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Nano-mechanical properties and structural of a 3D-printed biodegradable biomimetic micro air vehicle wing

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Abstract
The biomimetic micro air vehicles (BMAV) are unmanned, micro-scaled aircraft that are bio-inspired from flying organisms to achieve the lift and thrust by flapping their wings. The main objectives of this study are to design a BMAV wing (inspired from the dragonfly) and analyse its nano-mechanical properties. In order to gain insights into the flight mechanics of dragonfly, reverse engineering methods were used to establish three-dimensional geometrical models of the dragonfly wings, so we can make a comparative analysis. Then mechanical test of the real dragonfly wings was performed to provide experimental parameter values for mechanical models in terms of nano-hardness and elastic modulus. The mechanical properties of wings were measured by nanoindentre. Finally, a simplified model was designed and the dragonfly-like wing frame structure was bio-mimicked and fabricated using a 3D printer. Then mechanical test of the BMAV wings was performed to analyse and compare the wings under a variety of simplified load regimes that are concentrated force, uniform line-load and a torque. This work opened up the possibility towards developing an engineering basis for the biomimetic design of BMAV wings.

1. Introduction
Being very manoeuvrable and having high load bearing capacities make insect flight more interesting subject for aerodynamic researchers [1-5]. Their superb flight agility can be largely attributed to their complex wing structure. The wings of a flying insect generally contribute only 2% of the total body mass of an insect [6]. These lightweight wings must be able to flap millions of times throughout an insect’s lifespan; while enduring collisions, torsional loads, and many other forms of deformation [7]. Biomimicry of these attributes in an aircraft is highly desired. This has motivated research into a new class of micro-sized unmanned aircraft called Biomimetic Micro Air Vehicles (BMAV). Due to their small size and weight, BMAV would be ideal for flying indoors or in enclosed spaces. Fitted with micro cameras or sensors, they could be used to examine potentially hazardous areas (e.g. toxin spills, high voltage power lines, criminal activities, hostile forces, etc.) without endangering a human pilot [8].

Natural biomaterials are not only constructional materials but also functional materials. Research on the relationship between the structure function and performance of natural biomaterials is the basis for the development of biomimetic structures and materials. The structures, functions and materials of insect wings have optimised properties which have evolved over millions of years. The wings of dragonflies are mainly composed of veins and membranes.

The measurements of the mechanical properties of the wing of insects were mainly carried out using traditional tensile tests [9-11]. However, the tensile test cannot be appropriate to small scale samples of complex compartment. The new technique of nanoindentation is an excellent tool for the study of the mechanical behaviour of materials with nanoscale sizes [12-15]. Nanoindentation technique has been established the near surface mechanical properties of materials and it was used to measure the characteristics of the surface of the wing of dragonfly. Few studies were focus on the whole wing membranes only using nanoindentation [16-19]. Before improvements in nanoindentation technique, dragonfly wing research was primarily carried out through tensile tests [20]. At present, nanoindentation has become a useful tool for characterising the mechanical properties of thin elastic and viscoelastic materials [21, 22]. Thus the aim of this study will carefully concern the comparison of nanomechanical properties of veins and critical points of the dragonfly wings and bio-mimicked ones by nanoindentation.

2. Methodology

According to our previous study [20] the simplified dragonfly wing was modelled by using CAD software. PLA (Polylactic acid) is one of the most commonly used 3D printing materials. This biodegradable material has the virtue of being odorless and does not warp significantly like the other 3D printing materials. Due to its low melting point, using PLA as a 3D printing material does not require a heated bed. The 3D printer was utilized to “fine printing method” for this research since the sample size was approximately 8 cm with a thickness of 0.5 mm. Both forewing and hindwing were fabricated using PLA. Figure 1 shows the 3D model of a simplified dragonfly wing structure and figure 1 presents the fabricated dragonfly wings model. MarkerBot Replicator 2X experimental 3D printer that was used in this study was purchased from Markerbot (Brooklyn, USA). Grey PLA printing filament was purchased from MyDuino and used as received. CAD designs were drawn and visualized in Solidworks Software and transferred to 3D printable format using the Makerbot Desktop Software supplied with the Markerbot Replicator 2X.

