Flight in nature I: Take-off in animal flyers

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ABSTRACT

In this review paper, several take-off techniques of different species of animal flyers and gliders, both extinct and extant, are analysed. The methods they use vary according to animal group and size. Smaller animals, such as insects, rely on the use of transient aerodynamic techniques or the use of stored elastic energy. Medium-size flyers such as birds, bats, and other mammal gliders initiate flight by a jump which involves leg and wing movement coordination. The largest animals to fly, the extinct pterosaurs, are believed to have used a combination of aerodynamic and mechanic techniques in order to become airborne. The information presented here can be used as a resource for novel biomimetic unmanned aircraft design.

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NOMENCLATURE

t time (s)
m mass (kg)
b wingspan (m)
F take-off force (N)

1.0 INTRODUCTION

Flight is a very successful form of locomotion as it gives its users the capacity to move through three-dimensional space with low energy consumption, increased manoeuvring space and fewer obstacles. Through evolution by natural selection, nature has developed powered flight on four distinct occasions[1]. The first occasion is estimated to be over 410 million years ago, with the appearance of flying insects. The second occasion occurred over 200 million years ago when pterosaurs roamed the skies, followed by birds around 145 million years ago. The final group of animal flyers to appear were bats, which appeared about 60 million years ago. Non-powered flight is also seen in other animal groups such as mammals with flying squirrels and colugos, reptiles such as the Draco lizard and the flying snake, and marine animals like the flying fish and the flying squid. Furthermore, some plant seeds have also evolved gliding abilities as a means for dispersion; the Javan cucumber seed illustrating an amazing example[2].

Taking into account its 400 million year experience in flight, nature has been widely studied in order to find novel ideas for aircraft design. Due to the size and mass of nature's flyers, most nature-inspired concepts are applicable to Unmanned Aerial Vehicles (UAVs). Innovative research is currently being developed in areas such as aerofoil design, flight in a low-Reynolds regime, morphing wing aircraft, flapping wing aircraft, soaring and jump-initiated flight, to name but a few. Such studies, in which nature is used as inspiration for new products and processes, are called bio-inspired studies.

One important example of a bio-inspired aerofoil comes from the study of a dragonfly's wing, whose section is different from those commonly engineered as it consists of a corrugated thin plate, like the one shown in Fig. 1. In an initial project, Kessel studied its aerodynamic properties experimentally and found that for Reynolds number in the order of 10^4 and Angle-of-Attack (AOA) ranging from –25 ° to 45 °, the lift coefficient was higher and the drag coefficient was lower than that of a flat plate, a curved plate and a BENEDEK B-6457 asymmetric aerofoil[3].

Figure 1. Wing-section of a dragonfly[3]. Reprinted from *Aerodynamic characteristics of 'dragonfly wing sections compared with technical aerofoils'*, by A.B. Kesel, 26/09/2000, *Journal of Experimental Biology*, **203**, (20), p 3126.

Based on Kessel's results, Vargas, Mittal and Dong conducted a CFD study of the corrugated wing section of the dragonfly at a similar Reynolds number. Results showed that in between corrugated peaks there is a detachment and reattachment of the flow, which causes flow reversal and consequently leads to the formation of trapped vortices, as shown in Fig. 2. Because of this there are zones over the wing section where shear drag is negative, accounting for the reduction

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in the overall drag coefficient. Also, the vortices make the corrugated wing section seem like a thick aerofoil that has been optimised for the low-Reynolds number regime, explaining why the lift coefficient is high. These effects are enhanced as the Reynolds number is lowered[4]. Tamai, Zhijian, Rajagopalan, Hui and Hu explain this phenomenon by saying that the corrugated peaks accelerate the transition from one laminar to turbulent flow, that is, they work as turbulators[5].

