Geometric Analysis of Proportion and Movement of the Wings of the Bee, the Mosquito and the Butterfly

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Abstract. In this work, we present the research carried out at the Autonomous Metropolitan University Campus Cuajimalpa in México City, with the objective of studying if there is a relationship between different types of insect wings. In this project, we work with the European bee that belongs to the Apidae family, the common house mosquito of the Culicidae family and a butterfly of the family Nymphalidae. We find, using the geometric Morphometrics technique, the numerical values of the "X" and "Y" coordinates of the points in space and we model the solid. We built three prototypes in 3D printing, and made three virtual models with their respective stress analysis perform and movement simulation. For the physical prototypes, we used a 4mm tick ABS plastic, and a stainless-steel hook-shaped wire with of 2 mm of diameter was placed in the center of the wing's heavier parts as an axis. In addition, to perform the wing movement simulation and the stress analysis three proposals were made: (1) the wing without structure, (2) the wing with a straight structure and (3) the wing with the hook structure. From this research, the hypothesis of our project arises: the insect wing simulation differ if an axis passes through the center of the heavier parts of the wing. We concluded that there was less displacement and deformation of the wings of the insects when we performed the simulations using a hook-shaped structure. Since the hook-shaped structure allowed both the membranes and the veins to move at the same time, allowing the less heavy parts to move freely, thus creating a more realistic simulation.

Keywords: Wing, Proportions, Prototype, Stress analysis, Simulations, Movements.
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1 INTRODUCTION

The insects are the only invertebrates who have developed the flight capacity, therefore insect wings and their flight is the main subject of research when talking about insects.

The wing consists of two cuticular membranes supported by a complex framework of veins, which are hollow tubes that provide stability, form part of their nervous system, contain hemolymph that circulates across the veins and serves to maintain the cuticle moisture [2].

The veins can vary in diameter, length, shape and wall thickness; they can be flexible or rigid, and even can form a high-relief angle bracket where the longitudinal and cross veins intersect; the longitudinal veins run distally from the wing base and many branches as the wing broadens along the span. They are usually linked by cross veins. Together they form a supporting and conducting framework, which may be structurally very complex [2].

"The structure and architecture of the veins are crucial for the biomechanical properties of the wings and determine wing deformation during flight" (Ha, et al. 2013) [6].

The terminology of the wing venations of insects is important for almost all insect´s taxa classification. A complex nomenclature is used from one group to another but is generally based on the Comstock-Needham system (1898) (Fig. 1(a)) [4].

The principal regions of an insect wing are Costa (C), Subcosta (Sc), Radius (R), Media (M), Cubitus (Cu) and Anal veins (A). Small veins often found inter connecting the longitudinal veins are called cross veins. Due to the presence of longitudinal veins and cross veins, the wing surface is divided into number of enclosed spaces termed cell. Positive (+) and negative (-) veins indicate convex and concave veins, respectively (Fig. 1(b)) [13].

Figure 1: (a) Comstock – Needham system and (b) Regions of an insect's wing.

In the studied insect species, the shape, length and width of the wings (Fig. 2 and Tab. 1), and the size of its contour and veins are different (Tab. 2, 3 and 4) as well as their weight.

Figure 2: Wing: (a) Mosquito, (b) Bee and (c) Butterfly.

	Real size					Scaled		
	Mosquito	Bee	Butterfly			Mosquito	Bee	Butterfly
Long	19.9	8.66	40.23		Long	199	190.52	201.15
Width	5.02	2.32	19.2		Width	50.2	51.04	96

Table 1: Length and width of the insects studied given in mm.

Contour	43.96		
nerves	length	nerves	length
1	19.19	7	2.60
2	13.26	8	1.24
3	25.02	9	4.73
4	8.36	10	2.34
5	11.46	11	1.83
6	2.32	12	2.74

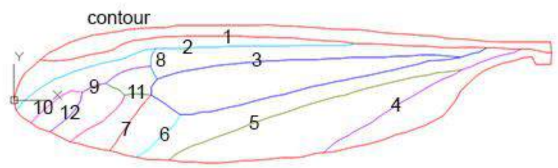


Table 2: Length of the outline of the mosquito and its veins given in mm.

Contour	10.73		
nerves	length	nerves	length
1	2.31	9	1.78
2	4.27	10	2.83
3	4.15	11	0.83
4	0.33	12	3.29
5	0.87	13	1.26
6	2.39	14	7.36
7	2.27	15	1.13
8	1.64		

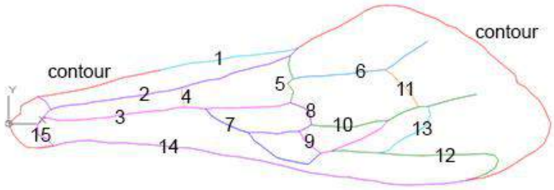


Table 3: Length of the outline of the bee and its veins given in mm.

Contour	97.62		
nerves	length	nerves	length
1	23.25	6	20.98
2	42.96	7	18.67
3	11.32	8	22.31
4	27.16	9	28.72
5	9.86	10	25.56

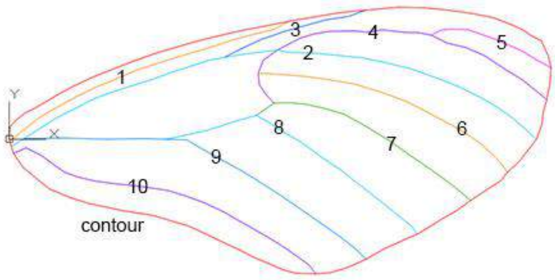


Table 4: Length of the outline of the butterfly and its veins given in mm.