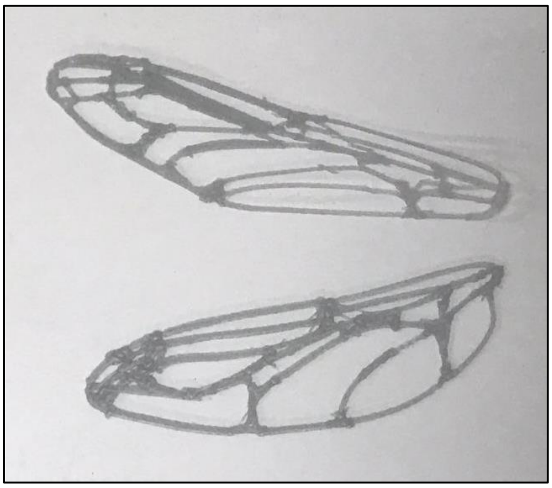
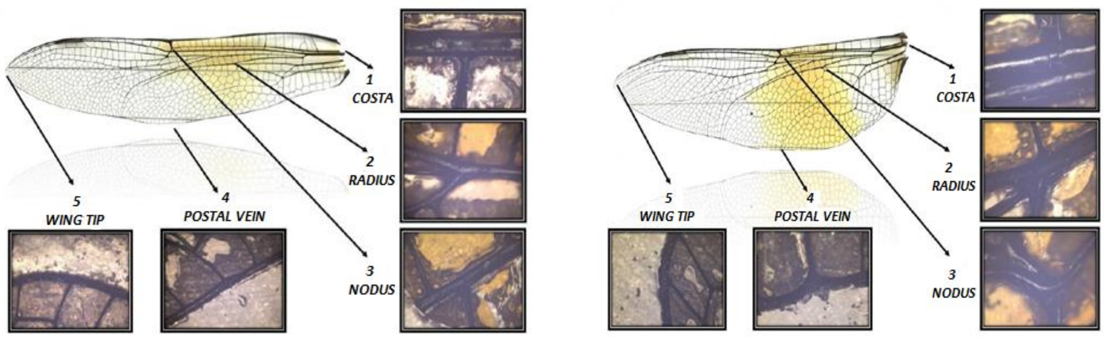


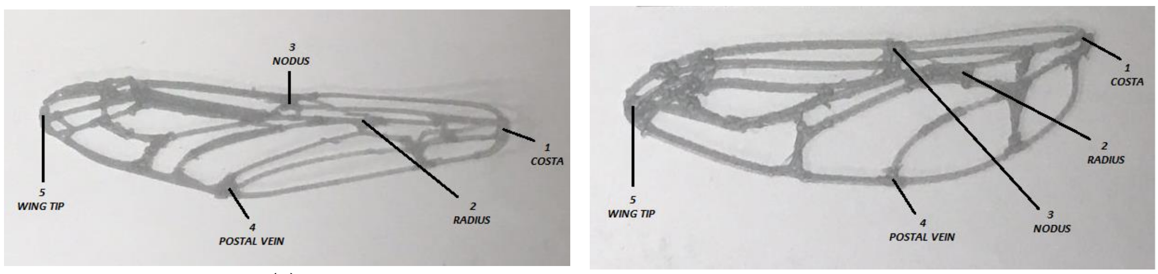
Figure 1. Fabricated dragonfly forewing and hindwing

Complete wing design (PLA based structure) and actual dragonfly wings were tested using Hysitron TI 750 UBI nanoindenter machine. Five points on a simplified BMAV wing and actual dragonfly wing were examined based on the crucial part in a wing structure as mentioned by Sun and Bhushan [1]. Figure 2 and Figure 3 display the location of the critical veins and points which are chosen for experimental tests.



