Marey, Etienne-Jules. - The mechanism of flight in the animal kingdom

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"*The Mechanism of Flight in the Animal Kingdom*," by Dr. MAREY; translated from *L'Aëronaute** by T. J. BENNETT, Esq.:—

Between the years 1869 and 1870, a course of lectures was delivered at the College de France, Paris, by Dr. Marey, on "The Mechanism of Flight in the Animal Kingdom." The results of Dr. Marey's researches have since appeared in the *Aëronaute*, and, as they are of great interest, it has been thought fit to publish a *resumé* of them in the present Report. The paper is divided into two sections: the first part relating to the flight of insects, and the second to that of birds. As our present space is limited, and there appeared in the last Report a paper on the flight of insects, by Mr. Sénécal,—the results obtained by that gentleman being almost identical with Dr. Marey's, it is unnecessary to reproduce them here.†

The first part of the section on the flight of birds is devoted to the study of the muscular force of birds, and the influence that the disposition of the muscles exercises upon flight. In a bird the muscles most developed are those which

* *L'Aëronaute* is a monthly periodical, published at Paris, specially devoted to Aëronautics. It is edited by Dr. Hureau de Villeneuve, Secretary of the French Aëronautical Society, who, it will be remembered, was the French Commissioner at the Aëronautical Exhibition held at the Crystal Palace in 1868. It contains many interesting papers, extracts of which we hope to publish in a future Report.

† It will not, however, be out of place to mention that Dr. Marey found that the wing of insects and birds described a figure of 8 looped in space, as shown in the diagrams attached to Mr. Sénécal's paper. This fact was discovered and made known to the world by Dr. Pettigrew, of Edinburgh, in a paper on Flight, which was published in the Proceedings of the Royal Institution of Great Britain, in March, 1867, nearly two years before Dr. Marey wrote. The paper was afterwards translated into French, and appeared in the *Revue des Cours Scientifique de la France* and *de l'Etranger*, of September, 1867. Dr. Pettigrew wrote to the French Academy, claiming priority of discovery with regard to the figure of 8 loop described by the wing, which claim Dr. Marey admitted.

serve to flex and extend the wing, and those which move the entire wing round the articulation of the shoulder. The extensor muscles, which are in the wing itself, give to that organ the different positions necessary for the accomplishment of flight, while the motive power is produced by the pectoral muscles, which are equal to one-sixth of the total weight of the bird. These powerful muscles occupy the whole of the anterior surface of the thorax, and it is at once evident that these organs play the principal part in flight, causing the wing to descend with great force and rapidity, and to find the resistance necessary for the support of the bird. Above the great pectoral there is a smaller muscle, whose office it is to raise the wing.

Although unable to arrive at the actual power developed by the bird during flight, yet it is possible, by experiment, to obtain the maximum effort made by the muscles of a bird. The power thus obtained will probably not correspond to the real force dispensed, but it will prevent us falling into the exaggeration which attributes to the muscles of a bird a force superior to the maximum effort of which they are capable. In physiology, the statistical force developed by a muscle is measured by finding the maximum weight it is capable of lifting. If the weight of one kilogramme (2¼lbs.) is placed upon the articulation of the arm with the forearm of the wing of a pigeon, which is placed upon its back, the bird is unable to lift it by the most violent efforts. Dr. Marey, however, wished to have a more precise measure of the force of the pectoral muscles. He therefore exposed the pectoral muscle of a buzzard, and cut off the wing at the elbow, the bird having been put under chloroform. A cord was then fixed to the extremity of the humerus, and to the end of the cord a box was fixed, into which shots were poured. The body of the bird was immovably fixed on its back, and the pectoral muscle excited by electricity. During the artificial contractions thus produced, shots were poured into the box attached to the cord, until the force of the muscle was overcome. The maximum weight the bird was able to lift was 2 kilogrammes 380 grammes (nearly 5¼lbs.) But the arm of the lever to which this weight is attached is the length of the humerus, which is about 90 millimetres (nearly 4in.), if measured from the point of attachment of the cord and the centre of the articulation of the pectoral muscle to the humerus. The distance between the root of the wing and the centre of articulation of the pectoral is 17 millimetres, and as the weight raised and the power developed by the muscle, each multiplied by the length of its respective lever, would equalize each other, we get by the following simple calculation the real force of the great pectoral muscle:—

$$\frac{2380 \text{ grammes} \times 90 \text{ mil.}}{17 \text{ mil.}} = 12 \text{ kil. } 600\text{g.}$$

