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Shaking the wings and preening feathers with the beak help a bird to recover its ruffled feather vane

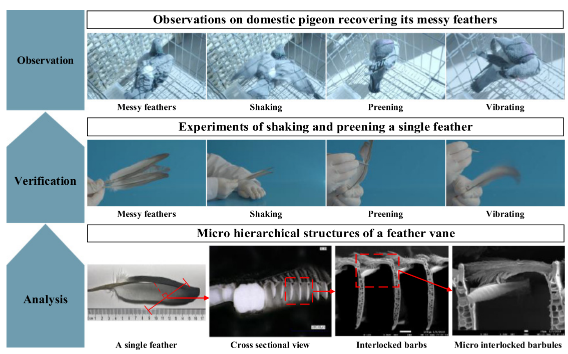
Jing-Shan Zhao [a,*], Jiayue Zhang [a], Yuping Zhao [a], Zhaodong Zhang [a], Pascal Godefroit [b]

[a] State Key laboratory of Tribology, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, PR China
[b] Royal Belgian Institute of Natural Sciences, Belgium

HIGHLIGHTS

- There is some space between the hierarchical structures of barbs and barbules.
- The space allows the separated micro-hooklets to recover and interlock.
- Shaking wings and preening feathers render deflections on rachis, barbs and barbules.
- Deformations of rachis, barbs and barbules provide the energy for vane self-healing.

GRAPHICAL ABSTRACT



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ABSTRACT

The feather of a bird consists of barbs which again comprise numerous barbules with micro-hooklets. This hierarchically organized feather structure provides a smooth vane to bear the load from the airflow; however, the feather vane is vulnerable to disruption by external pulling forces during collision with the branches of a tree and hitting some small obstacles in flight or strong turbulence. The feather is unable to carry the weight of the bird's body if the vane could not be recovered immediately. Here we discovered that the feather vane can be re-established easily by birds themselves. A bird can always recover its feather vane from ruffled state by shaking its wings and preening its feathers with its beak because of the cascaded geometries of barbs and barbules. This biophysical mechanism of self-healing suggests that the hierarchical vane structure can be used to design artificial feathers for a flapping robot.

1. Introduction

The feathers of modern birds have evolved from the Jurassic to the Cretaceous [1,2]: however, early feathers only had long, singular, unbranched filamentous integumentary structures [3]. The primitive structures that closely matched those of protofeathers were found in

* Corresponding author.
E-mail address: jingshanzhao@mail.tsinghua.edu.cn (J.-S. Zhao).

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the late Cretaceous. This offers new insights into the feathers' structure and function for flight [4]. Lateral rectrices of the tail of *Archaeopteryx* were slightly shorter than the distal ones and were asymmetrical. This suggests that the tail of *Archaeopteryx* possessed an additional aerodynamic function, which increased the total lift available to the animal [5].

The latest discoveries show that barbules provide adhesion within the vane of a feather through an interlocking hook-and-groove mechanism, which allows the effective capture of air in flight [6,7], however, the barbules of a feather may be split in some conditions, such as flying in strong wind, when landing on branches, and upon hitting objects in flight. In such cases, feathers tend to lose their load-bearing ability if they could not recover immediately. It is a death sentence for a bird to lose flying capacity.

During natural molting in many birds, old feathers are often passively pushed out of the follicles attached to the tips of the sheaths of incoming feathers [8]. This provides one way to update the feather and make sure that all feathers could play their correct role in carrying the weight. Nevertheless, the majority of birds have only one annual molt [9,10]. Waiting for new feather growth is unrealistic in most cases. The birds must have other ways to recover the smooth vane of feathers after the feather is split. Preening is believed to allow a bird to reposition the feathers and preen oil [11], to remove dirt or parasites from their plumage [12], and to assist in waterproofing of feathers [13].

The micro-interlock structure of barbules could promote the improvement of the existing design for folding [14] and self-locking [15] structures. In this paper, a new explanation of how birds recover their damaged feathers is proposed. The research into avian solutions to the split condition is of great importance to bionic material design and application in flying robots.

2. Method and experimental procedures

To discover how birds recover their ruffled feather vanes, the recovery performance of a pigeon, a parrot, and a white-eye bird was individually observed. Since there may be interference from other variables during the observations, the results of the observations were experimentally verified by repeating the same performance on a single feather. The microstructure of feathers was observed to reveal the reason why birds can recover feather vanes by means of such behaviors.