(a) (b)

Figure 2. Location of the veins and the critical point of the dragonfly wings; (a) forewing, (b) hindwing



(a) (b)

Figure 3. Location of the veins and the critical point of the BMAV wings; (a) forewing, (b) hindwing

The two mechanical properties measured most frequently using load and depth sensing indentation techniques are elastic modulus, E, and hardness H. In a commonly used method, data are obtained from complete cycle of loading and unloading.

Average values of hardness and modulus of actual dragonfly wing and simplified BMAV wing were acquired using a fixed displacement method using Berkovich indenter instead of Vickers pyramid. The Berkovich indenter is a good choice for standard testing because it produces plasticity at very low loads, and minimizes the influence of friction. According to the theory on nanoindentation test [12, 15, 23] the reduced modulus is expressed as:

$$E_r = \frac{\sqrt{\pi}}{2\beta}\frac{S}{\sqrt{A}} \quad (1)$$

Where S is the contact stiffness that is defined by $S=(dP/dh)$ unload and β is coefficient of Berkovich tip $\beta = 1.034$. The load and displacement during indentation process are analysed to obtain the contact area. The contact area, A is related to the contact depth h_c as:

$$A = \sum_{n=0}^{8}\left(C_n h_c^{1/2^{n-1}}\right) \quad (2)$$

Where C_n are constant depends on the indenter and given by machine calibration. In equation (2) h_c is determined by:

$$h_c = h_{max} - \varepsilon\frac{P_{max}}{S} \quad (3)$$

For the Berkovich tip, $\varepsilon = 0.75$ is a constant. The relationship between indentation load, P, and penetration depth, h, is as shown in figure 4. Maximum load P_{max} and maximum penetration depth h_{max} were recorded automatically by the indenter. From equations (1) and (2) we can obtain the reduced modulus E_r. The effects of a non-rigid indenter on the load displacement behaviour can be consider by defining an effective modulus E_r, as follows:

$$\frac{1}{E_r} = \frac{1-\nu^2}{E} + \frac{1-\nu_i^2}{E_i} \quad (4)$$

Where E is the Young's modulus and ν is the Poisson's ratio of the specimen. E_i and ν_i are the values from the indenter. Using diamond tip on the indenter the value for E_i is 1141 GPa and ν_i as

0.07 respectively. Poisson's ratio of the specimen is taken as 0.3 by default. The hardness of the material is defined by:

$$H = \frac{P_{max}}{A} \quad (5)$$

From equations (1) to (5), the modulus and the hardness of the samples can be obtained.

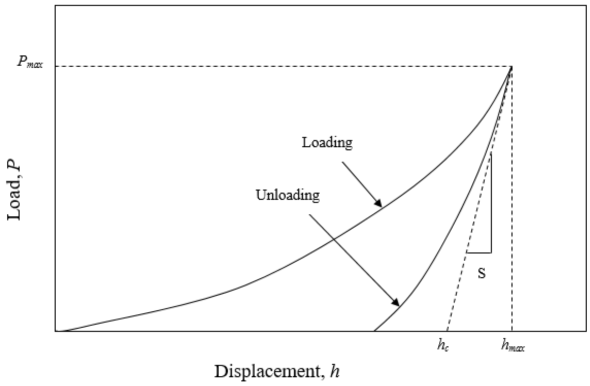


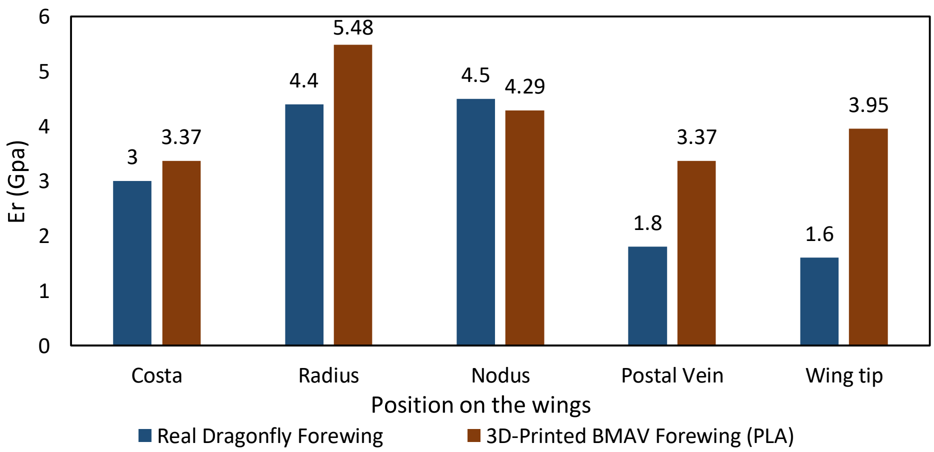
Figure 4. Schematic graph of the load via displacement of the nanoindentation test