In our research, we found a relationship between the parts 2, 3, 5, 8, 12 and 14 of each of the wings, because they are the heavier parts regardless of its shape, size and location and length of the nerves. (Fig. 3). In our study, the factors that we considered to perform the simulations of wing´s movements were deformation and displacement. Therefor we conducted three tests. We built three prototypes in 3D printing with an intermediate structure in the shape of a hook. We made three virtual models for stress analysis: (1) the wing without structure, (2) the wing with a structure straight and (3) the wing with the hook structure. In addition, we performed three virtual simulations.

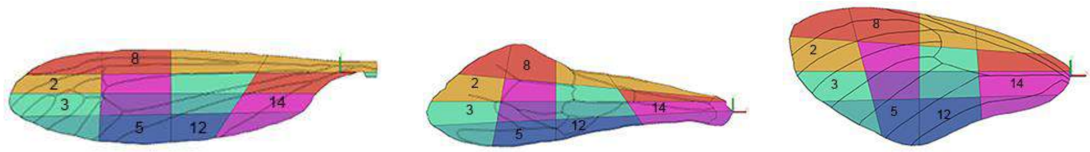


Figure 3: Heavier parts of the wing (a) Mosquito, (b) Bee and (c) Butterfly.

From the investigation that was carried out, the hypothesis of our project arises: the simulations of the movements of the wing of the insects differ if an axis passes through the center of the heavier parts of the wing.

This article has the following sections: in Section 2, we present the analysis of the wing proportions of the insects studied. In section 3, we present the development of the prototypes. In section 4, we explain the stress analysis that was performed in the virtual models. In Section 5, we present the analysis of the movement of the wings made in a 3D animation. In Section 6, we present the results. In Section 7, we present the contributions and finally in Section 8 the conclusions are presented. All figures presented in this paper are original and created by the authors at the Metropolitan Autonomous University Campus Cuajimalpa in México City.

2 ANALYSIS OF THE WING PROPORTION

In this section, we will only explain how we find the proportions of the bee. This same analysis was done with the mosquito and the butterfly.

First, we take the picture of the bee wing and open the JPG file in a graphics software (Photoshop); the points and lines were marked to delimit the outline of the shape of the wing and the location of the nerves (Fig. 4(a)), then the landmarks were marked in the software tpsDig2 (Rolhf 2008 [11])(Fig. 4(b)).

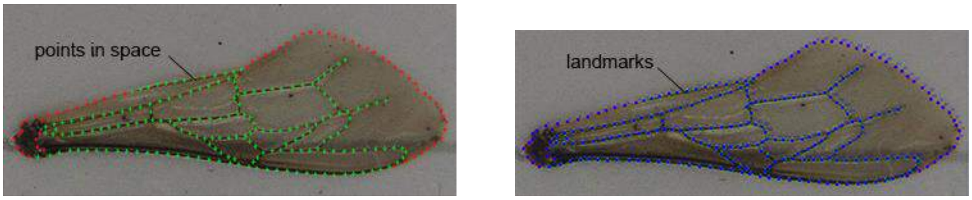


Figure 4: Bee wing (a) Points and lines in space and (b) Landmarks.

The numerical values of the “X” and “Y” coordinates were found by means of the geometric Morphometrics technique [14], as example, we show nerve #1 (Tab. 5). We concatenate the numerical values of "X” and “Y” coordinates, and we imported them by copying and pasting them to the software AutoCAD [10].

Points	X	Y	Concatenation		Points	X	Y	Concatenation
15	173	146	173,146		22	258	165	258,165
16	184	149	184,149		23	271	168	271,168
17	195	152	195,152		24	286	170	286,170
18	206	155	206,155		25	301	172	301,172

19	220	159	220,159		26	316	175	316,175
20	231	160	131,160		27	328	177	328,177
21	245	162	245,162		132	331	171	331,171

Table 5: Numerical values of the nerve #1 of the bee wing.

We trace the contour and veins lines (Fig. 5(a)). The wing was scaled to its real size (Tab. 1) and modeled to a height of 0.06 mm. The nerves were modeled with a height of 0.01 mm both in the upper part and in the back part of the wing, and with a thickness of 0.02 mm (Fig. 5(b)).

The centroid of the wing was found, two axes were traced, one transversal and the other longitudinal, and two cutting planes were placed (Fig. 5(c)).

The wing was sectioned into four parts (Fig. 5(d)). The centroid of each of the resulting parts were marked and four axes were traced, two transversal and two longitudinal passing through the centers of each of the parts reaching the wing contour.

Four cutting planes were placed (Fig. 5(e)) and the wing was sectioned into 16 parts (Fig. 5(f)).

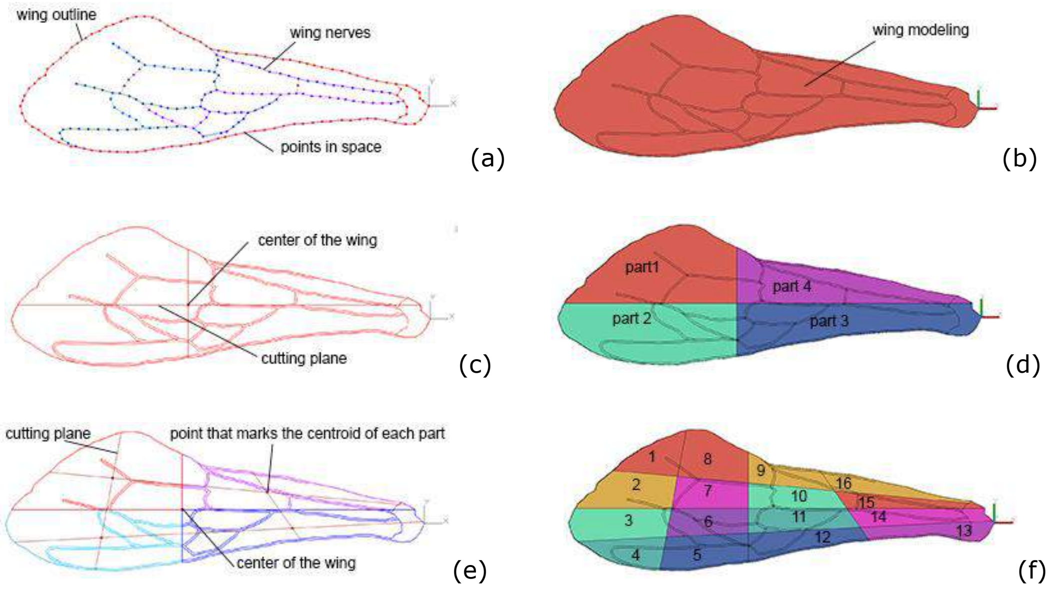


Figure 5: Bee wing (a) Points in space, outline and nerves lines, (b) Modeling, (c) Center and two cutting planes, (d) Four parts, (e) Center and six cutting planes, and (f) Sixteen parts.

