The LIS successfully transformed the original solid-solid contact mode into a solid-liquid-solid contact mode to achieve isolation of pollutants [39]. However, how to achieve rapid self-replenishment of lubricants on metals is still a complex problem [40–43].

Zhang et al. [1] introduced LIS surfaces on surgical electrodes, which significantly improved the antiadhesion performance of electrosurgical instruments. Li et al. [44] used a laser direct structuring method to create a new self-replenishing liquid injection surface, which is similar to the multilevel structure of the oral surface of *Nepenthes* with primary microgrooves and secondary microcavities. The surface exhibited stable antiadhesive properties.

Researchers have used the peristome surface of *Nepenthes alata* as an excellent biological template for antiadhesion surfaces, but it is still a challenge to prepare a particularly realistic oral edge multilevel structure surface on a metal substrate. Liu et al. [45] prepared a *Nepenthes alata*-inspired antisticking surface via nanosecond laser fabrication on a stainless steel substrate by combining nanosecond laser direct writing and spot shaping. The prepared electrode showed excellent cutting and antisticking properties. Inspired by the self-driven spreading of liquid films on the surface of pitcher plants, Zhang et al. [46] successfully prepared bionic microstructures on high-frequency surgical electrodes via laser etching technology. The original solid-solid mode was transformed into a solid-liquid-solid mode, which increased the current density, enhanced the spark effect, and reduced adhesion during cutting.

In this study, we used bionic replication technology combined with electroforming technology to successfully prepare a realistic multilevel structure of the peristome surface of *Nepenthes alata* on a copper-based substrate and applied it to the surface of electrosurgical instruments. The long-term lubrication mechanism of the peristome surface of *Nepenthes alata* was studied. The bionic layered structure on the peristome surface of *Nepenthes alata* was prepared via a bionic replication process as a negative template and then used as a cathode after conductive treatment. A highly realistic simulated growth-effect lubricating antistick surface was prepared using a phosphor copper plate as the anode and CuSO_4 as the electroforming liquid. The dynamic rules of the wettability and spreading of structures under different temperature fields were discussed. An electrocution test of pig liver tissue was conducted to test the antiadhesion performance of the self-lubricating slippery surface for bionic electrosurgery. The

long-term lubrication performance and thermal damage performance of the bionic electric knife under the action of a thermal field gradient were analyzed. The introduction of microstructures on the electrode surface can promote the occurrence of spark effects and improve the cutting effect. In addition, the antibacterial effect and biocompatibility were evaluated through inhibition zone experiments. We emphasize that the highly realistic multilevel structure on the peristome surface of *Nepenthes alata* prepared in this work on a metal substrate may provide a feasible strategy for advancing the application of biomimetic metal functional interfaces.

2 Materials and methods

2.1 Fabrication of biomimetic hierarchical structures

2.1.1 Fabrication of a cathodic model of the peristome surface of *Nepenthes alata*

First, the peristome surface of *Nepenthes alata* was cut into small segments, and the central support structure of its inner wall was removed. After the remaining structure was flattened, the gradient alcohol dehydration step was performed to fix the plant sample tissue. After completing the above work, bionic replication technology was used to perform polydimethylsiloxane (PDMS) replication on the peristome surface of *Nepenthes alata*. After demolding, the planar negative template of the PDMS substrate was obtained. PDMS (Dow Corning, USA) was used as received. Finally, the nanoscale metal coating was sputtered on the surface of the negative template via a magnetron sputtering process. To improve the adhesion between the metal coating and the PDMS template, a layer of Cr (2 min) was sputtered as the seed layer to prevent the casting and substrate from falling off during the subsequent electroforming process. A layer of Au (8 min) was then sputtered as a conductive layer. The surface was electrically conductive using this method to prepare for subsequent use as a core mold.

2.1.2 Microelectroforming process

A 40 mA/cm² direct current (DC) power supply was used as the power supply for the microelectroforming process. The bionic PDMS template after conductive treatment was used as the cathode core mold, a phosphorus copper plate was used as the anode, and CuSO_4 (200 g/L) was used as the main component of the electroforming solution. To avoid anode passivation, H_2SO_4 (40 g/L) was added to the electroforming solution to promote the dissolution of the copper anode and supplement the consumption of the deposited cathode metal. The addition of sulfuric acid can also prevent the hydrolysis of copper salt and increase the conductivity of the electroforming solution. The dispersing ability of the electroforming solution is improved to make the copper coating crystal fine. HCl (50–80 mg/L) was used to promote copper anodic dissolution and improve copper precipitation. Sodium dodecyl sulfonate (0.2 g/L) was added to the electroforming solution as a wetting agent to improve the wettability of the electrode. To refine the crystallization of the copper casting layer, a small amount of glucose was added as a leveler. The concentration of the electroforming solution was consistent under magnetic stirring. Finally, the mandrel was demolded to obtain a copper-based peristome surface imitation of *Nepenthes alata*. Sodium dodecyl sulfonate was obtained from Xilong Scientific Company Limited, China. CuSO_4 (copper sulfate), H_2SO_4 (sulfuric acid), and HCl (hydrochloric acid) were supplied by Beijing Chemical Works, China. Glucose was

obtained from Beijing Aoboxing University Biotech Company Limited, China.

2.2 Characterization of the structural characteristics

The process of adding a TiO_2 coating to the surface of the electroformed microstructure of the peristome surface imitation of *Nepenthes alata* was adopted, and the wettability and durability were tested. The TiO_2 coating was prepared via a magnetron sputtering process. The surface of the electroformed structure of the copper substrate was cleaned, and then magnetron sputtered. First, a Cr metal layer was sputtered on the surface (2 min) to enhance the adhesion between the TiO_2 coating and the copper substrate. The TiO_2 coating was then sputtered (12 min) to ensure that the surface microstructure was not affected by the coating thickness. Deionized water (0.5 μL) was added to the surfaces of three different copper substrate materials, a chromium coating, and a TiO_2 coating, to characterize the wettability. To characterize the wear resistance stability of the surface electroformed with the TiO_2 coating, the wear resistance was studied with sandpaper of different grits. The surface of the electroformed microstructure was downward and fixed at the bottom of a 100 g standard weight. The samples were placed on 2,000 grit, 1,500 grit, 600 grit, or 180 grit sandpaper, and they were slid 30 cm in both the positive and negative directions. In addition, fluorescently stained anhydrous ethanol was injected into the worn surface to observe the surface morphology and liquid spreading performance. For clear observation, sodium fluorescein (Kermel, China) was used for fluorescence staining. The liquid in an injection syringe fixed on a micropositioner was continuously injected onto the surfaces at a flow rate of 10 $\mu\text{L}\cdot\text{s}^{-1}$. The spreading behavior was recorded by a high-speed camera (I-speed LT, Olympus, Japan) equipped with a microscope (BX51, Olympus, Japan). For clear observation, sodium fluorescein (Kermel, Tianjin, China) was used for fluorescence staining. The liquid in an injection syringe fixed on a micropositioner was continuously injected onto the surfaces at a flow rate of 10 $\mu\text{L}\cdot\text{s}^{-1}$. The contact angle and liquid manipulation were recorded via a high-speed camera (AE120M, HF Agile Device Co., Ltd., China).