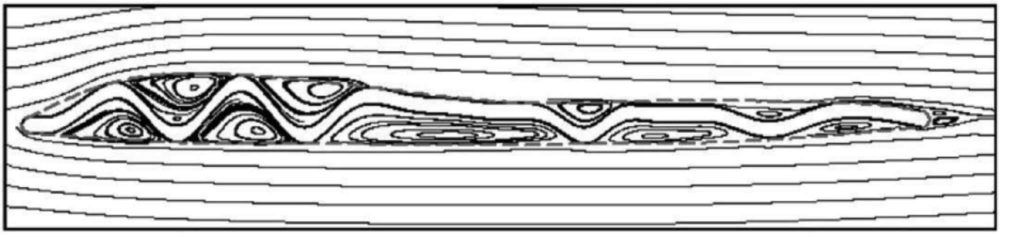

Figure 2. Time-averaged streamlines over a dragonfly's wing section[4] Reprinted from 'A computational study of the aerodynamic performance of a dragonfly wing section gliding flight' by A. Vargas, R. Mittal and H. Dong, 23/04/2008, *Bioinspiration and Biomimetics*, **3**, (2), p 10.

Related to morphing wing technology, Abdulrahim and Lind present a project that implements bird-inspired morphing wing strategies to a UAV in order to improve its manoeuvrability when flying in an urban environment. When compared to an equivalent fixed-wing configuration, the morphing wing out-manoeuvres it in missions involving deployment and recovery, long range cruise, loiter, direction reversal, steep descents and sensor pointing. All tests were carried out computationally with simulation tools[6]. This study led Grant, Abdulrahim and Lind to the development of a morphing wing that mimics the changes in wing geometry of a seagull (*Larus atricilla*), allowing an unmanned aircraft to have better trim capabilities at high AOA and improved sideslip performance when compared to a fixed-wing UAV[7].

Some successful attempts regarding flapping wing techniques have also been achieved. Trizila, Kang, Aono, Shyy and Visbal present a study in which a flapping rigid flat plate is computationally investigated in a low-Reynolds regime[8]. Results show how several lift enhancing mechanisms can have a positive effect without requiring additional power. This is done by applying a Pareto analysis in the vortex layer regions where significant differences between two-dimensional and three-dimensional effects are observed. Furthermore, environmental perturbations, such as wind gusts, are studied and techniques to improve aerodynamics performance while experiencing them are presented. Overall results contribute to the development of flapping wing mechanisms for UAVs.

Altenbuchner and Hubbard present another flapping-wing study in which a dynamic model is designed and validated with experimental results from a small-scale ornithopter constructed previously[9]. Their model includes inertial, gravitational and aeroelastic effects; aeroelastic predictions are obtained using finite element methods and aerodynamic loads are estimated with blade element theory. The project results in the production of a tool that accurately calculates the performance of a flapping wing Micro Air Vehicle (MAV). It also correctly predicts the path followed by the wingtip during one wing beat oscillation.

More recently, Ma, Chirarattananon, Fuller and Wood have developed an MAV, inspired by flies of the order *Diptera*, with hovering capabilities[10]. The vehicle uses state-of-the-art piezoelectric components to mimic the insect's muscles and thus generate the flapping movement of the wings. Control of the aircraft is done using a modular approach that allows it to hover, perform simple manoeuvres and reach a certain altitude while being tethered but unrestrained.

Another topic of interest in the UAV research community is related to soaring; a special form of gliding in which the flyer does not need to decrease its altitude or speed to maintain equilibrium as it can extract energy from the environment. Static soaring is a technique that has been studied extensively as it provides a means to increase the endurance of piloted gliders. In fact, two techniques for human-flown gliders have already been developed: the Piggot method and the Reichman method. Cowling, Wilcox, Patel, Smith and Roberts use these methods in the design of autonomous UAVs. The authors present an algorithm based on Reichman's technique that allows a point-mass model of a UAV to take advantage of thermals in order to increase its altitude and, thus, extending its flight time. Five different thermals were simulated and all of them were correctly exploited(11).