To find out the weight of the wings, an ABS plastic was used, with an elastic limit of 2900.75psi and, with a density of 1.38 g/cm³. The results obtained were the following:

- The weight of each of the four parts of each insect studied (Tab. 6).
- The weight of each of the 16 parts of each insect studied (Tab. 7).

Table 6 shows that when the wings are divided into four parts the weight difference is evident between the insect´s wings, but between the same parts of each of the insects, the weight is significant.

	Part 1	Part 2	Part 3	Part 4	Total weight
Bee	0.37	0.38	0.36	0.27	1.38
Mosquito	0.13	0.19	0.18	0.16	0.66
Butterfly	13.60	10.69	12.49	10.03	46.81

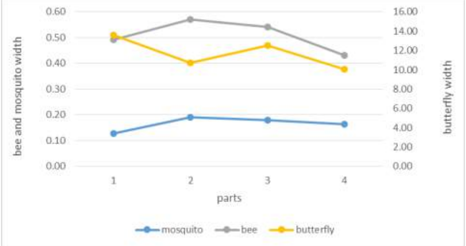


Table 6: Weight of each of the four parts of each insect studied given in grams.

	Part 1	Part 2	Part 3	Part 4	Part 5	Part 6	Part 7	Part 8
Bee	0.07	0.11	0.11	0.07	0.11	0.08	0.08	0.11
Mosquito	0.51	0.86	0.68	0.5	0.70	0.58	0.63	0.84
Butterfly	2.68	4.00	3.26	1.72	3.18	2.52	2.88	4.02
	Part 9	Part 10	Part 11	Part 12	Part 13	Part 14	Part 15	Part 16
Bee	0.07	0.08	0.09	0.10	0.08	0.09	0.06	0.06
Mosquito	0.55	0.56	0.66	0.84	0.67	0.72	0.57	0.47
Butterfly	2.92	2.48	2.85	3.89	1.89	3.87	2.83	1.80

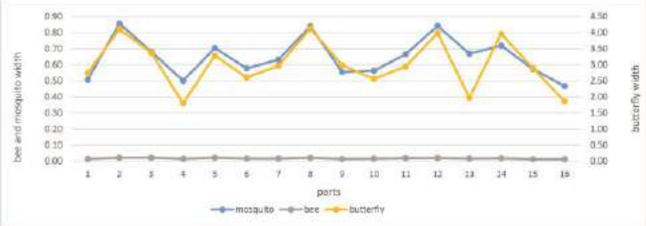


Table 7: Weight of each of the 16 parts of each insect studied given in grams.

Table 7 shows, that the parts 2, 3, 5, 8, 12 and 14 are the heavier parts of all the wings. Therefore, we conclude that the relationship between the wings of the studied insects is that the heavier parts of the wings are located in the same sections.

We made several tests to join the centers of each of the six parts of greater weight of the wings of each of the insects. At the beginning, we saw that we had different paths in each of the wings if we followed the order of the weights. We also observe that if the order of the nomenclature is followed, the resulting path would have many curves, which would cause problems when bending the internal structure that is intended to be placed; the path would cross through the lighter parts of the wings and, more weight would be added to the wings.

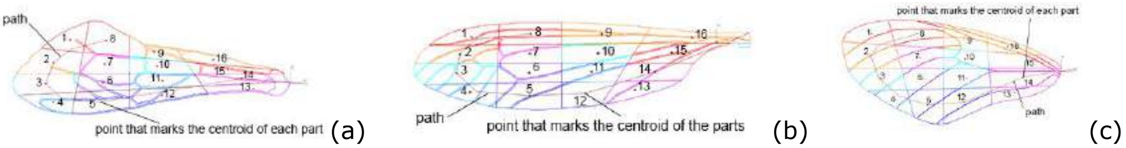


Figure 6: Hook path (a) Bee, (b) Mosquito and (c) Butterfly.

We realized that it was not necessary neither to follow the weights or the nomenclature to trace the path. Therefore, we conclude that if we follow points 8, 2, 3, 5, 12 and 14, the path that would give us in all the wings will be a hook (Fig. 6).

3 3D PROTOTYPES

In a previous study [9], we made the prototype in 3D printing of the same butterfly (Fig. 7). With the passage of time, the wings flexed due to their thickness and mainly because we did not put any internal structure.

Figure 7: Heliconius Doris obscurus butterfly.

For the new 3D prototypes, the wings were scaled to the maximum length that allows us to print the 3D printer (200 mm), with a thickness of 4 mm. The nerves have a height of 1 mm and a thickness of 0.7 mm. A 2.08 X 2.08 mm canal was opened to place the 2 mm diameter stainless-steel cable, the tolerance and the minimum distance that the 3D printer allows us to cover the entire surface was considered (Fig. 8). We choose the wire as internal structure since is light, durable and can be bent using a CNC bending machine.

