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A FOLDABLE FLAPPING WING DESIGN INSPIRED BY THE ELBOW-WRIST ANATOMY OF BATS

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Abstract

Bat flapping wings are perfect and feasible for application to high efficiency and maneuverable MAVs (Micro Aerial Vehicle) but have complex biology structure. Although there have been several types of flapping prototypes and kinematic models inspired by bats, they did not dig deep into biology and the low trajectory accuracy and aerodynamic power are the consequences. In order to solve these challenges, a profound investigation of the bat elbow-wrist anatomy is given in this paper and a foldable flapping wing is developed according to these discoveries.

1 General Introduction

It is acknowledged widely that MAVs with flapping wings can better overcome the aerodynamic problems with low Reynolds numbers ($Re < 10^4$). Relevant researches are becoming a hotspot in the aerial field. Many MAVs inspired by birds or insects within 3 DOFs are flying well [1-3] and researchers begin to focus on bats [4-5], whose wing are much more flexible, maneuverable and fully articulated. Bats also have similar size with MAV (under 30cm), feasible flapping frequency for engineering application [6].

Recent researches on bat wing DOF definition have developed in both simulation models and prototype establishments. G. Bunget built one of the most delicate models, with 4 DOFs for each wing: one at the shoulder, one at the elbow and two at the wrist [6]. Their simulation result pointed out that the rolling and yaw of the wrist are more important than the pitch of the wrist according to the wing-tip trajectory reproduction. However, It can only attain rough trajectories of both the wrist and wingtip. The existing prototypes have less DOFs [7-8], one of which have 3 DOFs [9]: two located at the shoulder are responsible for the flapping and abd/adduction and the third at the elbow responsible for the extension. Valuable load and aerodynamic analyses are carried out with this outfit. In this case, the wrist is a passive joint.

Because of the absence of adequate biological knowledge of the bat wing joints, those artificially simplified wings have obvious disadvantages: the flight efficiency is reduced, cannot fold up as bats do and cannot match the bat flight trajectory well. A systematic description and understanding of the bat wing joints and its unique flapping pattern are needed to cope with these challenges.

In this paper, a comprehensive anatomy analysis is first given for the bat elbow-wrist, especially for the wrist part which plays a key role in hand-wing motion implementation and folding-up when bats rest; secondly, a foldable flapping wing with 7 principle DOFs is developed based on the biological structure and component ratios.

The simulation results show that the flight trajectory of this kinematic model can mimic bat flapping pattern and give a good fit with the experiment data. This part of work will be shown in another paper.

2 Anatomy and Motion Analysis of the Wrist Region

The anatomy objectives are bones and tendons of the elbow-wrist of Rhinolophus Ferrumequinum (R. Ferrumequinum) that are stored in alcohol within one year. Bones are the basic structure which gives the motion possibility at the joint and archives DOFs while tendons are the strings that give the energy to this bone structure.

The authors drew lessons from biology writings on several bat species, some opinions or regulations of which, however, may vary from R.Ferrumequinum, to make sure findings of the organism were generally correct. Treatises on human anatomy and movement are also referred to in order to find similarities and compromises.

2.1 Bone Structure and Joints

The bat wing consists of humerus, radius, ulna, wrist and phalanges. The ulna has deteriorated into small short affiliations at both ends of radius. The first long bone connecting to the distal end of carpal is the metacarpal. Then the rest section bones connecting to metacarpals are phalanges. The joints in order from the wrist to the phalanges are radoicarpal joint, carpometacarpal joint, metacarpophalangeal joint and interphalangeal joint.

The wrist is composed of eight components: lunar, trapezium, trapezoid, magnum, unciform, scaphoid, cuneiform and pisiform [10], all of which form a group called the carpal. The eight bones can be divided into two sub-groups, since there is a significant flexion at the borderline of these two. We can call them proximal row and distal row, respectively, and the borderline is the intercarpal joint based on human anatomy terminology [11]. Lunar is dominant in the proximal row and trapezoid, magnum and unciform are so in the distal row.