Another interesting development in bio-inspiration is the production of jumping robots. Jumping is an important way of moving as it allows cruising easily over terrain obstacles, traveling longer distances with less energy and it is also used as a method flight initiation(12,13). Kovac and several of his co-workers have published a series of papers in which the development of a miniature jumping robot is described(13-16). Based on the click mechanism found on the legs of frogs (order *Anura*), locust and grasshoppers (*Acrididae* family), fleas (order *Siphanoptera*), and other leaping animals, an initial 7g jumping robot was constructed. One of its faults was its inability to land on its feet in order to continue hopping. This was corrected initially by putting a circular cage around it, and later by shifting its centre of mass. The latter characteristic also allowed the robot to steer in a controlled manner while on the ground or the air. The final addition made to the jumping robot was that of wings, similar to those of locust but without folding capacity, which allowed it to travel larger distances. The Jumpglider, name given to the robot by their developers, has a total mass of 16·3g. Other biomimetic jumping robots have been designed and reviewed(17).

The studies mentioned above, and many more that have not been included, show that most research is focused on the cruising stage of the flight. Little effort, however, has been focused on researching bio-inspired techniques for the take-off and landing phases. Certainly there would be many advantages in applying these techniques to UAVs; the ability to take-off and land multiple times without the use of a runway being the most attractive. If this capability was achieved, aircraft would be able to execute multiple missions without needing to return to base, which would allow a reduction in fuel consumption or an increase in flight endurance. Also, periods of loitering could be carried out on the ground instead of airborne, which would also reduce energetic requirements of the UAV. Additionally, if the aircraft's mission is of surveillance, it could carry out observations from a static position on the ground or an elevated surface like a rooftop or tree branch, making it more difficult to be detected. Finally, harsh weather conditions could be avoided by landing in a safe location and waiting for conditions to improve, without need to endanger or cancel the mission.

In this review paper several flying animals will be studied in order to understand how they take-off. Their techniques will be explained so they may serve as inspiration for new UAV concepts. The study will include extinct pterosaurs as well as living insects, birds, bats, gliding mammals, gliding reptiles and marine animals that have the ability to glide. Aerodynamic adaptations made by members of the *Plantae* kingdom are out of the scope of this work as they do not have specific take-off techniques that can be studied.

2.0 TAKE-OFF IN INSECTS

This study will start with the first animals that developed the ability of flight: insects. The smallest flying insect is the fairyfly, belonging to the *Mymaridae* family, with a body length of 0·15mm. The largest is the now extinct *Meganeura monyi*, similar to a dragonfly, with a wingspan of about

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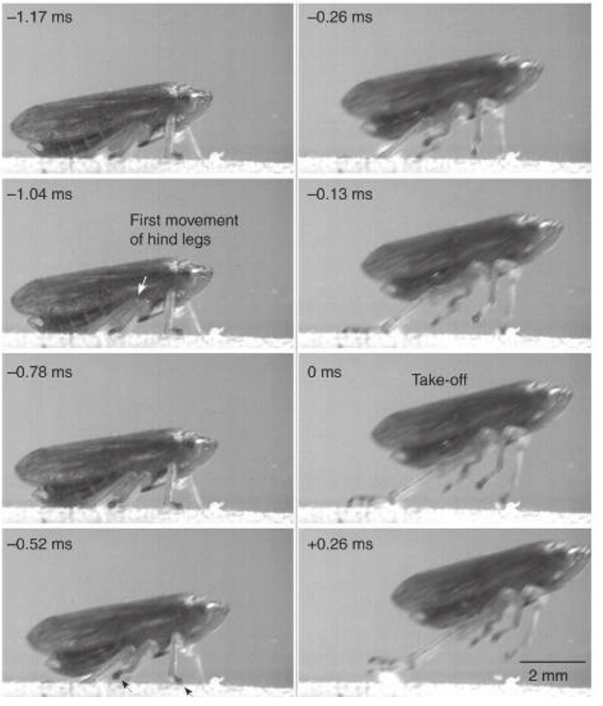

Figure 3. Take-off sequence of a froghopper insect[20] Reprinted from 'Jumping performance of froghopper insects', by M. Burrows, 06/09/2006, *J Experimental Biology*, **209**, (23), p 4609.