	Scaled		
	Mosquito	Bee	Butterfly
Long	199	190.52	201.15
Width	50.2	51.04	96
Scale value	10	22	5

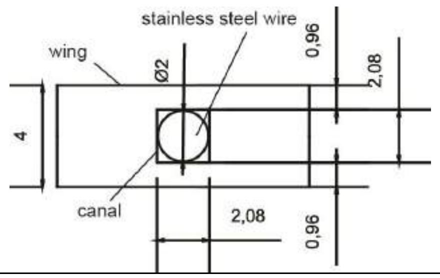


Figure 8: (a) Scale value given in mm and (b) Detail of the front view of the wing.

To make the prototypes, the wing of the bee, the mosquito and the butterfly were divided into two parts; a canal of 1.04 mm high and 2.08 mm width was opened on each side following the path (Fig. 9). The prototypes were built in the 3D printer, the stainless-steel wire was placed (Fig. 10); and, cyanoacrylate was used to glue each one of the wings. Finally, the wings were placed on a base to see if they do not flex (Fig. 11, 12 and 13).

The purpose of making the prototypes was to recreate the movement of the wing to observe and analyze the behavior of the wing with the hook structure. The hand simulates the muscles of the insect that contract and relax to create the movements of the wings. The screwdriver simulates the pivot on which the wing rests and does not move but supports the base of the wing with a lever movement (Fig. 14).

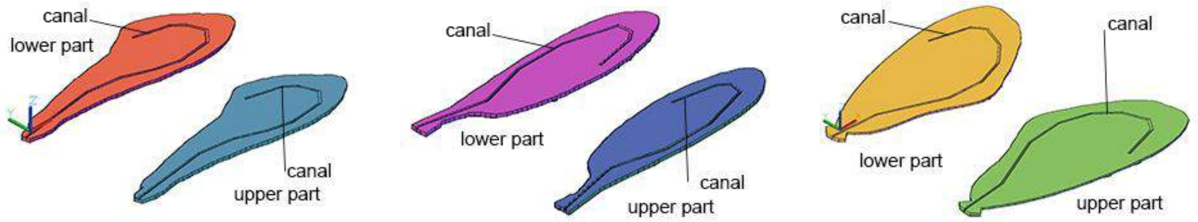


Figure 9: Canal (a) Bee, (b) Mosquito and (c) Butterfly.

Figure 10: 3D printing with the wire (a) Bee and (b) Mosquito.

Figure 11: Prototype of the bee wing.

Figure 12: Prototype of the mosquito wing.

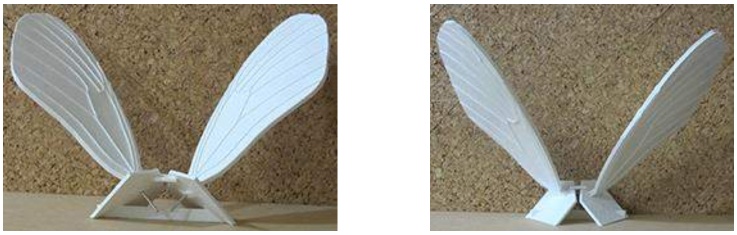


Figure 13: Prototype of the butterfly wing.

The results obtained were that first when we moved our hand from front to back, the wing moved freely, did not turn and returned to the initial position. In addition, when we moved our hand making circles, raising and lowering it, the wing always maintained its balance and moved freely following the path of our hand.

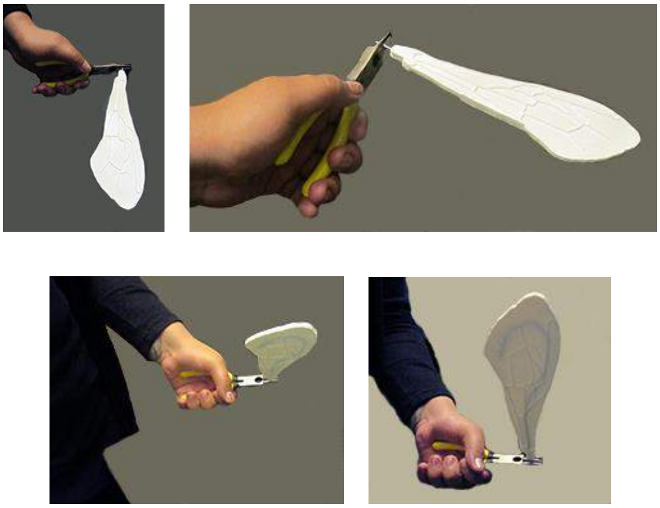


Figure 14: Behavior of the wing when we hold the structure.

We conclude then that the hook structure that is placed on the wings works to keep the wings stable and to recreate the movements, which is the purpose of our study.

4 VIRTUAL MODELS STRESS ANALYSIS

During flight, an insect wing deforms significantly (bending and twisting) as it flaps. Insect wing deformation can vary greatly from stroke to stroke, inducing thrust asymmetry between half-strokes; thus, wing deformation has an important function in the enhancements of thrust and lift throughout a stroke cycle [6].

Since the hook-shaped axis is intended to be placed on the wings of the studied insects, it was necessary to verify by means of stress analysis whether this structure is adequate to perform the simulations of wing movement at the 3D animations.

In this study, the simulation of the stress analysis was carried out in the software Inventor. An ABS plastic was used on the scaled wings, with an elastic limit of 2900.75 psi and a density of 1.38

g/cm³. In addition, stainless-steel with a density of 7.75g/cm³ was used for the structure. Three tests were performed on each of the studied wings with a force of 1lb placing them on the centroid of the wing: (1) the wing without structure, (2) the wing with a straight structure and (3) the wing with the hook structure. In the displacement of the wings, the results are as follows (Tab. 8):

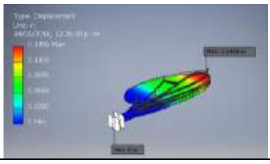
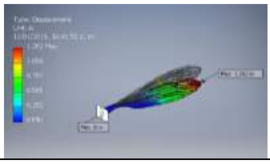
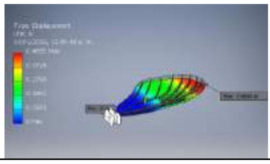
	Displacement		
	Bee	Mosquito	Butterfly
Without structure	0.61	1.26	0.47
Straight structure	0.21	0.51	0.14
Hook structure	0.16	0.12	0.08
			

Table 8: Displacement of the wings given in inches.