2.3 Observation of liquid spreading on the as-prepared surface

Deionized water (2 μL), anhydrous ethanol (2 μL), and dimethyl silicone oil (2 μL) were added dropwise to the surface of the TiO_2 -coated electroformed microstructure. The spreading length of the liquid along the outlet direction and in the opposite direction was measured, and the dynamic spreading law under different temperature conditions (20–250 °C) was explored.

2.4 Anti-sticking performance of the bionic electrosurgical electrode in the cutting of soft tissue

The electrosurgical electrodes, which were made of 316 L stainless steel, were obtained from Beijing ENJOY Technologies Company Limited, China, and were used as typical electrosurgical instruments in this study. There are micropores in the middle of the electrosurgical electrode head. During the experiment, the lubricant gradually seeped out from the micropore to ensure sufficient lubricant on the surface of the electrosurgical electrode. Soft tissue adhesion on the front and back of the electrosurgical electrode was compared under three conditions: dry surface, water lubricated surface, and silicone oil lubricated surface. The area of the wound and heat injury area of pig liver tissue were measured. The antibacterial properties of the prepared bionic electrosurgical electrode against *Escherichia coli* and *Staphylococcus aureus* were

compared. The conventional electrosurgical electrode and bionic electrosurgical electrode were cut into small pieces of 4 mm² and placed in agar culture medium after high-temperature sterilization. The samples were placed in a thermostat incubator at 37 °C (18 h) to observe the size of the bacteriostatic circle.

3 Results and discussion

3.1 Fabrication of imitations of the peristome surface structure

The multilevel microgroove structure (Fig. 1(b)) is distributed on the peristome surface structure of *Nepenthes alata* (Fig. 1(a)), which has long-acting lubrication characteristics (Fig. 1(c) and Movie S1 in the Electronic Supplementary Material1 (ESM)). On the basis of this feature, it is replicated on the surface of metal-based materials by electroforming processes. The phosphor copper plate is the anode, copper sulfate is the main component of the electroforming solution, and the DC supply is used as the power of the micro electroforming process (Fig. 1(e)). The support of the peristome surface structure of small segmental *Nepenthes alata* was removed, and the tissue was dehydrated and fixed. The bionic replication process was then carried out to replicate the surface structure with PDMS. After demolding and conducting treatment, the planar negative template of the PDMS substrate can be obtained (Fig. 1(d)). Finally, the fabrication of the imitations of the peristome surface structure of *Nepenthes alata* was realized.

By scanning the three-dimensional structure of the prepared surface, it can be seen that the wedge-shaped blind hole structure in the secondary groove on the surface is complete (Fig. 1(e)), indicating that accurate replication of complex microstructures can be achieved by electroforming. The wettability of the prepared surface was characterized. Anhydrous ethanol was added dropwise to the surface of the electrical casting of the peristome surface structure of *Nepenthes alata*, and the liquid spread rapidly to more than 5 mm within 0.3 s (Fig. 1(f)), whereas the reverse showed a cutoff effect, indicating that the structure had liquid unidirectional transport characteristics comparable to those of the biological prototype.

The copper substrate structure, chromium coating structure, and TiO_2 coating structure were analyzed via X-ray diffraction (XRD) energy spectra. First, the surface elements of the copper substrate were analyzed (Fig. S3(a) in the ESM). The weight percentages of Cu, Cr, Ti, O, and C were 61%, 16%, 8%, 11%, and 4%, respectively. After the chromium coating was sputtered for 2 min, the surface element weight ratio reached 35%, 37%, 4%, 19%, and 4% (Fig. S3(b) in the ESM), and the weight ratio of the Cr metal increased, indicating that the chromium coating was successfully prepared. In addition, after the TiO_2 coating was sputtered for 12 min, the weight ratio of each element reached 34%, 18%, 13%, 28%, and 8% (Fig. S3(c) in the ESM), indicating that the TiO_2 coating was successfully prepared on the surface.

3.2 Long-acting lubrication mechanism of the peristome surface on *Nepenthes alata*

The macrostructure and microstructure of the peristome surface of *Nepenthes alata* were observed (Figs. S1(a) and S1(b) in the ESM), and wedge-shaped blind holes (Fig. S1(c) in the ESM) were found in the secondary grooves on the surface. The tail of the blind hole extends to the edge of the secondary groove. The tail of the first wedge angle forms an angle with the edge, and each edge intersects at least two wedge-shaped blind holes. That is, the tail of

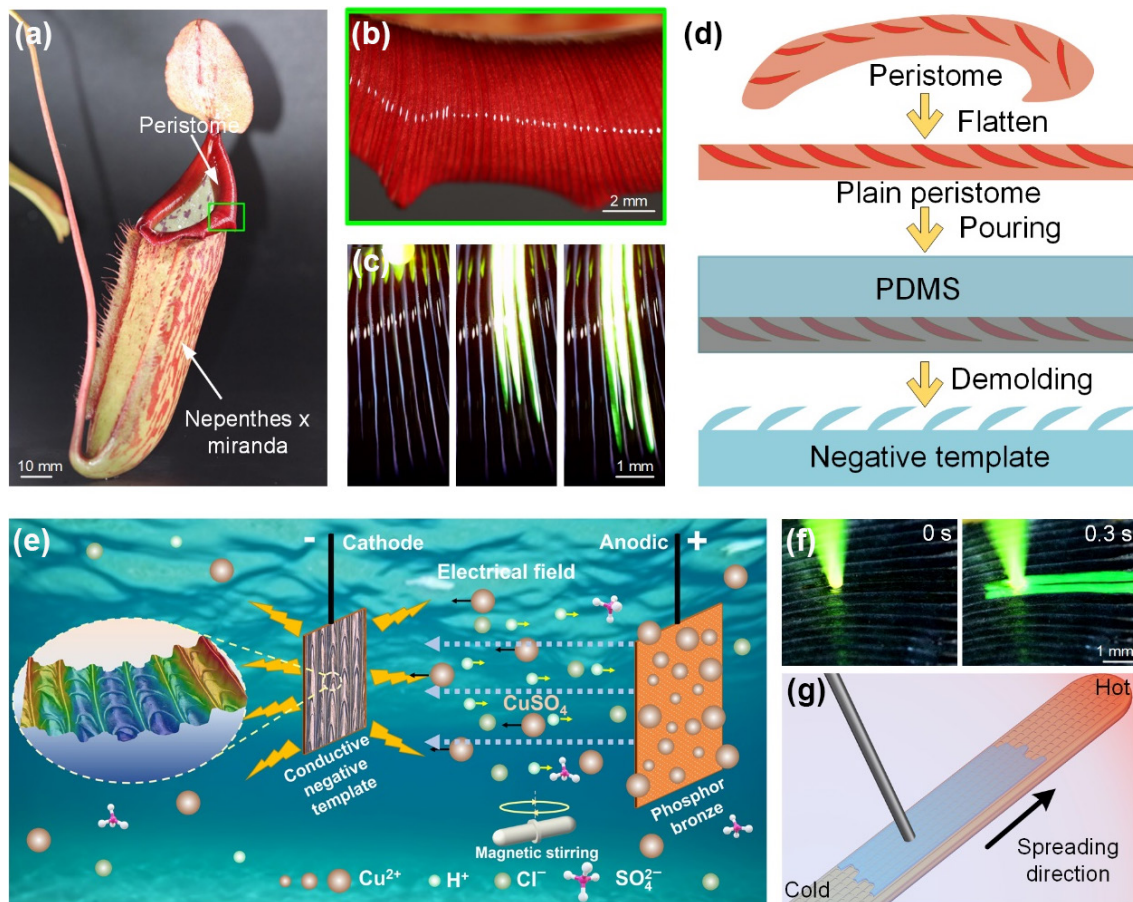


Fig. 1 Fabrication of imitations of the peristome surface structure of *Nepenthes alata*. (a) Image of *Nepenthes alata*. (b) Macroscopic groove morphology of the peristome surface structure of *Nepenthes alata*. (c) Directional spreading of liquid on the peristome surface. (d) Preparation of an electroforming core mold to imitate the peristome surface. (e) Electroforming technology preparation process. (f) Liquid-directional spreading process on the surface of electroformed microstructures. (g) Inverse thermal field transport of liquids.