Bones related to the right wrist region (distal part of the radius, six basic components of the carpal and proximal part of the metacarpal) were processed using micro CT in order to know what each joint looked like. The pisiform and the scaphoid were ignored for they are tiny and subject to other wrist bones. Every scanned bones were assembled together to represent the joints in reference to bat biology. Fig. 1 is the individual components of the right wrist region. The lateral articular surfaces of the lunar limit the movements of the trapezium, trapezoid, magnum and unciform to a single plane, that of lateral extension and medial flexion [10]. Fig. 2 shows the general view of the bone structure of the wrist region when the hand-wing is fully extending.

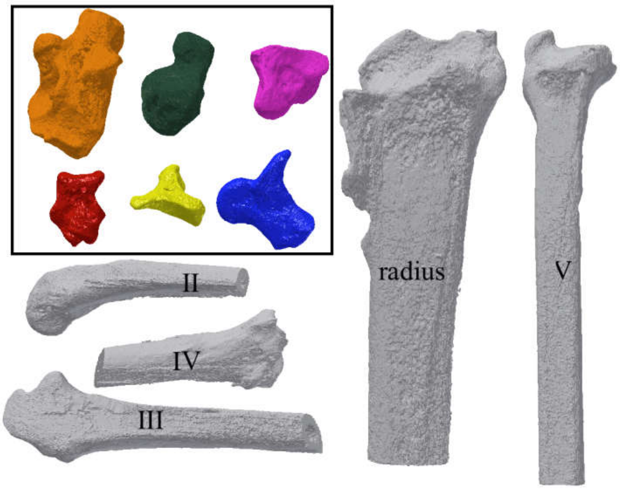
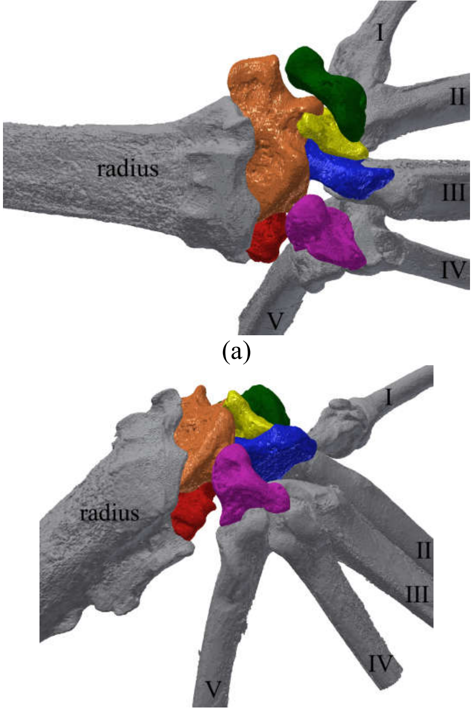


Fig. 1. Individual components of the right wrist region (left to right in the top-left box: lunar, trapezoid, uniform, cuneiform, trapezium, magnum).



(a)

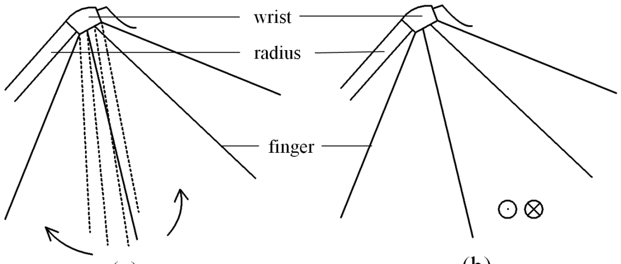
(b)

Fig. 2. The bone structure of the right wrist region when the hand-wing is fully extending (color annotation is the same as in fig. 1): (a) dorsal view; (b) lateral view.

2.2 Motion Analysis

Trapezoid, the magnum and the unciform sit on the lever of the lunar and leaning against the panel at the back. Each of the three is like a spherical joint to make up the intercarpal joint. Spherical joints can give them 3D rotations. Besides, they can also flirt from the unciform to the trapezoid with the same trend of directivities, but the range of this motion (yaw) is limited by the process of lunar and cuneiform as shown in fig. 2.