Admitting that the muscular contraction produced by electricity is as powerful as that produced by the will, yet even if we double or quadruple the results obtained, it will still be below the force that Koster attributed to the muscles of man. Dr. Marey calculates the centre of pressure of the air acting on the wing to be at two-thirds of its length, measuring from its root, which, in the buzzard experimented upon, was 40 centimetres (about 16in.) The weight of the bird was 785 grammes. Experiments with models have proved that the resistance the wings encounter must be more than equal to the weight of the bird to ensure flight; therefore the pressure of the air under each wing would have to be more than equal to half the weight of the body, which, in the present instance, is 392 grammes. The force of each pectoral muscle multiplied by the length of its short lever (17 millimetres) should exceed the weight of half the body 392 grammes, multiplied by its long lever (40 centimetres).

From this we get the following formula:—

$$F \times 17^{mm.} = 392 \times 400^{mm.}$$

F represents the force of each muscle, which was found to be 12 kil. 600 grammes.

$$12{,}600gr. \times 17 = 392 \times 400 = 214{,}200 = 156{,}800.$$

It has already been stated that the motive power should be greater than the resistance of the air, and the above calculation shows that in the present case it is in the proportion of 51 to 43·5. Dr. Marey has repeated the same experiment on a pigeon, when the results obtained were in the proportion of 70 to 43.

It appears from the above two experiments that the muscles of a bird have always a reserve of force which may serve them in certain circumstances. Without accepting the exaggerated accounts of large animals being carried off by birds of prey, we may mention a few authentic examples of heavy weights being lifted by birds. Silberschlag had a tame eagle that was able to fly with a copper ball weighing 4lbs. attached to it. Dr. Marey himself found that a pigeon could lift a weight of 100 grammes; a buzzard 300 grammes; whilst a duck could hardly support 60 grammes.

One of the most striking peculiarities of a bird's muscle is the extreme rapidity with which it is worked. This rapidity is an indispensable condition in flight, for the wing would not find a sufficient fulcrum on the air unless moved with great velocity; the resistance of the air increasing to the square of the velocity.

Dr. Marey next proceeds to examine the form of the pectoral muscles in different species, and the effect which it has upon the wing movements. It is only necessary to observe the flight of the wild duck and the buzzard to be struck by the difference in the movement of their wings. The wild duck in flying describes with its wing an angle of almost 90 degrees, whilst the buzzard makes an extremely short stroke. If a wild duck and buzzard are dissected, it will be seen that in the duck the pectoral muscle is extremely long, whilst in the buzzard it is short; but the muscle in the latter presents a transverse section vastly greater than that of the duck's. If we compare the different species of birds which have the pectoral muscle large and short with those who possess long and thin ones, we find that in the former the surface of the wings is extensive, whilst in the latter it is very small. But the resistance of the air against a plane surface in motion is proportionate to the extent of that surface. Thus, everything else being equal, a large wing will require a greater effort to move it than a small one. But the extent of the contraction of the muscles is proportionate to the length of its fibres, while the maximum effort that it is capable of producing, is proportionate to its transverse section. Two muscles having the same weight, one of which has a transverse section four times that of the other, but only a quarter the length, will lift 4lbs. through 1ft., while the long and thin one will lift 1lb. through 4ft. in the same period of time, the force expended in both cases being equal. Two birds having muscles of equal weight will develope the same force, but if the pectoral muscles present the difference in form mentioned above, the work will be performed in a different manner. The bird with small wings will multiply by a long stroke the little effort they offer to the resistance of the air, while the one with a large surface will expend equal power in multiplying, by a shorter stroke, the greater resistance that the air offers to its wing. It is thus possible to calculate the force developed by a bird during flight, it being only necessary to know the resistance the air offers to the surface of the wing, and to multiply for each stroke of the wing this resistance by the length of the stroke. The problem, however, is not so easy as it at first appears, for there is every reason to believe that the velocity of the wing is not uniform, and that at different periods of the stroke it moves with a different velocity, which would consequently cause a corresponding increase or decrease in the pressure of the air on its surface.