75cm. Most living flying insects are relatively small, so it is hard to experiment with them in order to carry out observations of their take-off mechanisms. This, however, has not prevented researchers from studying them. Dudley generalises the take-off strategy in the following way: first, the animal jumps into the air by rapidly extending its legs without using its wings. Once contact with the ground is lost, the insect starts its wing movements to produce the required aerodynamic forces for flight. He observes that wing movement is not necessary for take-off but to compensate for the momentum generated by the legs when pushing off the ground[18].

Brackenbury goes further with a description of the jump performed by insects prior to flight initiation. He comments that most insects leap as specialised hoppers; initially they carry out a backwards rotation which positions the animal in a way such that the leg extension during the jump is maximum. Elastic energy stored in the tendons will help with the take-off propulsion, although specialised muscles are also engaged. The author also mentions that insects have developed a special type of protein that acts like a rubber band. When the animal starts its backward rotation, this protein is loaded and held by a catch, much like a spring being compressed and locked. Once the animal is ready to jump, the catch is released, thus, catapulting the insect into the air, after which wing flapping commences[19]. Burrows reports the jumping procedure of several froghopper species, including the *Philaenus spumarius*, and his observations show that it follows the general description given by Brackenbury. Fig. 3 shows the jumping sequence of this insect[20].

Many specific species have been researched, the fruit fly (*Drosophila melanogaster*), whose mass and wingspan are near 1mg and 5mm respectively, being one of the most common. In a study conducted by Zumstein, Forman, Nongthomba, Sparrow and Elliot it was shown that this particular

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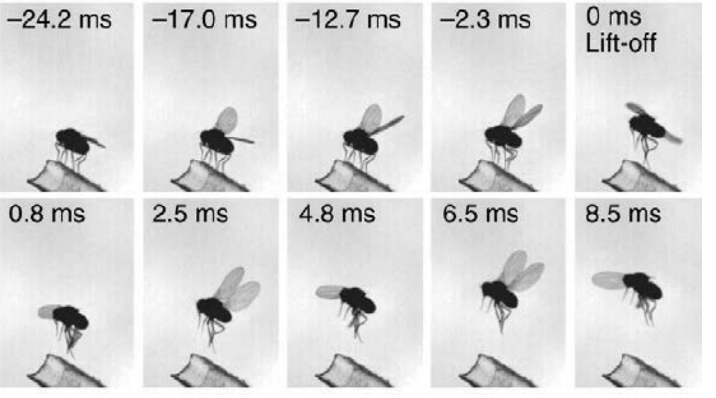

Figure 4. Voluntary take-off of the fruit fly[22] Reprinted from 'Performance trade-offs in the flight initiation of Drosophila', by G. Card and M. Dickinson, 12/11/2007, *Journal of Experimental Biology*, **211**, (3), p 344.

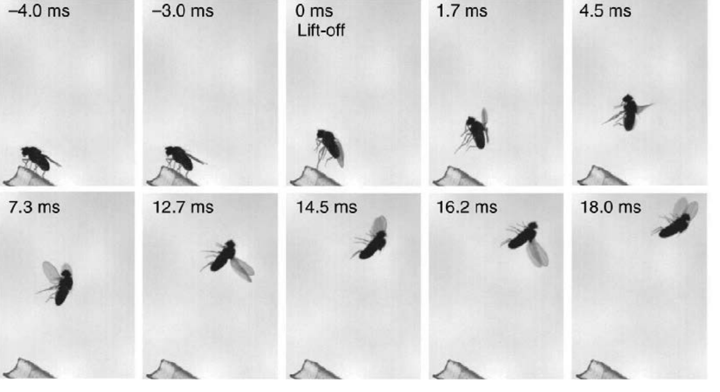

Figure 5. Escape take-off sequence of the fruit fly[22] Reprinted from 'Performance trade-offs in the flight initiation of Drosophila', by G. Card and M. Dickinson, 12/11/2007, *Journal of Experimental Biology*, **211**, (3), p 344.