During experimental observation of a pigeon, some of the main flying feather vanes (of the 3rd, 4th, and 5th main flying feathers) on the left and right wings of the pigeon were disrupted. The state of the damage of the feather vanes can be summarized into two cases: (1) non-adjacent barbs formed a “hook-to-groove” connection, or adjacent barbs formed a misaligned “hook-to-groove” connection; (2) adjacent barbs formed a mismatched stack. The pigeon was placed in a pre-prepared glass room. Its recovery procedure of the damaged feathers was recorded using a high-speed camera that could record 180 frames per second.

Then, similar observations were undertaken on a parrot and a white-eye bird. All of these three birds were in good health and exhibited normal behaviors, and their feathers were intact and orderly. We had established mutual trust during long-term contact with them, and they could naturally express their series of feather recovering performance even when observers were present.

After experimental observation, a single feather taken from a living pigeon was disrupted in the same way as seen in the experiments. We clamped the specimen between two main feathers adjacent and kept the narrow-edge vane of the feathers covering the wide-edge vane of the adjacent feathers, the specimen feather was held by one hand. Then another hand moved a pair of tweezers to make the feather experience the same effect as seen in the recovery performance of birds in experimental observations.

After experimental observation and verification, the microstructure was observed using a scanning electron microscope (SEM) to elucidate the reason for the observed recovery behavior.

3. Results and discussion

3.1. Experimental observations

In the experiments, vanes of feathers were tousled and the performance of the bird was observed (Fig. 1). In the observation experiments, every bird could always recover its messy vanes by shaking its body and preening feathers with its beak.

The pigeon had a clear perception of the damage to its feathers. Immediately after being put back into its cage, the pigeon shook its body and wings, trying to recover its messy feathers. When the pigeon shook its feathers, it repeatedly flapped its wings, which not only shook the feathers but also caused collisions between adjacent feathers. Thus, the feathers were re-disrupted, and then recombined to their normal state. During the observations, the pigeon usually completes several cycles of flapping action. Each flapping action included a complete cycle from slightly expanding the wings to retracting them to their initial state.

After shaking its wings, the pigeon used its beak to preen the feathers of the body surface in order. The pigeon showed different ways of preening its feathers. The pigeon's neck was very flexible and its head could be turned 180° or to even greater angles. When preening the flying feathers on the wings, the bird could hold the feathers from four directions, which was achieved by the torsion on both sides of the neck and the bending upward or downward of the head. The pigeons made full use of the curvature of its upper beak and the flexibility of the neck and used the beak to bite the feathers at different angles, which greatly increased the probability of the vanes being recovered.

When the pigeon preened its feathers, the cambered beak helped to hold the feather shaft, which could bend the feather shaft and reserve the elastic potential energy.

In the preening stroke, the beak played three roles, including: (1) Separating the adjacent barbs that had partially unhooked. (2) Directly zipping the adjacent barbs that were originally slightly separated. (3) Pulling the feather shaft to bend and deform and store the elastic potential energy.

Among them, case (3) caused the feather shaft to vibrate after being released, which promoted the recovery of the separated barbs. After one or several cycles of preening with the beak, the feathers with a small number of barbs that had separated would be completely restored.

After repeated shaking and preening, the messy vanes were recovered. The same observations were also conducted on the parrot and the white-eye bird.

Experimental observations proved that the feathers of the birds could be repaired from a messy state to a normal state. Although the recovery postures and frequencies of the feathers of these three kinds of birds were different, the birds could eventually restore their feathers to an orderly natural state by shaking the feathers and preening the vanes thereof with their beaks.

3.2. Experimental verification

In order to check this biomechanical procedure, we experimented with shaking a single feather manually and preening it with a beak-like tweezer (Fig. 2).

To ensure the integrity of the flying feather, all sample feathers in this experiment were acquired from a living pigeon. The 5th main flying feather of the pigeon was selected as the object of our self-repair experiment.

A large area of damage treatment was prepared on the feather vanes, and the damage was more serious than that the pigeons suffered in actual flight. The specimen feather was clamped between two main feathers adjacent, and the narrow-edge vane of the feathers was kept covering the wide-edge vane of the adjacent feathers. The spacing of two adjacent feathers imitated the maximum unfolding state of the pigeon's wings during shaking of the feather.