the first wedge angle and the tail of the second wedge angle intersect. This structure forms the continuity of the secondary grooves on the peristome surface of *Nepenthes alata*, and it is also an important factor in the continuous unidirectional transport of the liquid.

The ambient humidity was controlled to 45% RH when the ambient temperature was 25 °C. Absolute ethanol (0.5 μ L) and deionized water (0.5 μ L) were added to the surface of the peristome surface of *Nepenthes alata*, and the volatilization and residence time of the liquid on the surface were observed. For comparative observation, both liquids were colored with fluorescein sodium and observed under a microscope. The volatilization time and liquid residence of anhydrous ethanol on the surface (Fig. 2(a) and Movie S2 in the ESM) are due to the volatility of anhydrous ethanol. When the liquid (0.5 μ L) was added to the surface, a crescent-shaped fluorescent liquid residue remained in the wedge-shaped blind hole of the secondary groove at 30 s, and the fluorescent liquid almost completely evaporated at 40s. The volatilization of the liquid was observed when deionized water (0.5 μ L) was dropped at the same position on the surface (Fig. 2(b) and Movie S2 in the ESM). At 120 s, crescent-shaped fluorescent liquid was distributed in the wedge-shaped blind hole of the secondary groove and could be maintained after 420 s. This shows that the wedge-shaped blind hole in the secondary groove on the peristome surface of *Nepenthes alata* has the characteristics of long-acting retention of microliquid.

The storage characteristics of the liquid in the wedge-shaped blind hole of the secondary groove at the peristome surface of

Nepenthes alata were further analyzed. The green crescent-shaped fluorescent liquid indicated that the liquid was retained inside the wedge-shaped blind hole (Fig. 2(c)). In the opposite direction, the liquid exhibited cutoff behavior in the microstructure (Fig. 2(d)). When there is very little liquid on the surface of the needle, a small amount of liquid can still be fixed in the secondary groove wedge-shaped blind hole structure, which provides a structural basis for the long-term storage of liquid on the surface of the mouth. When there is little liquid on the peristome surface of *Nepenthes alata*, the secondary groove wedge blind hole structure can still hold a small amount of liquid, providing a structural basis for long-acting storage of liquid on the peristome surface. The blue area represents the liquid fixed in the wedge-shaped blind hole (Fig. 2(c)). Owing to the angle β at the bottom of the wedge-shaped blind hole being the smallest, according to the gradient Taylor capillary rise theory, the top of the blind hole has the strongest liquid holding capacity, which is beneficial for stabilizing the microliquid in the wedge-shaped blind hole. However, the outermost end of the liquid held in the blind hole converges with the edge of the secondary groove to achieve the wetting effect of the microliquid.

To characterize the relationship between the long-term storage of microliquid on the peristome surface of *Nepenthes alata* and the humidity of the external environment, the humidity environment variables were controlled to be 45% RH, 65% RH, 80% RH, and 90% RH. Fluorescein sodium solution (0.5 μ L) was added to the peristome surface to control the humidity of the environment. The liquid stored in the secondary groove on the

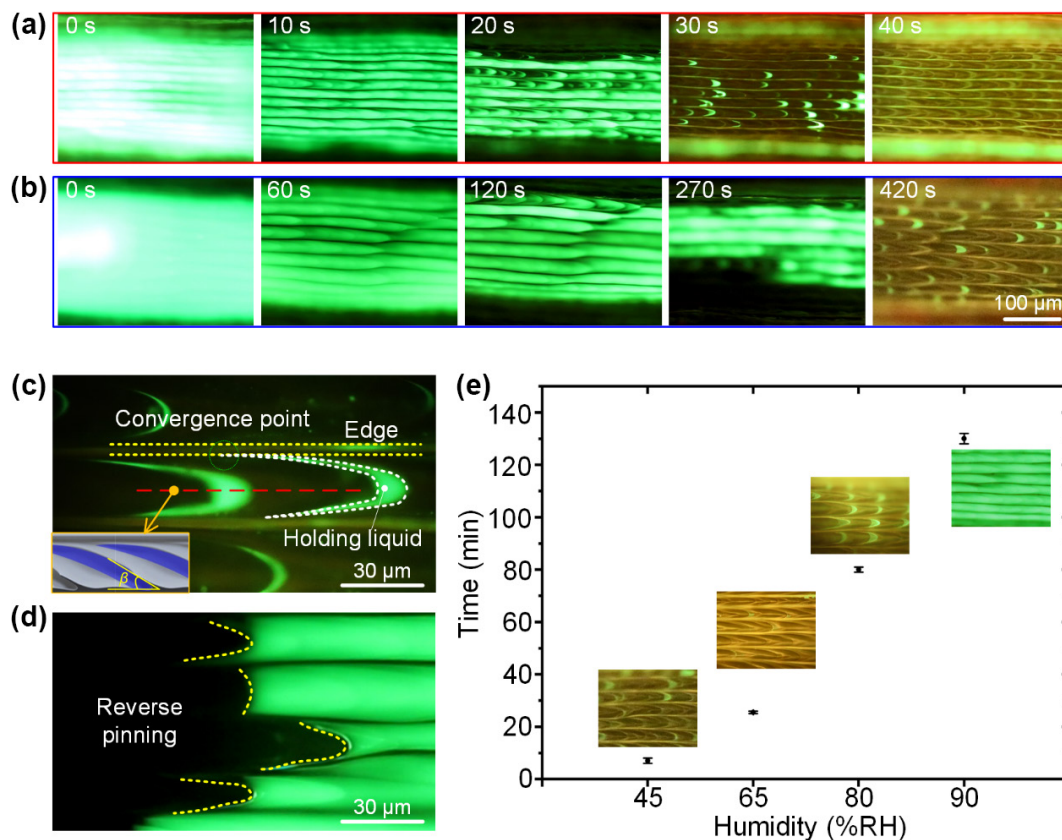


Fig. 2 Long-acting lubrication mechanism on the peristome surface of *Nepenthes alata*. Relationship between volatilization and residence time in the secondary tank for (a) ethanol and (b) deionized water. (c) Behavior of the holding fluid in the microstructure. The partially enlarged picture shows the cross-sectional model diagram of the red dotted area. (d) Direction pinning performance of the holding liquid in the microstructure. (e) Effect of humidity on the volatilization time of liquid on the peristome surface of *Nepenthes alata*.

peristome surface of *Nepenthes alata* was continuously observed under a microscope, and the volatilization time was recorded. Figure 2(e) shows a comparison of the liquid storage times in the secondary groove under different humidity conditions. The liquid storage time in the secondary groove increases with increasing humidity of the external environment. When the humidity environment is 45% RH, the liquid storage time in the secondary groove is approximately 10 min, and some liquid remains stable in the wedge-shaped blind hole. When the humidity was 65% RH, the surface liquid storage time was increased to 25 min. As the humidity increased to 80% RH, the liquid volatilization time was significantly extended to 85 min, and the amount of liquid inside the wedge-shaped blind hole remained almost constant. When the ambient humidity is 90% RH, the liquid in the secondary groove has difficulty volatilizing, and the liquid film can be maintained for 130 min.