fly does not rely on stored elastic energy and that the average peak force produced during the jump is 101µN per leg, with the jump lasting around 5ms[21]. In a separate study, Card and Dickinson describe the difference between spontaneous and escape-flight initiation of this species. When launching freely the fly raises its wings – a position that can be held for several seconds – after which the animal extends its mesothoracic legs. The leg movement shows to be highly co-ordinated with the initiation of the wing flapping. As a result, flight is stable with practically no rotations about any axis. The jump sequence can be seen in Fig. 4. When taking off in response to a threat, the fly also extends its mesothoracic legs but without coordinating the movement with its wings; in this case the fly jumps off without previous wing extension. Although the initial trajectory is similar, leaving at an angle close to 45°, the acceleration is almost doubled making the velocity higher. Also, roll and pitch rotations are observed, making this flight less stable. This take-off procedure is seen in Fig. 5. The authors conclude by remarking that most of the power for the jump comes from the legs[22]. Similar results are also reported by Trmiarchi and Schneiderman[23].

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Fontaine, Zabala, Dickinson and Burdick confirm the previous results and further explain that the fly is able to become stable by feedback received from the ocelli, that is, by using the apparent displacement of the characteristics of the environment due to the movement of the observer[24].

Chen, Zhang and Sun study another insect species, the drone fly (*Eristalis tenax*). Their observations show that it has a slower take-off compared to fruit flies. This is because the drone fly only uses the aerodynamic forces produced by their flapping wings in order to initiate flight, which is explained by the fact that it carries out 13 wing strokes before finally taking off. The use of other transient aerodynamic processes is not mentioned, except ground effect although this is disregarded. The insects used in this study varied in mass between 100mg and 136mg, while their body length was between 14·7mm and 15·2mm. Total take-off time was in average 62·2ms with a maximum acceleration of 7·73 ms^{-2}[25].

Another insect that has been studied is the dandelion thrip (*Thrips physapus*). A study carried out by Ellington shows the take-off sequence used by this insect is very similar to those of flies, but with one simple yet important difference. As it is shown in Fig. 6, thrips have long hairs called cilia, attached to the wings. Once the wings are opened, the animal makes a flexion of its abdomen, which is intended to take the cilia to the open position. Once this is complete the body is returned to the horizontal position, where it is ready for take-off. No physical or dynamic data of the observed insects is reported[26].

Dragonflies are another type of flying insect. They are observed to follow the general take-off procedure mentioned earlier, in which the launch force comes only from leg propulsion. However these insects require warming up before initiating flight. According to Pond, who examined two different species of dragonfly – the *Aesna grandis* and the *Aeshna cyanea* – these animals carry out a series of vibrating motions with their wings before launching into flight. This movement lasts between 25ms and 150ms and was observed to start either upward or downwards. Following this, the wings stop moving and after around 100ms, the take-off procedure was initiated. The author does not report quantitative data of the studied species[27].

Although they are mostly terrestrial insects, beetles also possess flying capabilities. Nachtigall carries out a study of the take-off sequence of the tiger beetle (*Cicindela hybrida*) which is shown in Fig. 7. The process starts with a lowering of the body, during which it nearly makes contact with the ground. In this moment the structures that cover the wings, called elytra, start

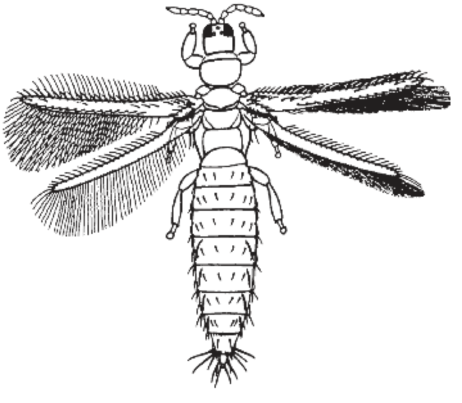

Figure 6. Dandelion thrip with extended cilia[26] Reprinted from 'Wing mechanics and take-off preparation of thrips (Thysanoptera)', by C.P. Ellington, 14/05/1979, *Journal of Experimental Biology*, **131**, (1), p 131.