3. Result and discussions

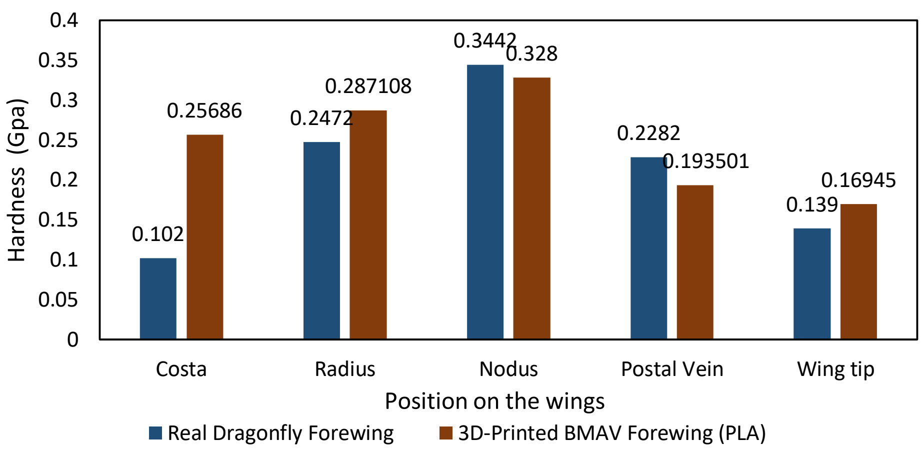
The force–displacement curve is shown in figure 4. The nanoindentation tests were done in two different settings that were called load control and displacement control. Therefore, in load control tests the maximum load for each test is fixed to 9999.25 μ N and in displacement control approach, the maximum depth is fixed to 499.93 nm.

Figure 5 shows the modulus and hardness of dragonfly forewing and hindwing and simplified PLA forewing and hindwing. Different points on the wing bear different loads on actual dragonfly wings, therefore their mechanical properties were different because of adaptation. Relatively speaking, the mechanical properties of a real dragonfly wing vary with the position. Group of researchers [24] examined the mechanical properties of the costa, radius and postal veins of a dragonfly wing and concluded that variation in modulus were in between 0.5 GPa to 3.5 Gpa. The modulus and hardness we retrieved from different points were comparable to previously published article [7, 25, 26].

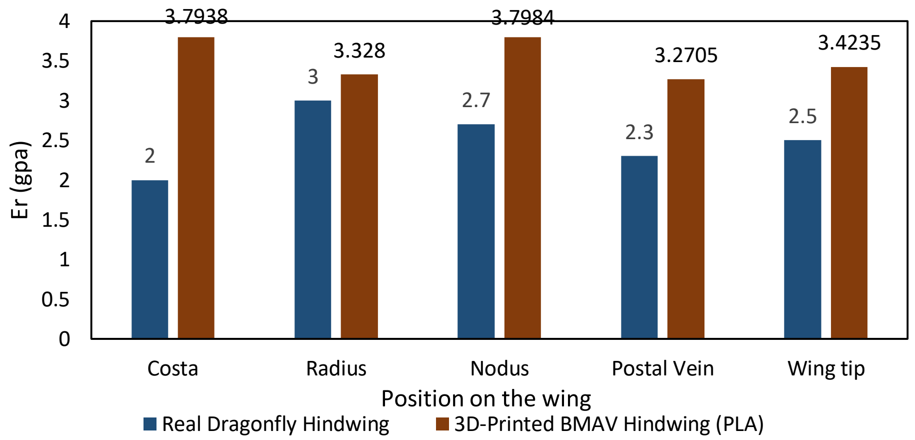
The hardness of actual dragonfly wings varies in all the points. A study conducted by Smith et al. [11] discovered that dragonfly wing veins have an air-filled hollow section. Hardness might be influenced by the diameter of the hollow section in a particular point on the vein. The simplified BMAV wing structure is drawn by fine lines of melted PLA in a course of outer layer flowed by stacking layer by layer until complete. The surface profile is jaggy, this leads to a lower hardness than actual dragonfly veins that grow throughout its lifespan and strengthen key points on the wing profile.