3.3 Wettability and wear resistance

Considering the safety and cost of electrosurgical instruments in minimally invasive surgery, metal materials such as stainless steel substrates are often used to make electrosurgical instruments. To improve soft tissue adhesion during operation, the process of adding a TiO₂ coating on the surface of the electroformed microstructure to imitate the peristome surface structure of *Nepenthes alata* was adopted in this study, and its wettability and durability were tested.

The wettabilities of the three kinds of imitation peristome surface structures of *Nepenthes alata* made of a copper substrate (Figs. 3(a) and 3(d)), chromium coating (Figs. 3(b) and 3(e)), and TiO₂ coating (Figs. 3(c) and 3(f)) were characterized. Figure 3(g)

shows a comparison of the contact angles of the three surfaces when deionized water or dimethyl silicone oil was added to the surface. Deionized water (0.5 μL) was added to the copper substrate and the chromium coating microstructure surface. The contact angles θ were 96° and 89°, respectively, and the difference along the groove direction was not significant. However, owing to the anisotropy of the surface microstructure, the contact angles of the two boundaries of the deionized water droplets on the TiO₂ coating surface are 31° and 48.9°, indicating that the bionic microstructure surface of the TiO₂ coating has hydrophilic properties. When dimethyl silicone oil was added to the three kinds of structural surfaces, the contact angle of the TiO₂ coating was less than 10°, indicating superoleophilic wettability.

In minimally invasive surgery, the instantaneous operating temperature of the electrosurgical electrode exceeds 300 °C. Therefore, further exploration of the dynamic spreading law of the liquid on the peristome surface of *Nepenthes alata* with TiO₂ coatings at different temperatures is necessary. The dynamic spreading process of anhydrous ethanol (2 μL) on the surface of the TiO₂ coating was observed at room temperature (20 °C) (Fig. 3(h) and Movie S3 in the ESM). Anhydrous ethanol has good unidirectional spreading characteristics on the surface. The spreading distance along the exit direction is 5.2 mm within 1.2 s, whereas the reverse direction shows an obvious cutoff effect. Deionized water (2 μL) does not have an obvious spreading effect at a normal temperature (20 °C). However, when the temperature increases to 150 °C, the deionized water moves rapidly in the exit direction under the Leiden-Frost effect (Fig. 3(i) and Movie S3 in the ESM). Under normal temperature conditions (20 °C), when dimethylsilicone oil drops onto the surface of the electroformed

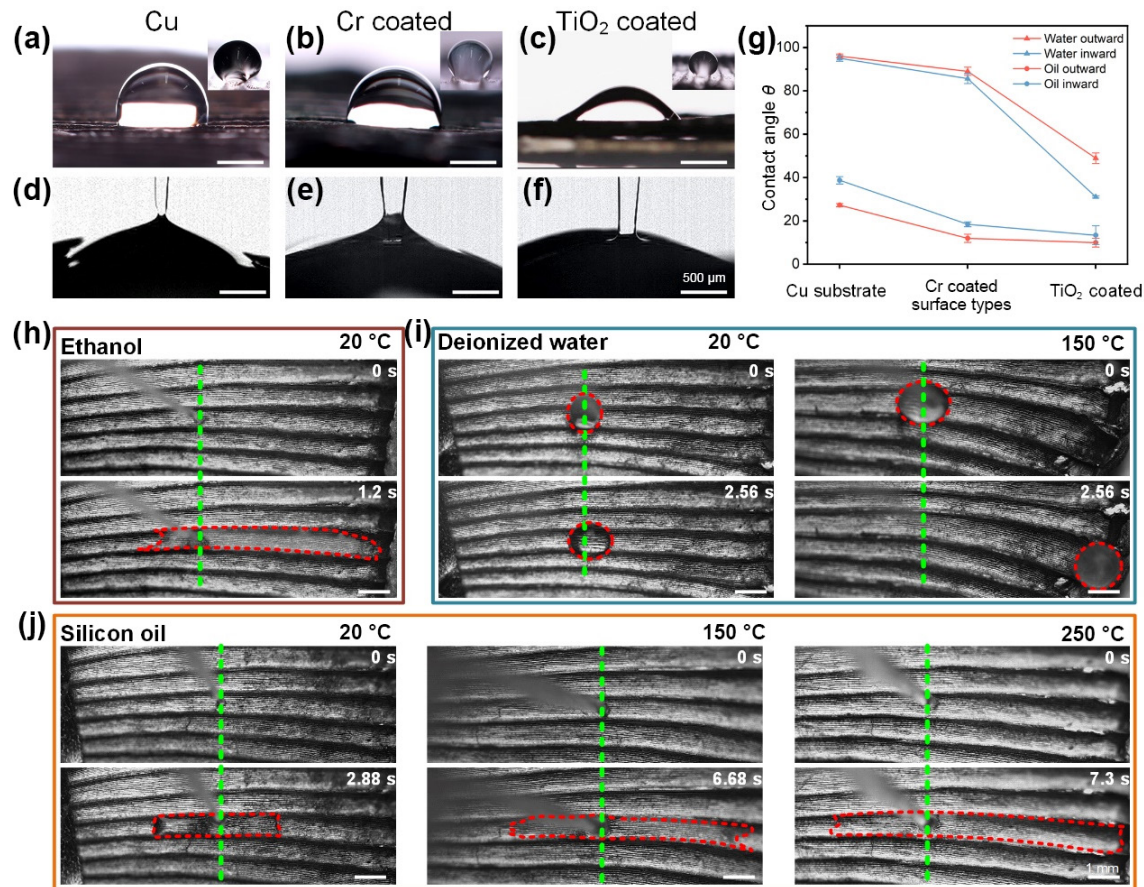


Fig. 3 Wettability and wear resistance of imitations of the peristome surface structure of *Nepenthes alata*. (a) Contact angle of Cu substrate surface, (b) Cr coating surface, and (c) TiO₂ coating surface. (d, e) Dynamic contact angle of dimethicone added dropwise. (g) Comparison of three surface contact angles. (h) Anhydrous ethanol spreads on the electroformed surface. (i) Deionized water spreads on the electroformed surface. (j) Spreading of dimethyl silicone oil on the electroforming surface.

microstructure to imitate the peristome surface of *Nepenthes alata* with a TiO₂ coating (Fig. 3(j) and Movie S3 in the ESM), the unidirectional transport performance of dimethylsilicone oil is not obvious. When the temperature increases to 150 °C, it clearly has unidirectional spreading characteristics. Within 6.68 s, the spreading distance along the exit direction is 4.7 mm, whereas the reverse spreading distance is only 2.1 mm. When the temperature increases to 250 °C, the unidirectionality of the spreading is further strengthened, and the spreading speed is also further improved. Within 5.3 s, the spreading distance in the exit direction reaches 5.6 mm, whereas that in the reverse direction is only 2.2 mm. This shows that dimethylsilicone oil dripped onto the surface of the electroformed microstructure, which mimics the peristome surface of *Nepenthes alata* with a TiO₂ coating, has good unidirectional spreading characteristics at high temperatures.