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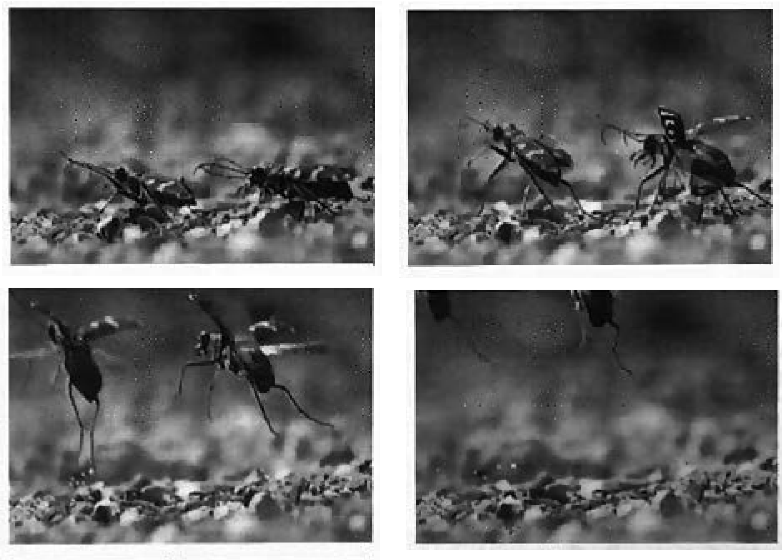

Figure 7. Take-off sequence of the tiger beetle[28] Reprinted from 'Take-off and flight behaviour of the tiger-beetle species Cicindela hybrida in a hot environment (coleopteran Cicindelidae)', by W. Nachtigall, 29/12/1995, *Entomologia Generalis*, **20**, (4), p 255.

to unfold. Simultaneously, the animal begins to thrust itself off the ground using the middle legs only. Once the elytra are fully extended, the front legs are raised towards the elytra in order to keep them open during flight and then extend the wings. After this the wings begin flapping and the beetle becomes airborne. Once the middle and back legs no longer touch the ground they are repositioned; the middle legs are raised to aid in the support of the elytra, while the rear ones are extended in the direction opposite to the flight trajectory. During take-off the elytra are positioned over the beetle's body in an acute angle, but they are completely stretched upwards once in flight. Animal size and mass is not measured. Take-off lasts 120ms in average, in which a maximum acceleration of 7ms^{-2} is produced[28]. Studies on the large grain borer beetle (*Prostephanus truncatus*) show that they prefer to take-off when there are fast winds and that the preferred direction of flight is downwind if the wind speed is high, whereas they fly upwind when wind speed is low[29].

Another ground creature that also has the capability of flying is the praying mantis (*Mantis religiosa*). According to the observations made by Brackenburry, this insect brings its wings to a fully extended position above its body before jumping into flight. Then it starts pushing with its hindlimbs to propel itself off the ground, while simultaneously flapping its wings[19]. A similar insect, the Thailand winged stick insect, currently known as the Sipyloidea sp 'Thailand 8' as it has not been categorised yet, has a similar take-off technique. The process can be seen in Fig. 8 and it starts with a curling of the abdomen in the forward direction with simultaneous elevation of the wings. Subsequently, it starts pushing down onto the ground with its hindlimbs. Once these have lost contact with the ground, the abdomen begins to curl back down in order to increase the take-off force and flapping of the wings begins. When all the legs have no contact with the ground, the abdomen has reached its initial position and the animal is completely airborne. This process takes around 100ms to occur, in which an acceleration of 10 ms^{-2} in produced. This animal was

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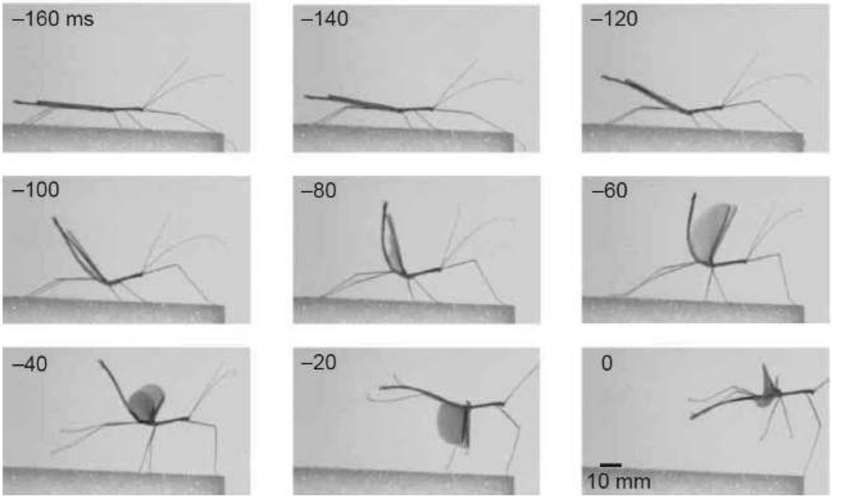