When the phalanges partly or fully spread out within the paper plane or phalange plane Π as in fig. 3(a), which means abducion and will be discussed later, and then swing in and out of plane Π as in fig. 3(b), the rotation has an angular velocity $\boldsymbol{\omega}$. $\boldsymbol{\omega}$ can be decomposed into two components as in fig. 4(a): perpendicular to radius ($\boldsymbol{\omega_1}$) and parallel to radius ($\boldsymbol{\omega_2}$). $\boldsymbol{\omega_1}$ is interpreted as pitch and $\boldsymbol{\omega_2}$ as roll in engineering view of other previous researches mentioned before. Another parameter at the intercarpal joint is Angle A in fig. 4(b). Angle A, provided by the joint surface orientation of the lunar reletive to the radius vertical axis as in fig. 4(b) is about 27°. It makes $\boldsymbol{\omega}$ not simply perpendicular to the axis of the radius as human hand, but a tilt vector. What is more, the orientation of $\boldsymbol{\omega}$ is also dependent on the yaw of the wrist. Consequently, $\boldsymbol{\omega}$ is not constant.

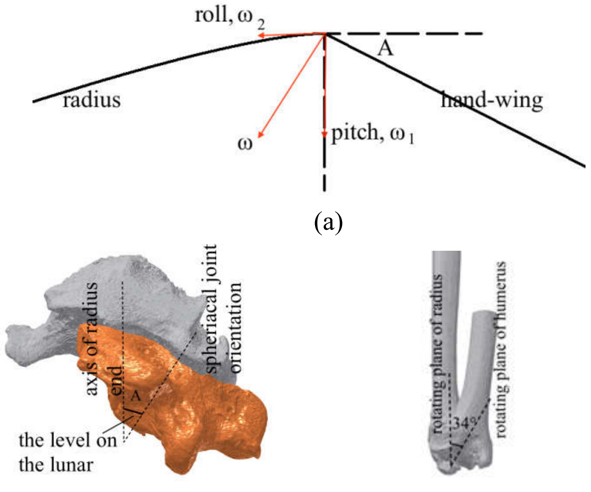


(a) (b)

Fig. 3. Lateral view of phalanges swing (a) within plane Π and (b) in and out of plane Π.

When the phalanges are fully extending in plane Π, the angle between Π formed by the phalanges fixed into trapezoid, magnum and unciform and the plane which contains radius is less than 20°.

The metacarpals are firmly embedded into the distal row of carpal and mere flexion is found at the carpometacarpal joint. Mere motions between radius and lunar are found, and it is assumed that there is no relative movement here at the radiocarpal joint.



(a)

(b) (c)

Fig. 4. Elbow-wrist characteristics. (a) The decomposition of ω; (b) Angle A, surface orientation of the lunar; (c) The elbow structure of the left bat wing.

2.3 Discussion about Motion Resolution

One popular statement tells that metacarpal can flex [10] but it doesn’t mention the intercarpal joint or any other joint exactly contributes to this flexion. So this flexion is applied to the intercarpal joint as a compromise in this paper. The flexion of the wrist is limited to a small range but it is still larger the extension during straight flight. Much of the hand-wing flexion is passed down from the flapping of the shoulder. Metacarpophalangeal joint and the interphalangeal joint provide the dominant and extensive flexion to get the high chamber. It is also important to know that bat metacarpals and phalanges themselves have ductility and can curve within one single bone to enhance the high chamber and maintain efficient lift and thrust.

Add/abduction has two meaning in general: one is that the fingers are brought together and separated apart, while the other is the hand-wing moving forwards and backwards. Biologists don’t distinguish these two kinds of motions so clearly for bats. The statement is always like “limiting the wrist and carpometacarpal joints in anteroposterior plane is to get rigidity to act against the force of air stream and metacarpal can add/abduct [12]”. It doesn’t mention intercarpal joint or which joint exactly gives this so-called abd/adduction. So the minor abd/adduction at the intercarpal joint is defined as the yaw as the nomination in the human anatomy [11].