To find out the real nature of the movements of the wing is then the next question which presents itself. Dr. Marey has invented a very ingenious apparatus for the measurement of the frequency of the strokes of the wing and the relative duration of the periods of elevation and depression. He places at the extremity of the wing an instrument, which, at each movement of that organ, connects and breaks an electric current. This current passes through a registering apparatus, which traces, by means of a style, upon a revolving blackened cylinder, a crenulated line. Each change of level in the tracing corresponds to a change in the direction of the wing. A small cable containing two fine wires establishes the communication between the registering apparatus and the bird, which is allowed to fly at liberty in a room 15 metres square and 8 metres high. This apparatus, applied to different species of birds, enables us to state with accuracy the frequency of the movements of their wings. The following are the results obtained :—

	Complete strokes per second.
Sparrow	13
Wild Duck	9
Pigeon	8
Buzzard	$5\frac{3}{4}$
Screech Owl	5
Harrier	3

The frequency of the strokes varied as the bird was rising, in mid-flight, or alighting. The tracing also informs us of the relative duration of the up and down strokes. Contrary to general opinion, the up stroke was found to be quicker than the down. This inequality between the two periods is more apparent in birds with large wings and slow movements. Thus in the duck, which has narrow wings, the duration of the two movements is almost equal. They are unequal in the pigeon, and still more so in the harrier. The following are the real figures:—

	Total duration of a complete stroke.	Up.	Down.
Duck	$6\frac{2}{3}$ hundredths of a second	3	$3\frac{2}{3}$
Pigeon	$7\frac{1}{2}$ „ „	3	$4\frac{1}{2}$
Harrier	$21\frac{1}{3}$ „ „	$8\frac{1}{3}$	13

It is very difficult to determine the precise instant of the change in the direction of the line traced by the style, owing to it sticking to the magnet. Dr. Marey does not think it possible to estimate a movement of less duration than the $\frac{1}{200}$ part of a second with the electric method.

Dr. Marey invented another instrument, in which the swelling of the pectoral muscle, as it contracts to draw the wing down, is made to record the movements of that organ. At the same time it indicates the successive action of the principal muscles attached to the wing. A corset is fastened tightly round the bird, and between it and the pectoral muscle is placed a small shallow basin of metal containing a spiral spring, and covered by a thin sheet of indiarubber. The registering apparatus, which is fixed in the centre of the room, consists of a similar basin, but without a spring, to the rubber of which is attached a lever, carrying a tracing style. These two basins are connected by a long indiarubber tube about 12 feet in length. Their mode of action is as follows:—When pressure is applied to the rubber of the first basin, the air is forced out through the tube into the second basin, thus raising the style which traces on a blackened cylinder. When the pressure ceases the air re-enters the first basin, in consequence of the elasticity of the spring, and the style descends. Precaution must be taken to prevent the elongation of the indiarubber tube which establishes the communication between the bird and the registering apparatus. When the bird flies it raises a portion of the tube, which, being elastic, would stretch by its own weight, and produce a rarefaction of the air in the interior of the apparatus, interfering with the signals recorded. To prevent this, the tube is bound to the telegraphic cable, care being taken that it is a little longer than the cable to prevent traction. It is not necessary to take into consideration the elasticity of the tube in a transverse direction, the sides being thick enough to withstand the feeble changes of pressure produced in the interior.