Figure 8. Jumping take-off sequence of the Thailand winged stick insect[30] Reprinted from 'Jumping in a winged stick insect', by M. Burrows and O. Morris, 16/05/2002, *Journal of Experimental Biology*, **205**, (16), page 2406, Copyright 2002 by the Company of Biologists Ltd. Reprinted with permission.

also observed to take-off without jumping, in which case it only used the flapping of the wings to get aloft. As it can be seen in Fig. 9, in this case the abdomen no longer curls up; instead it curves upward before leaving the ground. Male specimens used for this experiment had an average mass of 164mg while female specimens averaged 924mg[30].

Up to now regular flying insects and terrestrial insects with flight capabilities have been explored. Information of aquatic flying insects, however, has also been reported. Brackenbury presents a detailed illustration of the backswimmer (*Notonecta maculata*). This small insect has a body structure similar to beetles, with the difference that it can swim in a backwards position in ponds by using its legs as paddles. Its thick forewings, which act as a protective cover for the hindwings, remain tightly closed. When the insect prepares itself to fly, it first produces a very small opening within its forewings so that air can enter in and dry out the wet body parts. When ready, the backswimmer raises its hindlimbs pointing its knees forward, which is different from insects like grasshoppers and locusts who point their knees backwards. After this, the animal rapidly extends its legs and becomes airborne. In order to protect their wings from getting wet, the animal does not start flapping until it is about three body lengths above the water[19].

The last insects studied were the butterflies whose take-off technique varies significantly from other insects. Brackenburry carried out a study with over 30 different butterfly species, after which he determined the take-off mechanism used by these animals. The method, named clap and peel, is only possible due to the large wing area and small aspect ratio of the animal. It starts with the butterfly clapping its wings together in a vertical position over its body. After this, the wings begin to peel apart while keeping the wingtips together, generating a tubular region within the wings. Throughout this movement the hindwings are joined together and their anal veins are expanded, creating an air-tight seal between the butterfly's body and the wing surface. When the wings finally separate, the seal is broken and the pressure differential suctions the butterfly into flight. At this point, the body is pitched back to a near vertical position such that the first upstroke occurs horizontally to the ground. After this, flapping continues in order to climb and cruise. No physical or dynamic measurements are reported[19,31].

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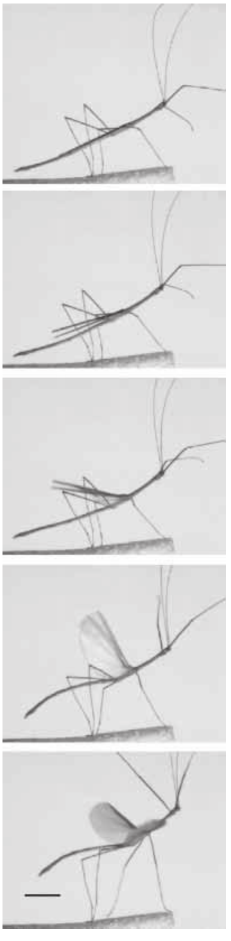

Figure 9. Flapping take-off sequence of the Thailand winged stick insect[30] Reprinted from *'Jumping in a winged stick insect'*, by M. Burrows and O. Morris, 16/05/2002, *J Experimental Biology*, **205**, (16), p 2407.