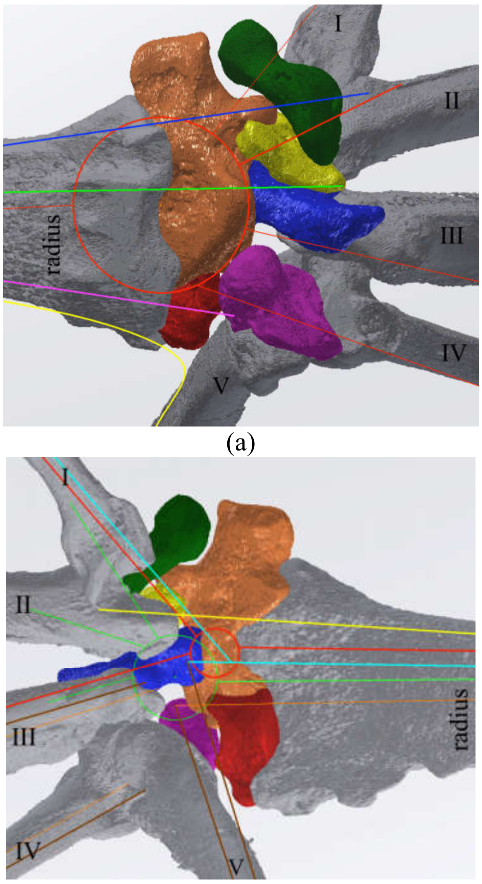
When the phalanges swing in plane Π as in fig. 3(a), trapezoid, magnum and unciform can face in different directions, which means different elevations, with the help of the tendons that are used for the wrist to extend and flex, and the final result is abduction, again as the nomination in the human anatomy [11]. Because of the accurate forces of the extensors and flexors, the phalanges are usually extending and abducting during the flight and flexing and adducting at rest.

It is depicted in fig.2 that the IV and V both located in unciform. Only IV and V have obvious shift between abduction and adduction when bats are flying straightly or maneuvering. This gives one possible reason that the abd/adduction happens more at the intercarpal joint than carpometacarpal joint for II and III because only IV and V have the unique advantage to move relative to each other to add/abduct in carpometacarpal joint.

2.4 Sorting and Distribution of Tendons and Muscles

Tendons are the intersected and intricate ductile strings that give the joints energy to have relative motions.

Different kinds of tendons and muscles spreading along the radius and then attaching to various spots of the wrist and/or further to phalanges show their individual responsibilities. They are named after the order in which they are found in this paper, and their relative positions which help identify their functions are also recorded. The tendon map shown in fig. 5 was compared with that in the treatises and they matched well although they have various nomination with this paper [10]. Circles in fig.5 denote that tendons stretch out to the wrist, covered by a layer of synovial membrane whose areas are indicated by the radii of the circles and continue to run toward different phalanges with corresponding branches.



(a)

(b)

Fig. 5. Tendon and muscle distribution on the Right Wrist. (a) Dorsal view: blue- β, green-γ, red-5A (1,2,3,4), pink-5B lower, yellow-5B upper. (b) Ventral view: yellow-4, green-2b outer, cyan- α, red-2a,brown-muscle (1,2,3,4) ,orange-2b inner.

Most of these plenty of tendons can also be classified as extensors and flexors. The proximal ends of extensors connect to the radius. A majority of the proximal ends of flexors and muscles connect to the carpal, forming powerful tissues that can flex the phalanges effectively to get high chamber and lift/thrust. The extensors or flexors that connect to the wrist can only extend or flex wrist while ones extending along the phalanges can extend or flex both the wrist and phalanges. The extensors spreading along the phalanges are also to balance the flexors when the phalanges acts against the air stream force during flight. The cooperation of the inner or outer pair of flexor and extensor for the wrist can either abd/adduct the phalanges or yaw depending on the insert point of tendons. Table 1 is the summary of tendons and muscles by their functions.