The bird is set at liberty at one end of the room, the dovecote in which it is ordinarily kept being placed at the other extremity. The bird, in endeavouring to reach the cote, produces the traces on the blackened surface. Experiments with this instrument show that at the commencement of flight the strokes of the wings are fewer but more energetic. After a few strokes they attain a regular rhythm, which again becomes irregular when the bird alights. If the traces obtained are a *facsimile* of the movements produced by the muscles, they will inform us of the nature of the resistance the wing meets with during the different periods of the stroke. Seeing that the muscles for the elevation and the depression of the wing are very unequal in size, we are led to suppose that if the resistance was equal in the ascent and descent of the wing, the duration of the up-stroke would greatly exceed that of the down. But as it is the contrary that takes place, Dr. Marey concludes that the wing in the up-stroke cuts through the air with its front edge, thus meeting with very little resistance.

Dr. Marey next wished to determine the manner of the movements made by the wing. In order to do so, he employed a modification of the apparatus described above. To two stands, solidly made, two levers in aluminum are connected by means of universal joints, which allow them to move in any direction. To each lever two similar basins to those described above are placed at right angles to each other, one acting vertically and the other horizontally. The vertical acting basins or drums on each lever are connected by an indiarubber tube, as are also the horizontal drums. The apparatus being thus constructed, if a movement of any description be imparted to one of the levers, the other lever will imitate that movement with perfect fidelity. One of these levers was fastened on the back of a buzzard by the help of a corset, which allowed the wings and feet to act freely. A light platform of wood, placed on the back of the bird, carried the apparatus. The lever being firmly lashed to the wing, transmitted its exact movements to the registering lever placed in the centre of the room.

After many unsuccessful attempts, owing to the breaking of the machine, Dr. Marey succeeded in obtaining satisfactory results. He found that during the flight of the bird the registering lever described an ellipsis with a sharp summit; very extensive at the commencement of flight, but losing little by little its ampleness, preserved for some time a uniform character.

The next point to be considered is the rotation of the humerus on its own axis, and the changes in the plane of the wing produced during flight. The wing of the bird should in the down-stroke find sufficient resistance to raise the flexible and posterior part of the wing. This produces a change in the plane of the wing, but the rotation of the humerus round its own axis at each contraction of the grand pectoral muscle acts in a manner more efficacious, for it places the wing, at the beginning of the down-stroke, in a position favourable to the double office that it has to perform, viz., that of supporting and propelling. It is only necessary to examine the point of attachment of the grand pectoral muscle to the humerus, to perceive that it is fixed to the anterior margin, and that any contraction of the muscle must tend to produce a movement of rotation of the humerus round its own axis. The conformation of the humeral articulation freely allows of this movement. It is possible by the electric excitation of the muscles of the wing, to measure the maximum amount of rotation imparted by them to the humerus.

In the experiment previously described, made for the purpose of finding the statistical effort developed by the pectoral muscle, it was found that at each contraction of the muscle the humerus executed a movement of rotation on its axis. A small lever was fixed in the bone perpendicular to the humerus, when it was seen from the angle formed by the two positions of the lever, that this rotation corresponds to an angle of 35 to 40 degrees in the buzzard. But there is no doubt that in the down-stroke the resistance of the air to the posterior portion of the wing imparts a far greater angle of inclination to the plane of the wing.

We are now in a position to study the action of the wing, for it is evident that in the down-stroke it will have a double effect, viz., that of supporting the bird and imparting to it a horizontal motion. The wing also supports during the up-stroke, for the rapid horizontal motion of the bird causes the air to impinge on the under surface of the wing, which is inclined upwards, and thus causes it to act after the manner of a kite.

There is still another movement of the wing, and that is its flexion during the up and its extension during the down-stroke. Several small birds fly in this manner, but Dr. Marey was unable to see the least traces of it in the flight of the large birds upon which he experimented.