Table 8 shows that the structure in the form of hook has the least displacement mostly in the mosquito. Using this structure, we proceed to make the 3D animations of the movements of the wings to check our hypothesis.

5 3D ANIMATION OF THE WINGS MOVEMENTS

The insect flight consists of a semi-automatic cycle movement that is influence by the insect structure such as shape and size of the wing and the insect body [7] (Fig. 15).

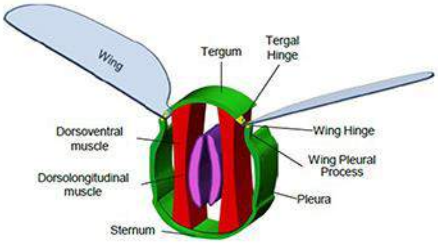


Figure 15: Dipteran insect´s exoskeleton [7].

The simulation of the movements of the wings was made in the software 3D Studio Max. We considered two movement types to make the simulations: the rotation movement on the “X” axis and the translation movement on the “Y” axis. In each of the wings of the insect studied, a pivot was used as a support point to perform the movements.

Twenty-two turns were applied for every five squares of 105 in total of each wing (left and right). We show in Table 9 the numerical values that were used to perform the rotation movements and, of the translation movements (given in degrees).

Frame	Movement	Rotation	Rotation		Frame	Movement	Rotation	Rotation

	number	on the "X" axis	On the "Y" axis		number	on the "X" axis	On the "Y" axis
0	1	-45	0	55	12	95	-35
5	2	-45	35	60	13	0	-50
10	3	0	50	65	14	-30	-35
15	4	65	0	70	15	-45	0
20	5	95	-35	75	16	-45	35
25	6	0	-50	80	17	0	50
30	7	-30	-35	85	18	65	0
35	8	-45	0	90	19	95	-35
40	9	-45	35	95	20	0	-50
45	10	0	50	100	21	-30	-35
50	11	65	0	105	22	-45	0

Table 9: Numerical values of the movements given in degrees.

Before performing the 3D animation, in the AutoCAD software the wings of the studied insects were placed according to the following movements: rotation -45°, translation -50°, rotation 95°, translation 35° and translation 50° (Fig. 16). This was done to verify the position of the wings in space in each of the movements.

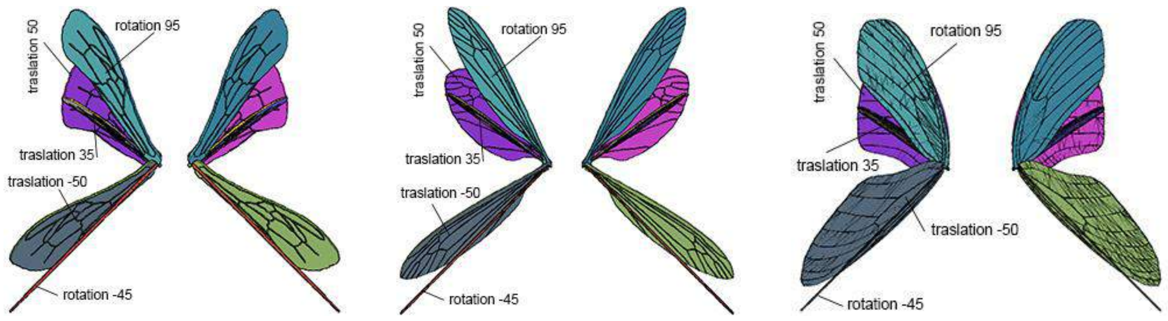


Figure 16: Front view of the movements of the wings (a) Bee, (b) Mosquito and (c) Butterfly.

In the movement of -45°, the wings are in an inclined position and, in the following movements; the wings are in an oblique position.

The bodies are reign by the laws of physics, so that it is important to consider them when making an animation. In our research, we only focused on gravity, as this have an effect on how the body movements will modify. So, to perform the 3D animations, the wing membrane was considered as a surface to simulate the movements as real as possible, the nerves were conserved with their thickness and high and, the axis was used with the hook form. As an example, in Figures 17, 18 and 19 we show the turns and displacement of the bee, mosquito and butterfly in frames 0, 10, 20 and 25.

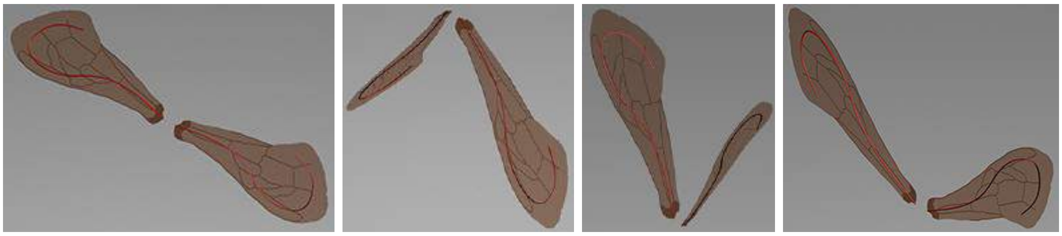


Figure 17: Movement of the wings of the bee.