Table 1. Summary of tendons & muscles' function

Function		Group of tendons
Extensor	Extension of the wrist	β, γ ,5A 2,5A 3,5A 4,5B upper (to the dorsal carpal or metacarpal)
	Extension of phalanges	5A 3, 5A 4, 5B upper (along the dorsal phalanges)
Flexor	Flexion of the wrist	4, 2b outer, 2a (to the ventral carpal or metacarpal)
	Flexion of phalanges	tendons from metacarpal, muscle 1,2,3,4(along ventral phalanges)
	Yaw (abd/adduction of the wrist)	5B Lower, 2b inner for adduction; β, γ,4 for abduction
	Abd/adduction of the phalanges	5B upper, muscle 2,3,4(to phalange IV and V) and some extensors and flexors for the wrist

2.5 Elbow Structure

Fig. 4(b) is the bone structure at the elbow, also from scanning files. If only the joint contact surface is considered, it is concluded that the radius is rotating in the plane that has an angle of 34° relative to that of the humerus. So assuming that the radius is fixed in the paper plane, the humerus will rotate around the elbow in a plane, which is perpendicular to the paper plane and has a 34° slant clockwise.

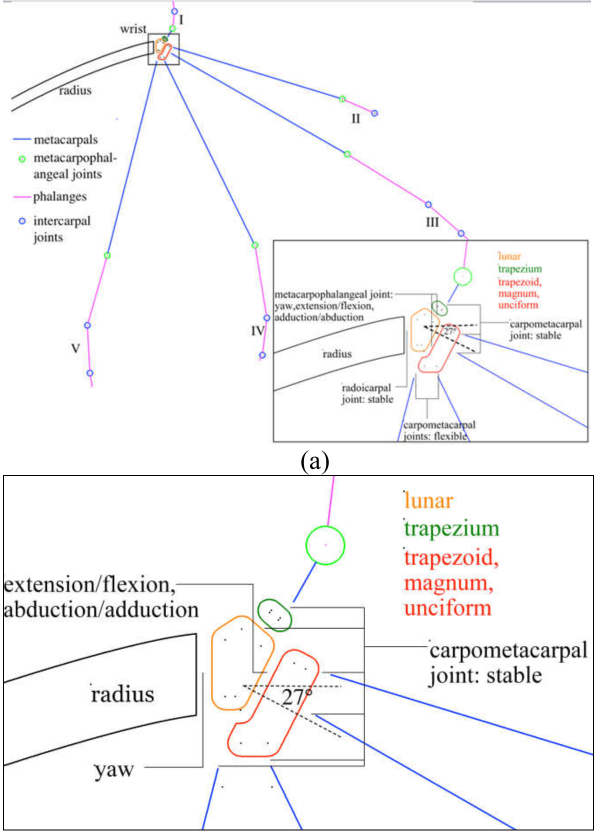
3 DOF Identification for the Bat Wing

Although the wrist has many kinds of motions, they can have effect on others and one may be produced by another. So the DOFs at the wrist can be reduced.

The wrist comparison between the original biological structure and reformed mechanism is shown in fig. 6. The yaw is put at the proximal edge of the wrist to reduce the complexity within the wrist. The scale of the lunar is small enough that it does not matter much whether this joint is located at the edge of wrist or within the wrist as long as the model has the same motion principal.

Table 2 shows the DOF identification of the bat hand-wing on the basis of the analysis of the anatomy. It is assumed that the bat wing has 7 DOFs in all to complete the prime motion features during the flight.

It should be noticed that only one extremely flexible phalange with the distal interphalangeal joint is included in this case. The proximal interphalangeal joint is stable. The thumb does not contribute much to the motion implementation and is negligible.



(a)

(b)

Fig.6. The comparison between (a) original structure and (b) reformed engineering model.

Table 2. DOF identification for the bat wing

Position	No.	Function
Shoulder	3	Up/down(flapping)
		Forwards/backwards
		Pronation/supination
Elbow	1	Forwards/backwards
Wrist	2	Extension/flexion (being decomposed into roll and pitch; the latter give assistance to the abd/adduction of the phalanges)
		Yaw(abd/adduction of the wrist)
Phalange	1	Extension/flexion