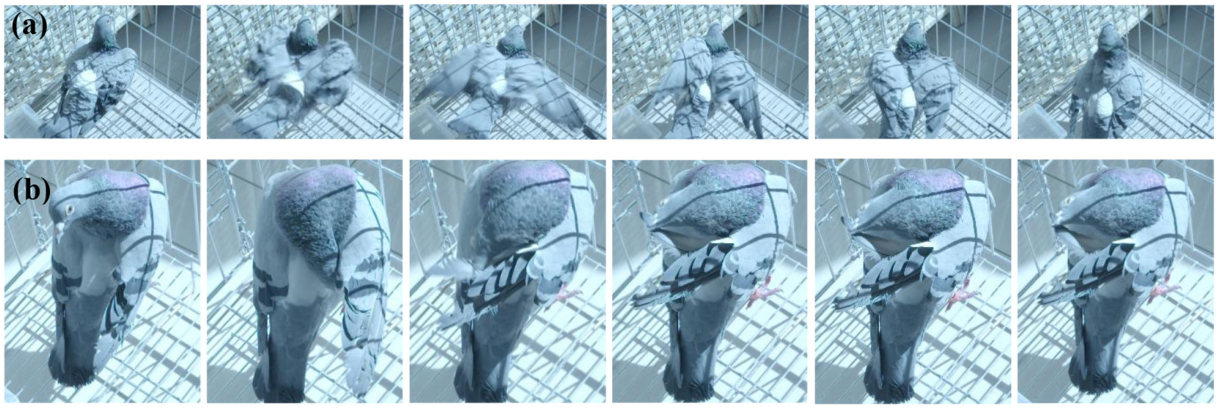

Fig. 1. Domestic pigeon recovers its messy feathers. (a) Shaking the wings to recover the ruffled feathers. When detecting that the barbules of a feather are split, the pigeon first shakes its wings to recover them. After shaking the wings several times, most of the feather vanes are recovered to their normal state. Only a small number of vanes remain in a mess. (b) Preening the ruffled feathers. After detecting some feathers are still in a mess, the pigeon uses its beak to preen the split barbules from the root to the distal of the vane. The pigeon often repeats this process with its beak until the feathers are completely recovered.

In this experiment, during the shaking actions, we held the three feathers in the right hand, and then applied a slapping action on the back of the left hand, so that the feathers could hit the back of the hand to produce vibration. After about 15 to 18 beats, most of the disrupted barbs were recovered.

In our observations, the pigeon used its beak to preen feathers. Hence a pair of tweezers that was bent and sharpened to a similar curvature to the beak was made. The curvature of the upper beak of the pigeon was key to the mimicry here. The cambered tweezers were employed to reproduce the preening performance.

During the preening operations, the root of the feather shaft was held between the experimenter's left thumb and forefinger, while the right hand held the cambered tweezers used to preen the feather vane from the root to the tip. The head of the pigeon was able to turn through 180°, and it could be raised and lowered to achieve multi-angle positioning and multiple preening to one flying feather, so that the flying feather would undergo barb separation and recombination in various ways. This multi-angle preening method was also imitated during the simulated preening experiment. In this experiment, the smooth surface of the vane was restored from the split mess state after one to several cycles of preening.

3.3. Microstructure observation and analysis

As the feather composes of barbs that stem from the feather shaft and barbules that branch from barbs, forming a rigid feather vane [6,10], the original state can be re-established easily by lightly stroking through the feather [7]. The results show a high robustness and flaw-tolerant design of the feather structure [16,17]. This durability of bird feathers against tears originates from their cascaded slide-lock system [18].