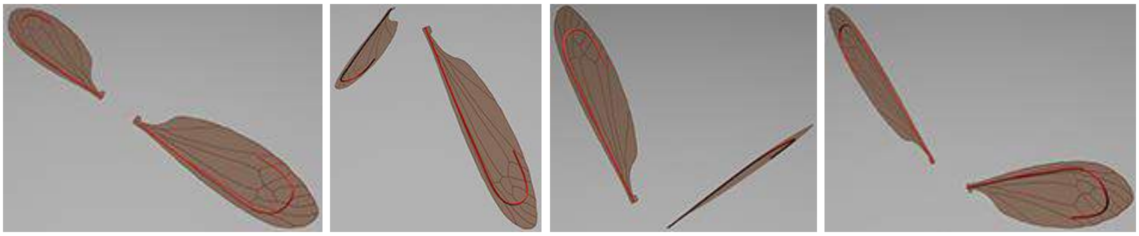


Figure 18: Movement of the wings of the mosquito.

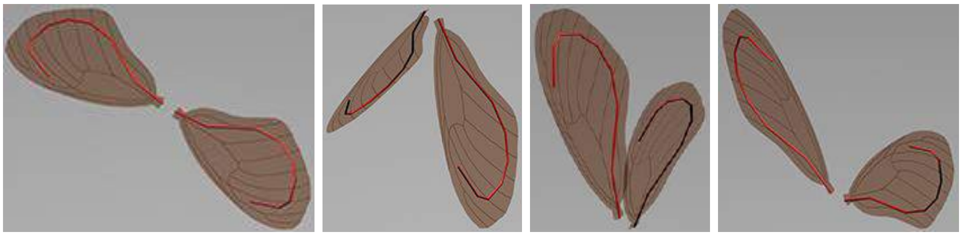


Figure 19: Movement of the wings of the butterfly.

6 RESULTS

Although the wings of the studied insects have different shapes, they vary in the number of veins, and the length of this veins are different, it was found that the heavier parts of the wings coincide in the same sections (Fig. 20).

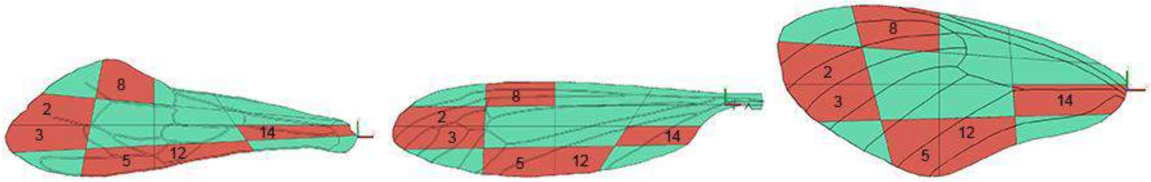


Figure 20: Heavier parts of the wing (a) Bee, (b) Mosquito and (c) Butterfly.

If we follow points 8, 2, 3, 5, 12 and 14, the path that would give in all the wings is a hook. The path and the hook shape change proportionally to the shape, the length and the width of the wing. (Fig. 21).

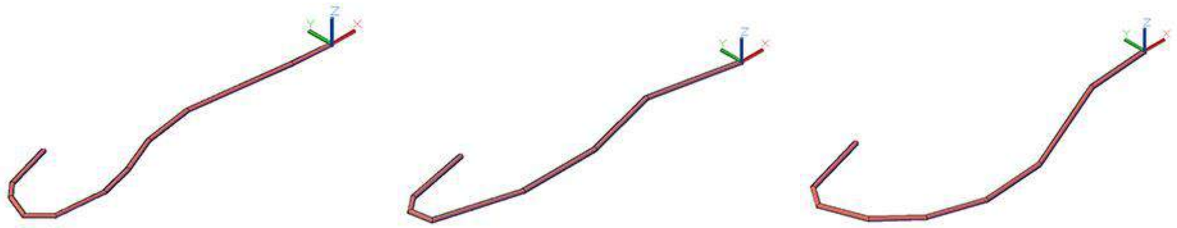


Figure 21: Hook shape (a) Bee, (b) Mosquito and (c) Butterfly.

We study the data series of the stress analysis comparing the displacement of the bee, mosquito and butterfly wings (Fig. 22) and, between the three models: (1) without structure, (2) with a straight structure and (3) with a hook structure (Fig. 23). In this study, an ABS plastic was used, with an elastic limit of 2900.75psi and, density of 1.38 g/cm³. In addition, a stainless steel with a density of 7.75 g/cm³.

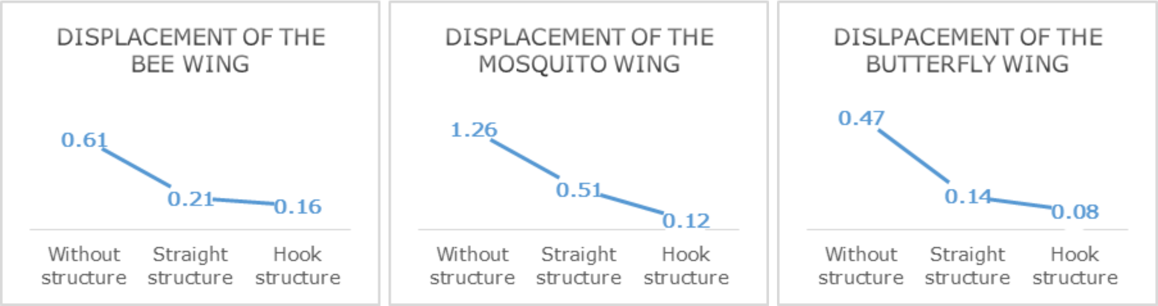


Figure 22: Displacement of the models with 1lb of applied force in inches.