In addition, the electrosurgical electrode is in direct contact with soft tissue, and its structural stability is also an important factor affecting the directional transport of liquid on its surface. To characterize the structural stability of the electroformed surface with the TiO₂ coating, the wear resistance of the sandpaper with different grits was studied experimentally, and the wear conditions and the directional spreading performance of the surface liquid after wear were characterized. Figure 4 and Movie S4 in the ESM show that the surface microstructure of the sample has different degrees of wear, and its degree of wear is negatively related to the grit of the sandpaper. By injecting fluorescently stained anhydrous ethanol into the worn surface (Figs. 4(d)–4(g)), it can be seen that the wear has little effect on the liquid spreading on the surface.

This is because the surface of the peristome surface of *Nepenthes alata* has a multistage microgroove structure, and its liquid directional spreading is formed mainly by the secondary groove structure on the peristome surface of *Nepenthes alata*. Therefore, the microstructure prepared by the electroforming process has excellent structural stability in liquid directional transport.

3.4 Inverse thermal field liquid transport mechanism

On the prepared surface with a temperature gradient field, the liquid can still overcome the thermal field gradient and be transported from the low-temperature region to the high-temperature region (Fig. 1(g)). As the liquid temperature increases, the surface tension decreases, and vice versa [47]. Therefore, the surface tension of the droplets on both sides of the gradient is different, which will produce a Laplace pressure difference, and the droplets will slip from high temperatures to low temperatures along the temperature gradient [48, 49]. However, the direction of liquid flow on the imitations of the peristome surface structure of *Nepenthes alata* is affected by the capillary force and thermal gradient force generated by the surface microstructure. Through the analysis of these two forces, we can accurately grasp the dynamic spreading law of the liquid on the surface of the electroformed structure of the imitations of the peristome surface structure of *Nepenthes alata*. The electroformed surface with a multilevel microstructure was placed in the middle of the thermal field gradient, and the low-temperature region and the high-temperature region were on both sides of it (Figs. 5(a) and 5(b)). Dimethyl silicone oil is injected into the bionic surface

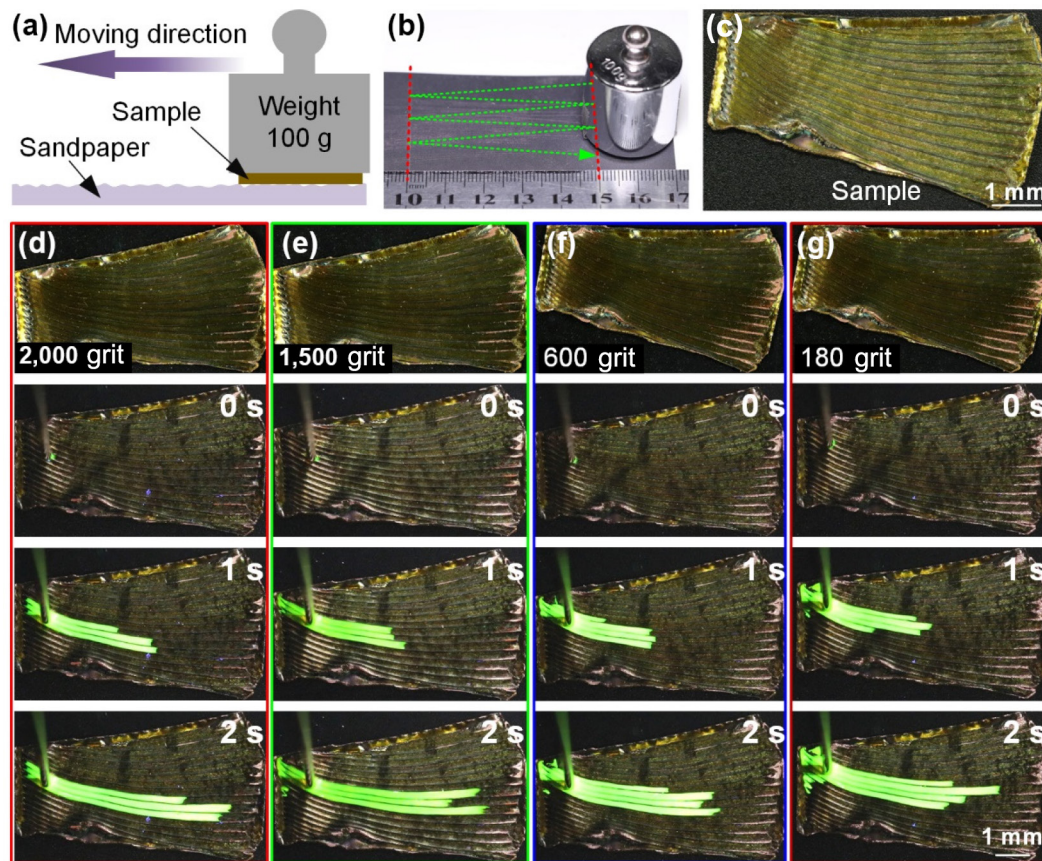


Fig. 4 Characterization of the wear resistance of the electroformed peristome surface of *Nepenthes alata* with a TiO_2 coating. Diagram of (a) experimental device and (b) slip. (c) Sample in the wear-resisting experiment. (d) Spreading effect of 2,000 grit sandpaper after friction. (e) Spreading effect of 1,500 grit sandpaper after friction. (f) Spreading effect of 600 grit sandpaper after friction. (g) Spreading effect of 180 grit sandpaper after friction.