The study of the different movements that the wing executes during flight leads us necessarily to enquire into the effect produced by each of these movements on the body of the bird. During flight two distinct effects are produced: the bird is upheld against gravity, and propelled horizontally. And now arise the questions:—Is the bird sustained at a constant level, or does it oscillate in a vertical plane? Is there a series of elevations and descents, of which the eye is unable to seize the extent and frequency? Is there no variation in the horizontal velocity of the bird? Does not the action of the wings impart a jerking motion? In order to resolve either of these questions experimentally, it is necessary that the oscillations of the bird should produce upon the membrane of a metallic drum a varying pressure coinciding with the rise or fall of a bird.

Supposing that a flying bird carries on its back a drum similar to those previously described, with the membrane turned upwards, and that this instrument is connected by a long tube with a registering apparatus,—if this membrane follows the movements of the bird, no displacement of the air in the apparatus will be produced, and the style will remain motionless. But if we prevent the membrane from following all the movements of the bird, if we give it a tendency to preserve a constant level while the drum is moved, the air in the apparatus will be compressed or rarefied, and the registering style will be moved. This tendency to preserve a constant level can be produced by loading the membrane with an inert mass, such as a disc of lead. By this disposition the horizontal movements are not registered, but the least movement in a vertical line is reproduced by the registering style, for when the bird ascends, the inertia of the mass resists the upward movement and produces a pressure on the membrane, which is communicated to the registering apparatus. The reverse is the case when the bird descends, for the inert mass remains behind, which is equivalent to its being raised, and the drum remaining fixed; the instrument is protected from the accidental pressure of feathers by a wire cage.

There is still the difficulty to be overcome of an inert mass placed upon an elastic membrane executing vibrations peculiar to itself, which would be recorded by the registering apparatus as well as the oscillation of the bird. The law of vibrations however teaches that the length of the period of vibration varies with the weight of the mass vibrating, and the elasticity of the rod or membrane that carries the mass. Greater the mass and feebler the elasticity the longer will be the period of vibration.

But the movements we have to deal with are tolerably short, some birds making eight or nine strokes a second. If we arrange so that the periods of oscillation of the disc of lead are longer than the oscillations of the bird we get rid of the difficulty.

Experiments made with several species of birds—duck, harriers, hen hawks, and owls—show that there are several types of flight in relation to the intensity of the oscillations in the vertical plane. In order to better understand the vertical oscillations of the bird, it is necessary to compare them with the movements of its muscle as recorded at the same time. The duck presents at each revolution of its wing two energetic oscillations, the one at the moment the wing is about to descend, the other at the moment when the wing is about to rise. To explain the ascension of the bird during the up stroke, it appears necessary to call in the action of the kite. The bird moving rapidly forward presents its wings to the air as an inclined plane, and thus transforms its horizontal force into an ascending one.

The preceding experiment furnishes very precious information in the theory of flight. If the bird executes a series of ascents and descents, the duration of the descending period will inform us approximately the amount of labour necessary for the bird to perform to enable it to rise again to the height from which it fell; and we see that the duck, which makes nine revolutions of the wing per second, executes during each revolution two vertical oscillations, that is to say, 18 per second; each oscillation being composed of an ascent and a descent, each fall of the bird cannot last more than one-thirty-sixth part of a second. If we substract the effect produced by the outspread wings acting after the manner of a parachute, we find that a body which falls during the one-thirtysixth of a second will only descend 52 millimetres. This fall repeated 18 times a second, makes a total rise of 9·36 centimetres necessary to maintain the bird at the same level during one second. In the tracing of the harrier, the descents are less than in that of the wild duck, probably on account of the large surface of the wings of the bird.

The second question to be solved relates to the determination of the phases of rapidity of flight. This can be done by placing the weighted drum vertically upon the back of the bird. The tracings furnished show that during the down stroke the velocity of the bird is accelerated, while in the up stroke its speed is diminished, owing to the tranformation of horizontal velocity into lifting force.

We are now in possession of the principal facts upon which to establish the study of the mechanical power developed by the bird during flight, and we see that it is the down stroke that developes the entire force which sustains and directs the bird in space.