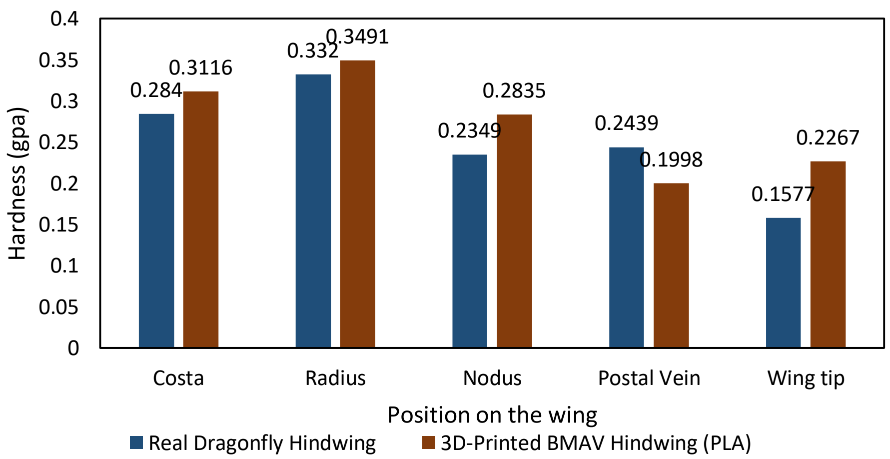
(a)



(b)



(c)



(d)

Figure 5. The comprasion of nanoindentation results of real dragonfly wings and BMAV wings based on critical points; (a) elastic modulus of forewings, (b) hardness of forewings, (c) elastic modulus of hindwings and (d) hardness of forewings.

Generally, the nanoindentation results for simplified BMAV wings are higher than real dragonfly's wings. As figure 5 (a) and (c) show, Radius and Nodus in both forewing and hindwing of real dragonfly displayed the highest modulus compared to other points. The Wing tip and the Costa points in the real dragonfly's forewing has the lowest modulus and hardness, respectively. According to figure 5 (a) and (b), same points for the lowest amount of Er and H were achieved for the BMAV forewing.

The maximum of Er and H appears at the Nodus for forewing, they are equal to 4.5 Gpa and 0.3442 Gpa, respectively. This shows that the various mechanical properties correspond to the flight mechanism. The Nodus is a location that serves to bear torsion. It plays an essential role in stability, greatly reducing the danger of buckling and structure failure [7]. The arc structure at the leading edge has the effect of preventing torsional deformation from becoming large, and the Nodus prevents the bending moment at the centre of the wing from becoming large [27].

4. Conclusion

Bionics is the imitation of the principles of biosystems and the creation corresponding techniques or artificial systems possessing the characteristics of biosystems. The main idea of bionics is to learn from natural systems and apply those lessons to technical innovation. Accordingly, in the current study, the nanoindentation method has successfully been used for testing the mechanical properties of real dragonfly wings and biodegradable BMAV wings. The mechanical test was performed to provide experimental parameter values for mechanical models in terms of nano-hardness and elastic modulus. The mechanical properties vary with the position on the wings. Based on the experimental data, in most of the points the nanoindentation results for simplified BMAV wings are higher than real dragonfly's wings. These results indicate that the 3-D printed PLA wings are comparable in hardness and elastic modulus to the real dragonfly wings. Therefore, the results can help to proceed further simulation and analysis in Bionics and gain more breakthrough in the future.

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