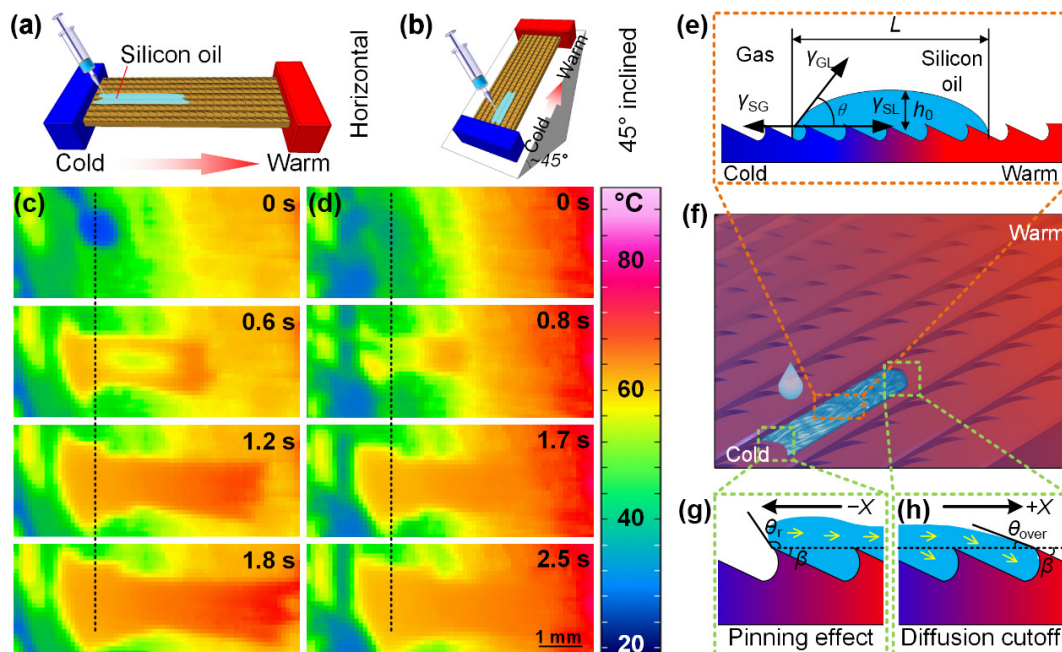


Fig. 5 Liquid transport mechanism in the inverse thermal field. (a) Experimental device diagram of the horizontal thermal field gradient. (b) Experimental device schematic diagram of the thermal field gradient placed at an angle of 45° to the horizontal direction. (c) Horizontal directional spreading of liquid in the inverse thermal field. (d) Liquid is oriented along the 45° slope of the inverse thermal field. (e) Inverse thermal field transport mechanism. (f) Liquid transport process in an inverse thermal field. (g) Reverse pinning effect. (h) Positive end effect. In the negative direction ($-X$), the spread of liquid tends to be bounded by sharp edges. In the positive direction ($+X$), pinning is determined by the intrinsic contact angle θ_0 , and the final diffusion state condition is $\theta_0 \geq \theta_{\text{over}}$. θ_0 is the static contact angle of the liquid.

with a syringe. The liquid can overcome the resistance caused by the temperature gradient field under the capillary force generated

by the multistage microstructure on the bionic surface and spread from the low-temperature region to the high-temperature region.

Similarly, when the surface is tilted, the liquid on the bionic surface can also spread from the low-temperature region to the high-temperature region in the direction of antigravity within a certain angle.

According to Fig. 5(c), the temperature in the high-temperature region is approximately 80 °C, and the temperature in the low-temperature region is approximately 20 °C. Here, the initial temperature of the low-temperature region is represented by T_o , and the final temperature of the high-temperature region is represented by T_w . Assuming that the temperature gradient is a constant value, the temperature gradient value can be expressed as Eq. (1):

$$\frac{\partial T}{\partial x} = \text{constant} = C_T \quad (1)$$

where C_T indicates that the temperature gradient value is constant. In addition, as shown in Fig. 5(e), it is assumed that the height h_o of the liquid on the surface of the bionic multistage microstructure is less than the liquid spreading length L and has the same viscosity and density. The internal pressure of the liquid is P , the external pressure is P_o , and the surface tension of the silicone oil is γ_{GL} . R is the radius of curvature of the liquid, with the following relationship (Eq. (2)) [49, 50]:

$$\tau = R \frac{dP}{dx} + \frac{\gamma_{GL}}{R} \frac{dR}{dx} \quad (2)$$

where τ is the shear stress on the liquid surface, and the change in the curvature radius dR/dx of the liquid is the additional force ($F_{\text{capillarity}}$) caused by the multilevel groove microstructure on the imitations of the peristome surface structure of *Nepenthes alata*. Since the normal direction of the gas-liquid interface points in the high-temperature region, $F_{\text{capillarity}}$ prevents the liquid from spreading to the low-temperature region. When the thermal field gradient C_T is lower than the critical value, the liquid will have a reverse thermal field gradient, spreading from the low-temperature region to the high-temperature region. During the diffusion process, the spreading in the positive direction (+X) and the pinning effect in the reverse direction (−X) are still maintained, as shown in Figs. 5(g) and 5(h).

The peak temperatures of the conventional electrosurgical electrode, the TiO₂-coated conventional electrosurgical electrode, and the bionic electrosurgical electrode on the dry surface and the wet surface (dimethyl silicone oil as the lubricant) during pulse discharge and the movement of the surface lubricant during discharge were compared, and the results are shown in Fig. S4 in the ESM. Under the same power conditions, when the lubricant is added to the surface of the electrosurgical electrode, the liquid bridge between the electrosurgical electrode and the electrode holder provides the necessary conditions for stable discharge, so the instantaneous temperature is slightly higher than that of the dry surface. The infrared thermal image at the moment of discharge reveals that, compared with the single-point local high temperature of the dry surface, the wet surface has a more uniform heat-affected region, which is helpful for the smooth operation of the electrocution. The lubricant on the surface of the conventional electrosurgical electrode and the TiO₂-coated conventional electrosurgical electrode transfers to the electrode holder under the action of the thermal gradient field generated by the discharge, resulting in a lack of lubricant in the working area of the electrosurgical electrode. The bionic electrosurgical electrode can continuously replenish the lubricating fluid in the working area through the surface anisotropic structure, which plays an important role in the antisticking stability of soft tissue during electrocution.

3.5 Electrical performance test

To verify the electrical properties of the RMSS electrode and the initial electrode, we used a high-frequency pulse power supply as the experimental power supply. We simulated different cutting states of the two electrodes, as shown in Figs. 6(a)–6(d). When the oil-free initial electrode cuts pig liver tissue, the peak-to-peak voltage between the electrode and the tissue is only 1,008 V, which is lower than the open-circuit voltage of 1,048 V. This indicates that there may be a short-circuit issue in the process. The oil-free initial electrode had a larger contact area with the pig liver tissue, resulting in a lower current density. It is difficult for breakdown discharge to occur when stimulated by high-voltage pulses. At the same time, direct contact between the electrode and the tissue will cause charge to leak from the electrode into the tissue, which can easily lead to a short circuit of the electrode, resulting in a pure heating mode. The peak-to-peak voltage between the electrode and tissue in pure heating mode is only 312 V. When the RMSS electrode cuts pig liver tissue, the current density on the surface increases due to the existence of the surface microstructure. Under the excitation of high-voltage pulse signals, spark effects are more likely to occur. However, direct contact between electrodes and tissue also causes a certain amount of charge to leak into the tissue. When the oil-free RMSS electrode cuts pig liver tissue, the peak-to-peak voltage in the circuit is 1,064 V, which is significantly lower than the open circuit voltage of 1,088 V. This may indicate a partial short circuit problem. The peak-to-peak voltage between the electrode and tissue in pure heating mode is only 232 V. Furthermore, when silicone oil is present between the electrode and the tissue, the high resistance of the silicone oil can effectively prevent the electrode from escaping into the tissue and maintain the charge difference between the electrode and the tissue. The electrode produces a better discharge effect. By testing the pulse signal, we found that the peak-to-peak voltage of the RMSS electrode moistened by silicone oil is 1,072 V, which is higher than the peak-to-peak voltage of the initial electrode moistened by silicone oil, which is 1,040 V. This finding indicates that silicone oil-wetted RMSS electrodes enable pulsed spark discharge to be implemented more efficiently. In addition, we compared the current and power trends over time of the initial electrode and RMSS electrode before and after cutting, as shown in Figs. 6(e) and 6(f). The resistance values and power values of the initial electrode and RMSS electrode before cutting clearly exhibited similar trends, but after cutting, the resistance value of the initial electrode increased significantly, and the power value decreased significantly. This shows that a large amount of tissue adhesion on the initial electrode surface causes its resistance value to increase significantly and its power value to decrease significantly. However, the resistance value and power value of the RMSS electrode before and after cutting exhibit small changes, which proves that the amount of surface tissue adhesion is small and does not affect the electrical performance of the electrode. To verify and compare the stability of the electrical performance during the cutting process of the initial electrode and the RMSS electrode, we conducted five-cycle electrocution experiments and recorded the changing trend of the peak-to-peak voltage and resistance between the electrode and the tissue with increasing number of cuttings, as shown in Figs. 6(g) and 6(h). The results show that as the number of cuts increases, the peak-to-peak voltage between the electrode and the tissue decreases. The peak-to-peak voltage between the RMSS electrode and the tissue is greater than that of the initial electrode, indicating that the RMSS electrode is more likely to generate pulse spark discharge. As shown in Fig. 6(h), as the number of cuttings increases, the initial