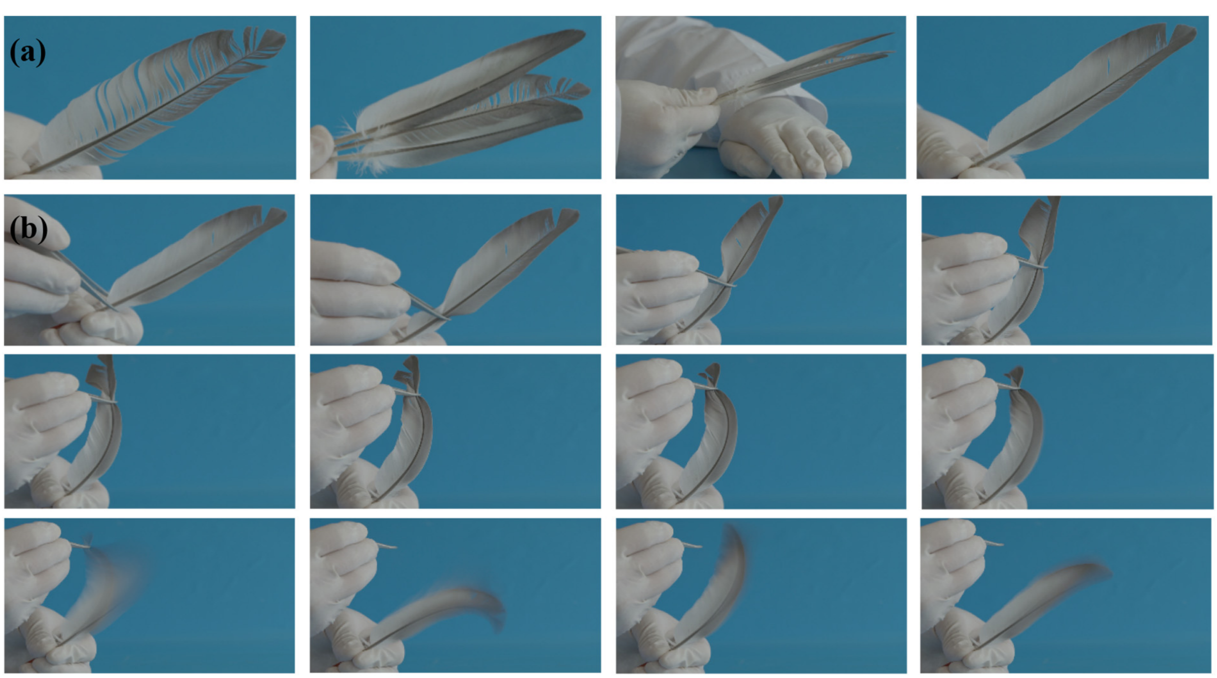

Fig. 2. Experimental preening of a split feather. (a) Shaking the messy feather. The messy feather was clamped with two natural ones and we collided them against the hand 18 times. Most of the splits were repaired. (b) Preening the split vane. We preened the vane with a beak-like pair of tweezers in accordance with the performance of beak. In the first experiment, we recovered the split of the vane by preening the feather once: in the second experiment, we recovered the vane completely by preening it five times.