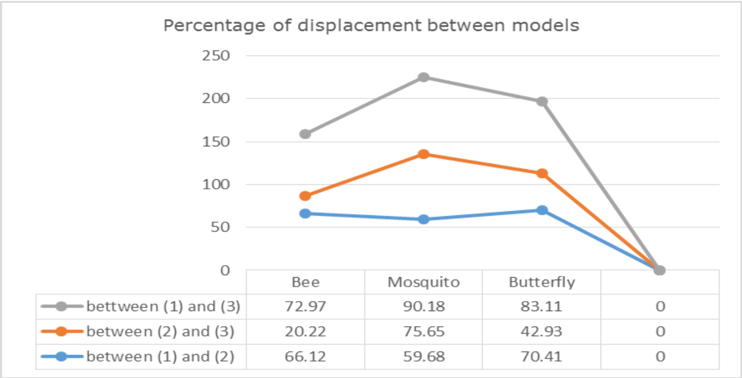
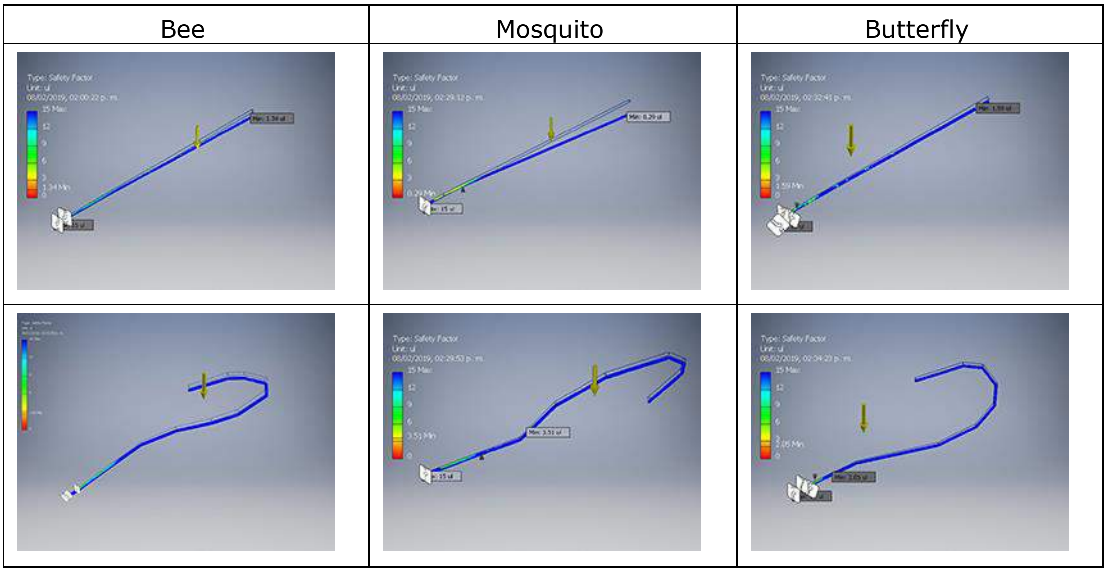


Figure 23: Percentage of displacement between models.

We found that, the largest displacement among the studied models it is from the mosquito between the straight structure and the hook-shaped structure; likewise, when it has no structure and has the structure in the form of a hook. In addition, the butterfly has the largest displacement when has no structure and has a straight structure.

We perform the analysis of the safety factor of the models and we realize that the safety factor is reduced with the structure in the form of a hook by 18.5% against the straight structure (Fig. 24).



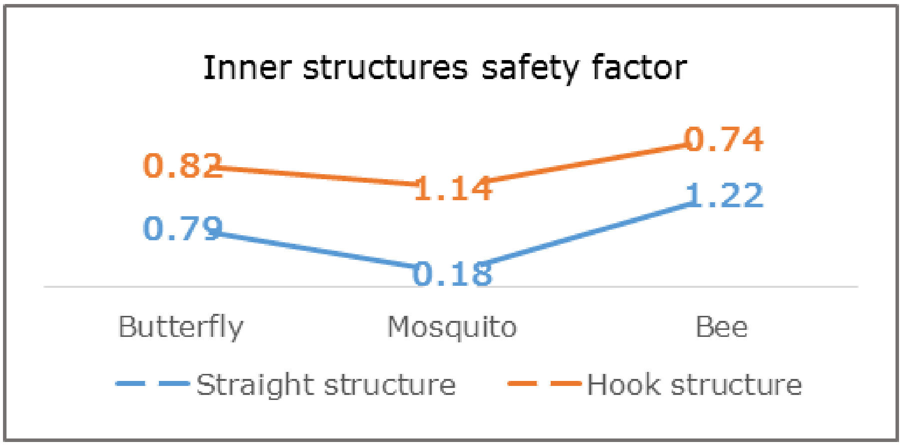


Figure 24: Safety factor of inner structure (a) Analysis results and (b) Graphic.

We use the force of gravity of 9.8m/s² to perform the stress analysis. Figure 25 shows the results of the displacement values when the gravity force affects the models: (1) without structure, (2) with straight structure and (3) with the hook structure in the bee, in the butterfly and in the mosquito.

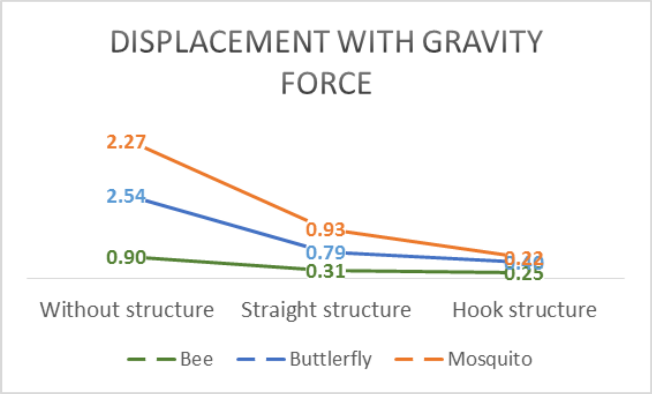


Figure 25: Displacement of the models with gravity force.

In the simulation of the displacement with a force of gravity, the results are evident between using and not using structure. When using a hook shaped structure, between the mosquito and the bee the difference is significant unlike the butterfly. However, if a straight structure is used, there is a big difference in the displacement between the wings of the three insects studied; the wing of the mosquito is the one with the greatest displacement followed by the butterfly and the bee.