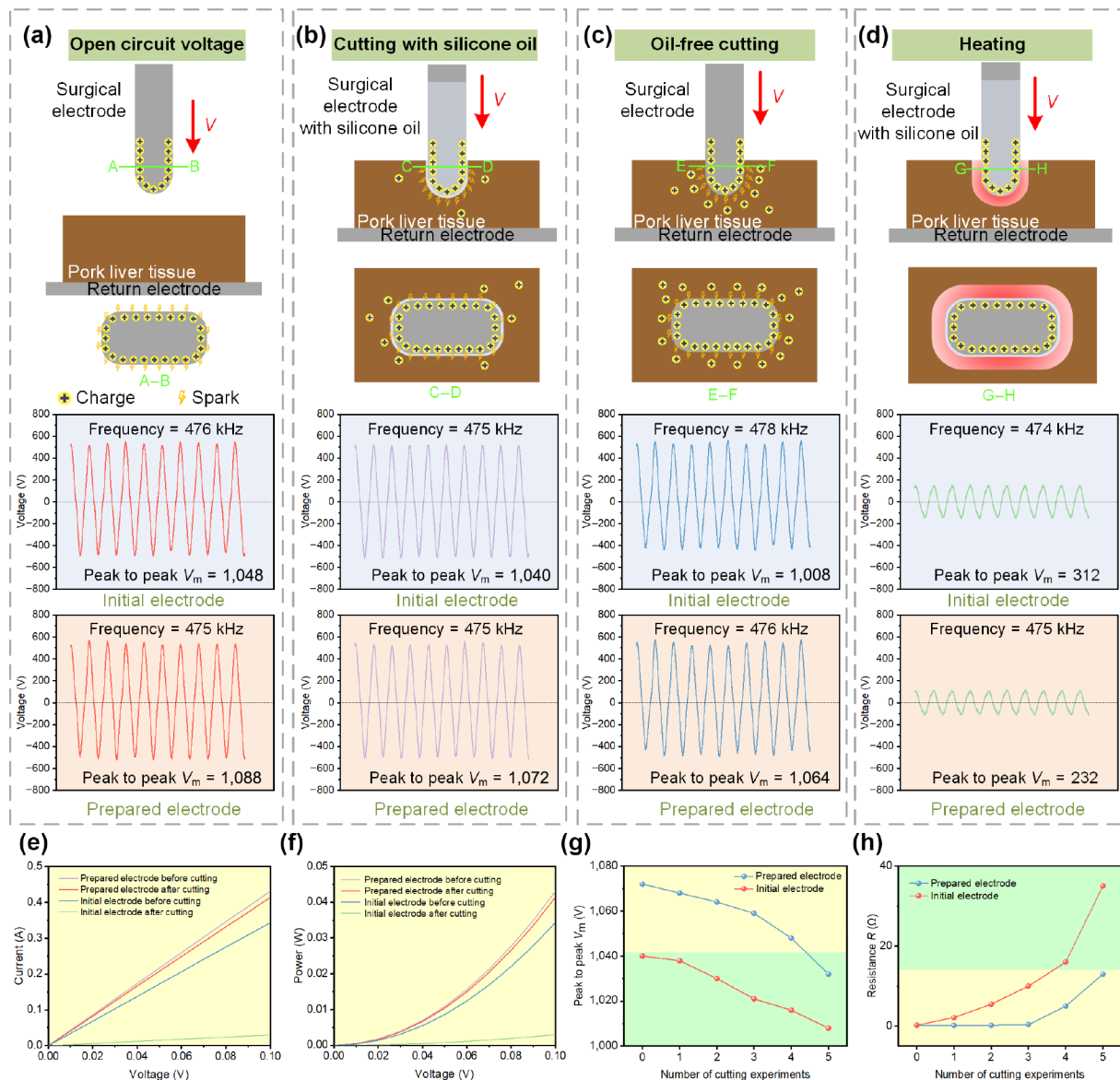


Fig. 6 Electrical performance comparison test results. (a) Pulse voltage in the open-circuit state. (b) Pulse voltage during cutting under silicone oil infiltration conditions. (c) Pulse voltage during cutting under oil-free wetting conditions. (d) Electrode heating state when the electrode is in direct contact with tissue. (e) Comparison of the changing trends of current with voltage. (f) Comparison of power variation trends with voltage. (g) Changing trend of the pulse voltage as the number of cuttings increases. (h) Changing trend of resistance as the number of cuts increases.

electrode resistance significantly increases, but the resistance value of the RMSS electrode is relatively stable. This finding indicates that the RMSS electrode has a lower degree of tissue adhesion and more stable electrical properties.

3.6 Study on the antisticking properties of soft tissue electrosurgical cutting with bionic electrosurgical electrodes

To characterize the soft tissue anti-sticking performance of the bionic electrosurgical electrode with imitation of the peristome surface of *Nepenthes alata*, an electroresection test of pig liver tissue was carried out. Lubricating fluid is injected into the micropores (Fig. 7(a)) in the middle of the knife head. During the cutting experiment, the liquid gradually exudes from the micropores to ensure sufficient lubricating fluid on the surface of the bionic electrosurgical electrode. After a single experiment, compared with the dry surface, water lubrication and silicone oil lubrication, there was no large soft tissue adhesion on the front or back of the electrosurgical electrode (Fig. 7(b)). The results

showed that the imitation of the peristome surface of *Nepenthes alata* has good soft tissue anti-sticking properties. The wound and thermal damage areas of pig liver tissue are shown in Fig. 7(c) and Movie S5 in the ESM. The blue wire frame, green wire frame, and red wire frame represent the dry surface electrosurgical electrode, water lubricated electrosurgical electrode and dimethyl silicone oil lubricated electrosurgical electrode cutting wound (yellow virtual coil), and thermal damage area (green virtual coil), respectively. The charring wound area of the dry surface electrosurgical electrode was approximately 2.45 mm², the charring wound area of the water-lubricated electrosurgical electrode was approximately 1.52 mm², and the charring wound area of the silicone oil-lubricated electrosurgical electrode was approximately 1.49 mm². The thermal damage areas were 6.09, 17.39, and 7.02 mm², respectively. On the basis of the wound area and the area of thermal damage, it can be concluded that the electrosurgical electrode lubricated with dimethyl silicone oil has the best soft tissue anti-sticking performance and the most