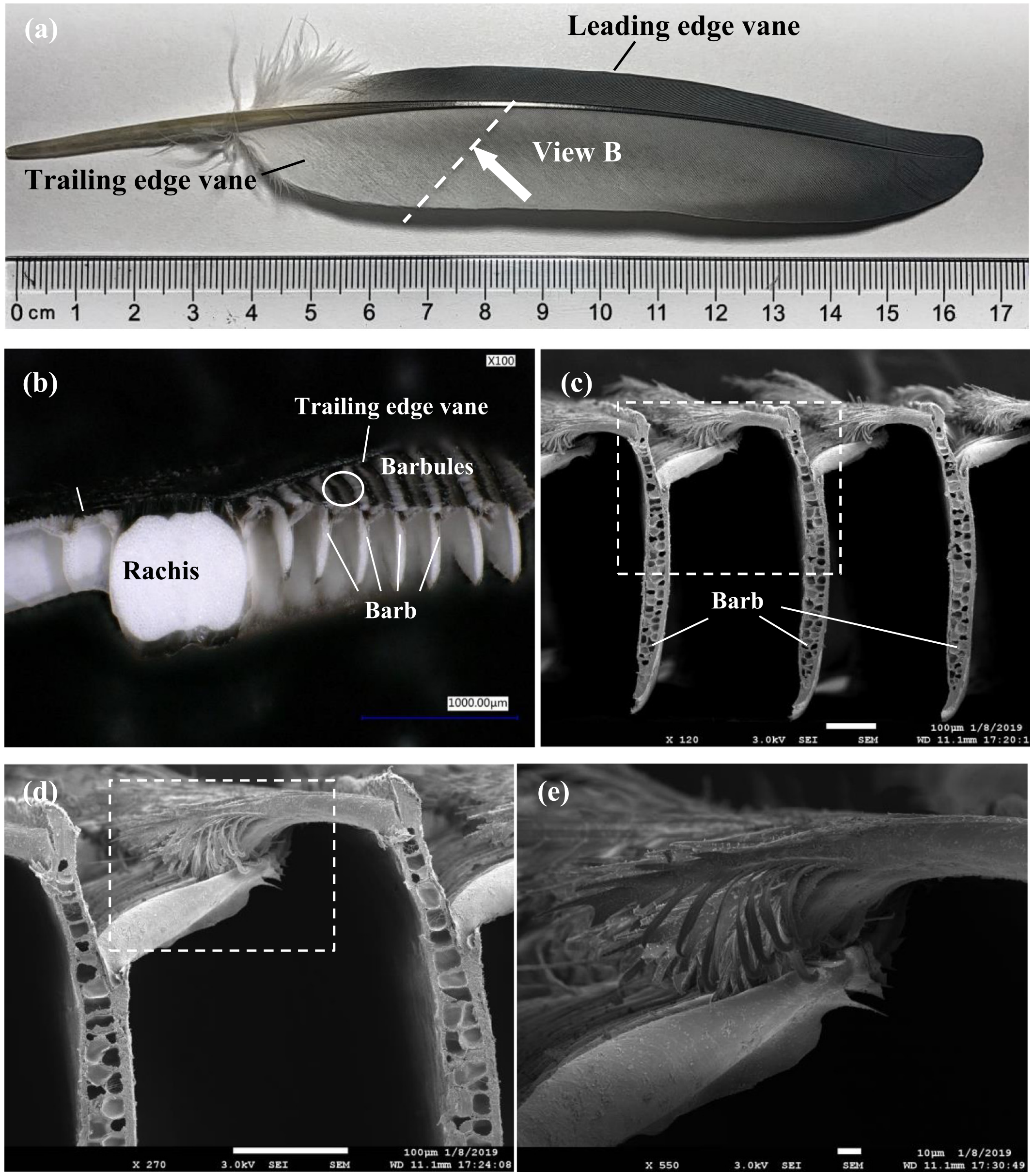

Fig. 3. Hierarchical structures of a feather. (a) A feather from the right-wing of a pigeon. Generally, it is an asymmetrical vane acting as a flight feather. (b) Major structures of the vane. The vane consists of barbs, individuals of which again comprise a lot of ordered barbules in sequence. Adjacent barbs mate well in nature. (c) SEM microgram of barbs attached to the rachis. The array of barbules on one side of a barb keeps the lower level in position relative to those on the other side. For the leading edge vane of a feather, the position of the barbules on the right side of the barb is lower than that of those on the left side. (d) Cross-sectional view of connected barbs. Each barb has a cascaded structure so that all barbs form a smooth feather vane. The continuous surface of a feather vane is interlocked by these numerous micro-hooklets. (e) Enlarged SEM micrograms. There is a certain space within the interlocked barbules: this space provides the facility for locking and unlocking between two adjacent barbules.

The vane of a feather is composed of hierarchical structures (Fig. 3). The major structures are cambered and inclined cross section of barbs on which there are curved proximal barbules [19–22]. The smooth surface of the vane seen under the SEM contains several highly ordered barbules in series at each side of the rachis [23–25]. This cascaded geometry allows the feather to heal by shaking the wings or by preening it with the beak because the largest force required to separate the barbule is as low as approximately 4 mN only [7].

The microscopic diagram (Fig. 4) illustrates the secret of self-healing of a teared vane. For the barbs on the right side of the rachis, the bow barbules of the barb are located below the hook barbules. The largest height difference varies from 50 μm to 80 μm based on our measurements: however, the bottom of the hook barbules is almost at the same level as the top of the bow barbules. This provides the necessary clearance between adjacent barbules to separate on the one hand, and on the other hand, the barbules of these two levels can touch each other tightly after mating. When flapping, under the action of higher pressure of air in flight, the hook barbules of each barb will first generate deflection which allows the barbules of the two layers to interlock.