4 Foldable Flapping Model Design

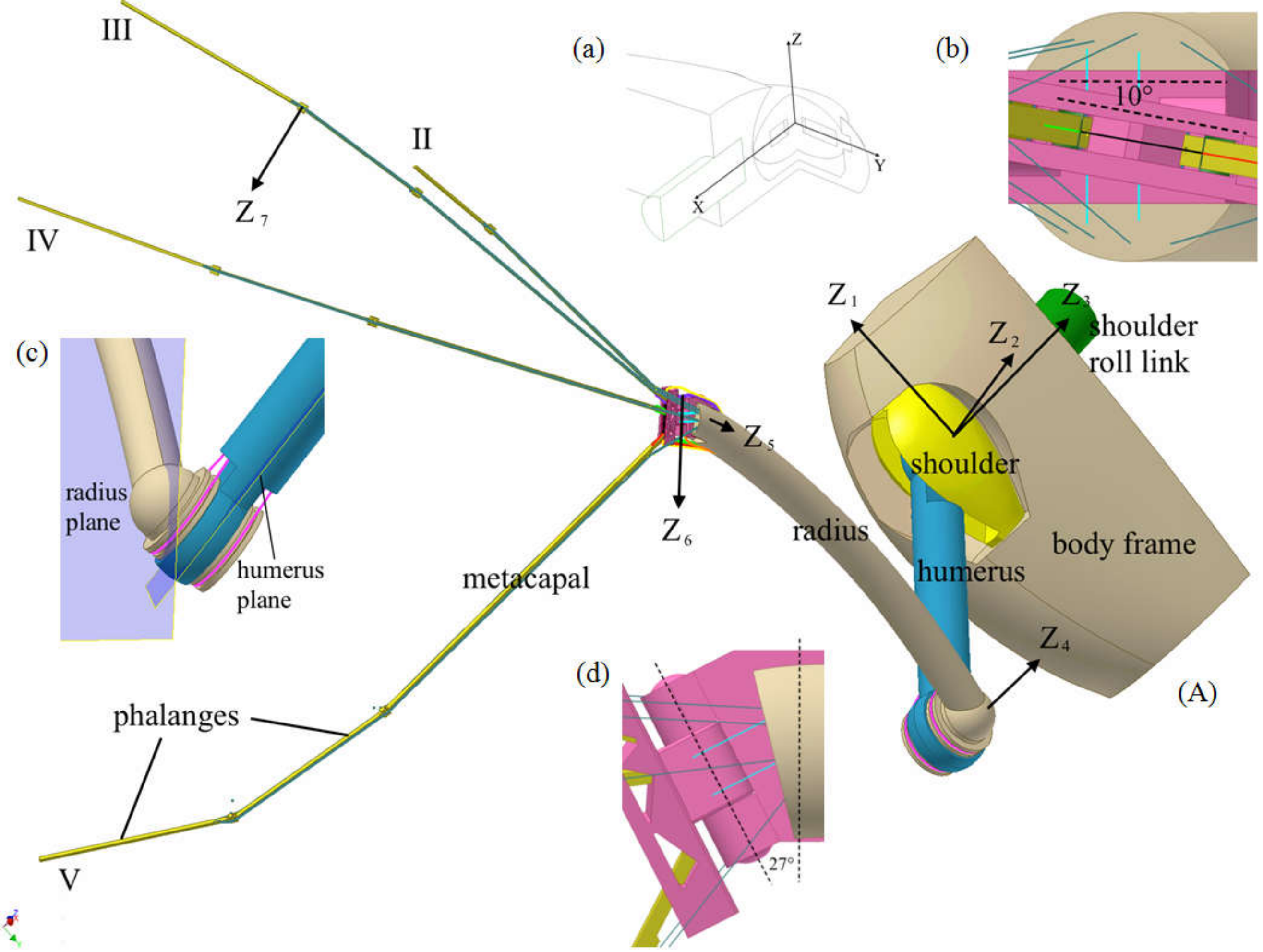
Fig.7 is the foldable flapping wing design inspired by the bat anatomy including both bones and tendons. The length ratio of humerus, radius, the third metacarpal and third phalange is 9.6:18.287:16.33:7.04:7.78.