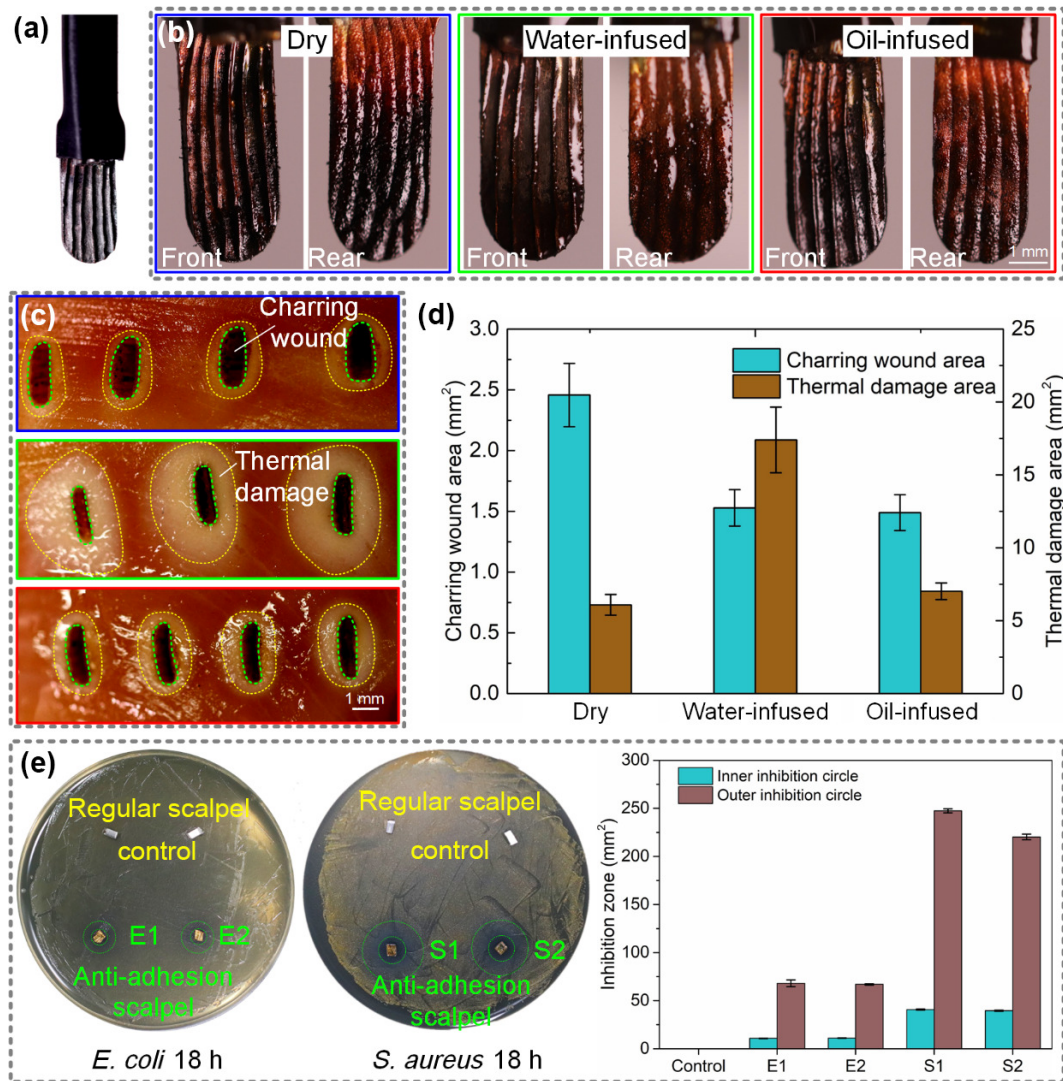


Fig. 7 Performance test of the antisticking electrosurgical electrode with imitation of the peristome surface of *Nepenthes alata*. (a) Picture of the bionic electrosurgical electrode. (b) Comparison of tissue adhesion. (c) Tissue wound morphology. (d) Comparison of the wound area. (e) Bacteriostatic test.

accurate cutting effect. The antibacterial property of the electrosurgical electrode is also an important factor in its evaluation index. The bacteriostatic circle experiment was carried out on the surface of the bionic electrosurgical electrode and the conventional electric knife to compare their antibacterial properties against *Escherichia coli* and *Staphylococcus aureus*. The synergistic antibacterial effect of TiO_2 nanoparticles has become a research hotspot for antibacterial agents in recent years. The antibacterial mechanism of TiO_2 nanoparticles is to achieve antibacterial effects by decomposing bacteria. According to the results shown in Fig. 7(e), the bacteriostatic circle of the conventional electrosurgical electrode is not obvious, whereas the bionic electric knife clearly produces a bacteriostatic circle on *E. coli* and *S. aureus*, indicating good bacteriostasis, which can effectively reduce the cost of cleaning and sterilization with electrosurgical instruments.

4 Conclusions

In summary, the formation mechanism and long-term wetting mechanism of the liquid film on the surface of the peristome of *Nepenthes alata* were studied and analyzed, and the long-term retention characteristics of the liquid on the secondary groove surface of the rim were characterized. The multilevel

microstructure of the peristome of *Nepenthes alata* was prepared on the surface of the metallic material. By modifying its surface and adding a TiO_2 coating, the wettability and unidirectional spreading law of liquid under different temperature conditions were explored. The results show that the prepared functional surface has good wettability and unidirectional spreading properties. The durability of the functional surface was verified via friction tests. The prepared functional surface exhibited reverse thermal field gradient lubrication characteristics. Through electrical performance tests, it was concluded that the introduction of a microstructure on the electrode surface can promote the occurrence of the spark effect and improve the cutting effect. Through an experiment in which fresh isolated pig liver was cut, its antiadhesion, thermal damage, and soft tissue antibacterial properties were characterized. The results show that the electrosurgical electrode with the imitated *Nepenthes alata* multilevel microstructure surface has good antiadhesion performance, significantly reduced adhesion, significantly reduced thermal damage, improved antibacterial performance, and extended service life. The charring wound area of the silicone oil-lubricated electrosurgical electrode was approximately 1.49 mm^2 , and the thermal damage area was 7.02 mm^2 . We believe that the fabrication of this realistic hierarchical structure of the *Nepenthes*

alata surface on a metal substrate provides new insights into antiadhesion surfaces, including minimally invasive surgery, industry, biochips, or other practical applications.

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Author contributions

Guang Liu and Jiajun Yang contributed equally to this work. Guang Liu, Jiajun Yang, Guang Yang, and Huawei Chen conceived the project. Guang Liu, Jiajun Yang, and Zehui Zhao designed the experiments. Guang Liu, Jiajun Yang, Yu Yan, and Kaiteng Zhang carried out the experiments. Guang Liu, Huawei Chen, Haipeng Yan, Yingdong Zheng, and Liwen Zhang discussed the results. Guang Liu and Jiajun Yang wrote the initial manuscript, which was approved by all the authors.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Electronic Supplementary Material

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