Both the rachis and the barb are elastic cantilevered beams in mechanical terms. Under the action of shaking, the beams will generate a corresponding deflection which provides the potential energy to overcome the tiny resistance forces in healing the split between two adjacent barbules. Preening with the beak also pulls each barb to generate a deflection and therefore it obtains some elastic potential energy to mate with its neighbor; due to the cascaded structure of the barbules

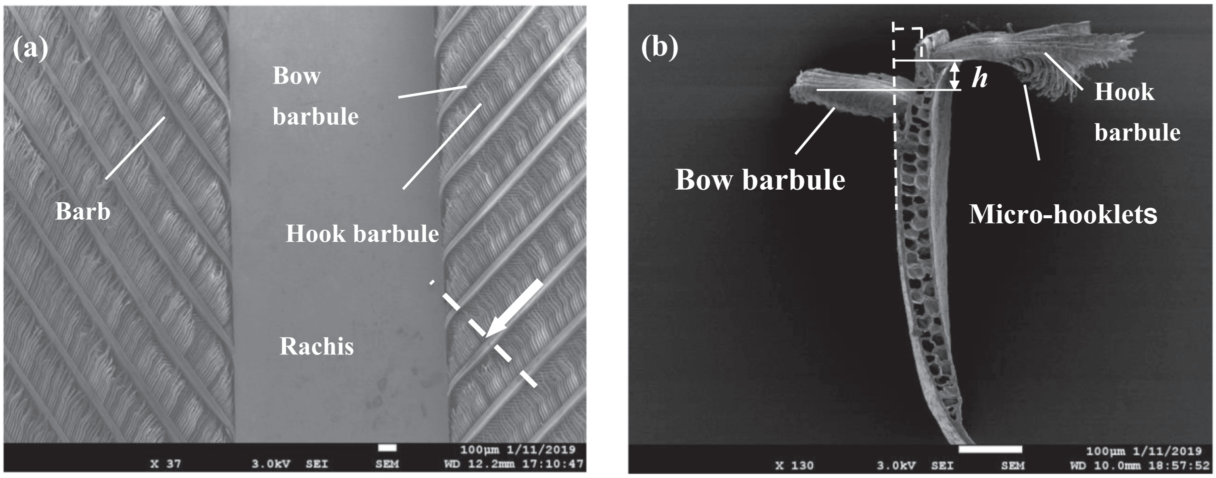

Fig. 4. Hierarchical geometry of a feather. (a) Dorsal side view of a barb. (b) Cross-sectional view of the barb. According to the previous experiments, the barbule space varies from 8 μm to 16 μm for birds weighing from 4 to 1100 g [6]. The spaces allow two adjacent barbs to be restored after splitting and ensures that they mate well. Different layer-structures of two neighboring barbs allow them to mate automatically under the action of preening.

on both sides of the barb, the correct recovery of the mating surface can be safeguarded one-by-one and then the smooth vane is restored in order.

The cascaded geometry of the feather allows the bird to recover its feather vane from a ruffled state by shaking wings and preening feathers with its beak.

4. Conclusion

In this work, the ruffled feather recovery performance of birds was observed by SEM and optical stereo microscope. The recovery behavior includes shaking the wings and preening the feathers with the beak. To verify that these two steps could recover messy feathers, we experimented by shaking a single feather manually and preening it with beak-like tweezers. The microstructure of the feather could be observed.

Both the rachis and barbs of a feather are elastic cantilevered beams. Under the actions of shaking and preening, the beams will generate corresponding deflections. The deflections provide potential energy to overcome the tiny resistance forces in healing the split between two adjacent barbules. The cascaded structure of the barbules ensures that the correct recovery of the mating surfaces can be safeguarded one-by-one and the smooth vane is restored.

Birds can always recover their feather vanes from a ruffled state by shaking their wings and preening their feathers with their beak on account of the cascaded geometry of the feather. This biophysical mechanism of self-healing of this hierarchical vane structure should be proposed to design artificial feathers for flapping flight robots in the future.

CRediT authorship contribution statement

Jing-Shan Zhao: Methodology, Supervision, Writing - original draft. **Jiayue Zhang:** Investigation. **Yuping Zhao:** Investigation. **Zhaodong Zhang:** Investigation.**Pascal Godefroit:** Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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