The shoulder has three rotating axes that meet the Cartesian coordinate convention as shown in fig. 7(a). The angle (assumed to be 10°) between the phalange plane and the radius plane is shown as in fig. 7(b). The elbow joint is shown in fig. 7(c) in detail. The angle between the humerus plane and the radius plane is 34°. Angle A (27°) is depicted in fig. 7(d). The metacarpals insert into the inner slot in the wrist. Tendons and sliders in fig. 7(e) and (f) are used to locate each phalange when the wing is abducting: black tendons between sliders assist to locate the sliders with help of the constant length and the other tendons in fig. 7(e) are used to pull the phalanges up. Once the correct positions of the phalanges are attained by sliders, the phalanges slip into the slots in the upper side of wrist. The cyan tendons on and under the wrist in fig. 7(f) are used for the extension/flexion of the wrist. The jasper tendons on and under the phalanges can give the motion of extension/flexion of the phalanges. The cluster of tendons at the hand-wing is led to the power device within the bone structure. Fig. 7(A) and (B) show the extending/abducted and folded-up/adducted flapping wing, respectively.

5 Conclusions and Future work

This paper commences with the bat elbow-wrist anatomy so that the motion, limitation and principles at these regions can be better understood. The bone structure, the tendon distribution and their individual and cooperative functions are discussed. Then a foldable flapping model with 7 DOFs is devised according to the discoveries.

The capability and validity of this model to reproduce the trajectories of bat wrist and wing-top during flight will be presented in the next paper.



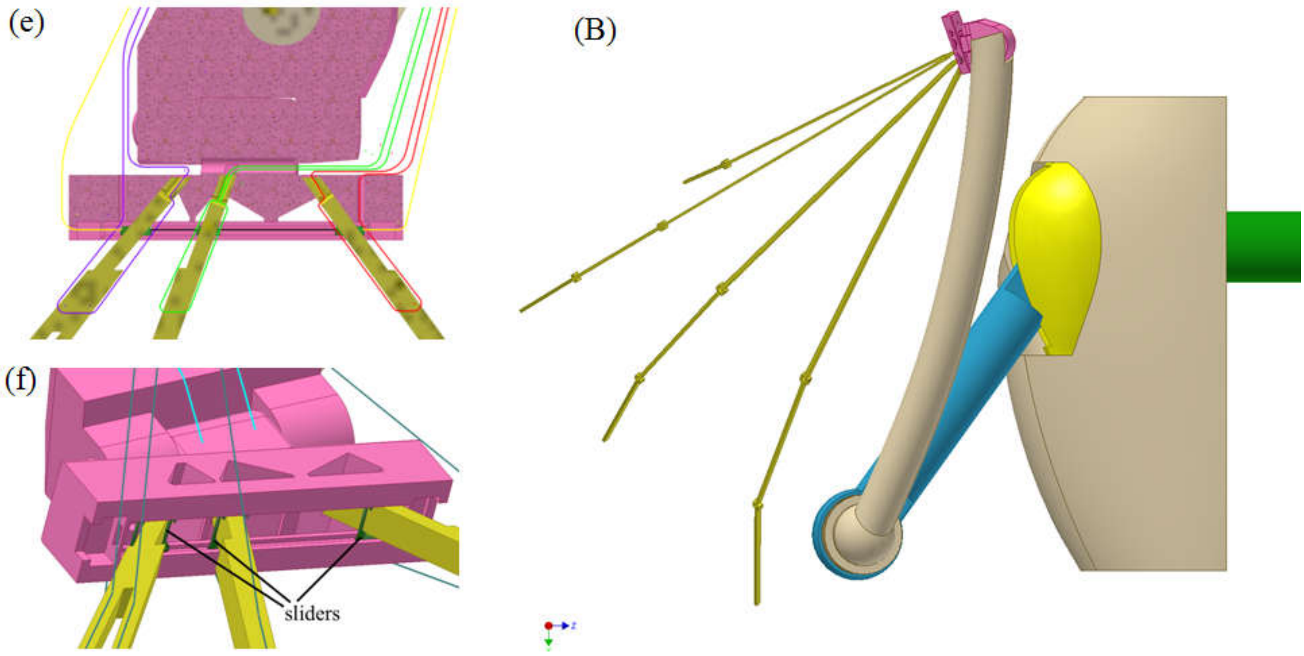


Fig. 7. General view of the foldable flapping wing: (a) three rotating axes at the shoulder. (b) - (d) angles of planes in the model. (e) - (f) tendons for the motions of the hand-wing. (A) and (B) are the gestures when the flapping wing is extending and abducted and when it is folded-up and adducted, respectively.

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