The wing deformation is different according to their size as well as position, size and shape of the vein framework, since these characteristics modify the centroid position resulting in different and complex traces and wing vortex [3] (Fig. 26).

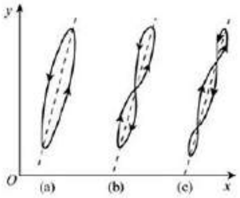


Figure 26: Three different traces of the wing centroid [3].

Figures 27 and 28 shows how the wings of insects are deformed in the simulation of their movements in 3D animation when a structure is not used or when the straight structure is used.

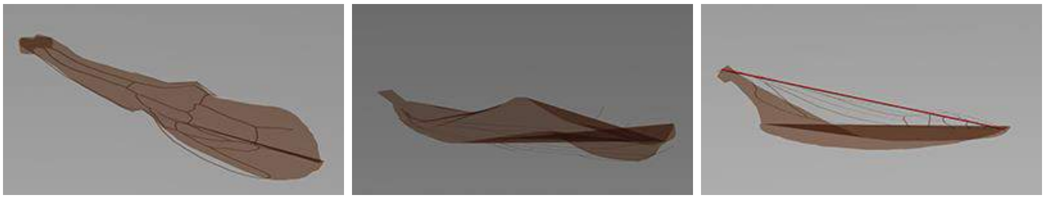


Figure 27: Deformation of the wings.

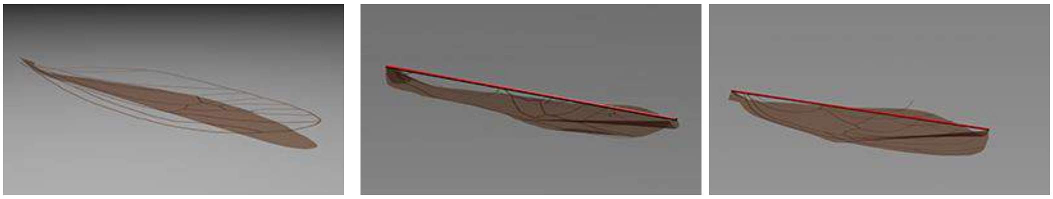


Figure 28: Deformation of the wings.

After having finished the whole study, we conclude that there was less displacement and deformation of the wings of the insects when we performed the simulations using a hook-shaped structure. Since the hook-shaped structure allowed both the membranes and the veins to move at the same time, allowing the less heavy parts to move freely, thus creating a more realistic simulation (Fig. 29).

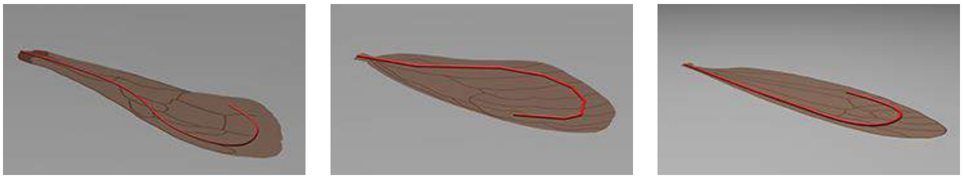


Figure 29: Wing with hook shaped structure in the animation environment (a) Bee, (b) Butterfly and (c) Mosquito.

With this study, our hypothesis was proved: the simulations of wings movement do differ when using an axle that passes through the heavier parts of the wing than when it is not used.

This is because, the hook structure that passes through the center of the heavier parts supports the set of loads of the own weight of the membrane and the wings nerves with stability and resistance and, preventing the wings from flexing (Fig. 30).

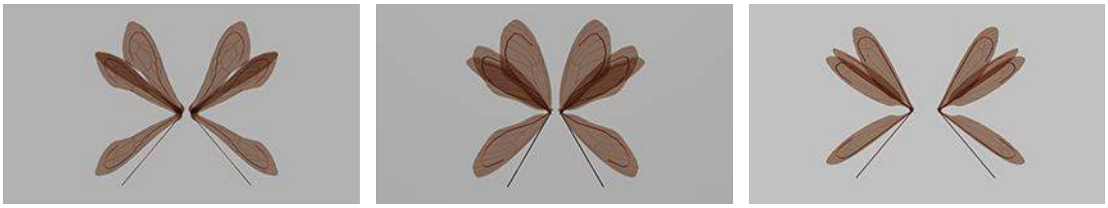


Figure 30: Wings movements (a) Bee, (b) Butterfly and (c) Mosquito.

It should be mentioned that Tofilski, in his paper: Draw wing, a software for numerical description of insect wing [12], wrote, "Pointing the landmarks is time-consuming and often associated with errors (Dedej and Nazzi, 1994) because the exact position of a landmark is ambiguous, particularly when veins are wide. Measurements of wing length and width have proved to be even less repeatable (Dedej and Nazzi, 1994). The problem of repeatability of measurements can be solved by automatic determination of landmarks".

We disagree with what the author mentions in his writing, since the method we use in this project and that we have used in other projects, we have not had any problem in locating the landmarks as well as knowing the length of the veins.

Our work is geometric, and with our method we perform the stress analysis, the 3D animations and the 3D printing of the prototypes and the author does not mention anything about it.

7 CONTRIBUTION

The paper we present contributes to scientific research since we find, from the morphological point of view, the true shape and magnitude of the wing and the location and length of its nerves. From the geometric point of view, we find that there is a relationship in the parts of heavier weight of the wings of the insects studied no matter their shape and size.

In addition, it is suggested to place a hook shape structure to make a simulation more realistic, since from the point of view of 3D animation should be placed an internal skeleton and virtual bones to define the limits of movement of the character.

8 CONCLUTIONS

We conclude that the hypothesis that we set out was verified: the simulations of the movements of the wings of the insects differ if the axis passes through the center of heavier the parts of the wing.

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