3.0 PTEROSAUR TAKE-OFF

Pterosaurs were flying reptiles that lived over 200 million years ago. According to fossil records many of their species existed, ranging from about 15g to 70kg in mass, and 41·2cm to 10·39m in wingspan. It is generally accepted that pterosaurs took off by jumping off elevated surfaces, such as trees or cliffs. This is a consequence of their size and weight; leaping from these surfaces allowed them to take advantage of gravity to gain the speed required to produce lift[32-36]. Some authors even believe that pterosaur take-off started from a completely inverted position, as seen in bats today[34].

Evidence has proven that a leaping take-off would be energetically efficient for pterosaurs. The locations of some fossil findings, however, show that these animals were also terrestrial, meaning that they should have some way of starting flight from the ground[32] Bramwell and Whitfield[34], as well as Bennet[35] believe that if the pterosaurs remained on the ground facing a breeze and expanded their wings at the proper AOA, with the correct camber configuration and possibly using the propatagium as a high lift device, the animal would have been able to take off. Another idea is that if the animal was in the ocean, it could have entered a wave and flap away when located over the crest[35].

The ideas of pterosaur ground take-off discussed in the previous paragraph are difficult to prove as there is no evidence to support them. As a consequence, other theories have arisen based on fossil evidence. Habib believes that pterosaurs, specifically the larger species, used a quadrupedal leap sequence when launching from the ground. His calculations show that pterosaurs had enough strength in both fore and hindlimbs to make a high power jump that would impart enough speed to produce lift. In fact, he believes that the resulting speed would have been enough to allow the animal to enter directly into fast flight[36].

Chatterjee and Templin developed a more sophisticated take-off technique for pterosaurs that also involved a quadrupedal posture. Using measurements from fossil findings, the authors produce a computational and a cast model of a pterosaur that has a quadrupedal stance when on the ground, with long arms and shorter legs. The orientation and form of the hands and feet matched with fossilised track paths found on what is believed to be a pterosaur take-off location in Germany. Calculations were carried out using the size, mass and aspect ratio of ten different species of pterosaurs and it was determined that they could take-off by using the process shown in Fig. 10. The first step would be to change their posture from a quadrupedal position to a bipedal one, where the wings would have to remain folded. After this the animal would start to run, shifting its body towards the front in order to create the proper launch angle. When the optimal take-off speed had been reached the pterosaur would launch forward while keeping its wings folded. This movement would be followed by a retraction of the legs so that drag would be reduced. Simultaneously the wings would be spread to begin the production of lift. In the final stage, when the animal is airborne, wing flapping begins. Performance calculations show that the biggest species of

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pterosaurs would need only a small burst of anaerobic power to be able to initiate flight like this. Metabolic calculations, however, show that for all species this power would be available. The authors also propose other techniques to facilitate take-off. One of them would be to exploit ground effect until the appropriate speed is obtained and climb can be started. The other would be to make the running start into a gentle headwind or down a small slope. These techniques would significantly reduce the required anaerobic burst needed to take-off[32].

4.0 BIRD TAKE-OFF

Birds are the animal group that have been studied the most as they are the largest living flyers. Their take-off techniques have been observed to vary with size and with their ecosystem. For the purposes of this study, birds have been categorised into five groups: tiny, small, medium, large and aquatic.

The category of tiny birds has been generated to accommodate those birds which are small enough to have the capability to hover, mostly hummingbirds. Their mass varies between 3g and 5g, with a wingspan between 10cm and 15cm. Tobalske, Altshuler and Powers present a detailed study of the take-off mechanics for the rufous hummingbird (*Selasphorus rufus*). Initially the bird stands still on the perch. When it is about to take-off, it makes a small countermovement in which the body and legs are bent through a small angle rearwards, as if it was gaining momentum. Afterwards, the body starts to rotate forwards and the legs begin to apply a force on the perch. Almost half way through its rotation, the animal extends its wings and starts flapping just as the legs reach the point of maximum applied force on the perch. After completing the first upstroke, all the force has been applied and the bird rapidly removes its feet from the perch to begin the flight. This sequence is shown in Fig. 11. Force measurements on the perch show that this animal uses both legs and wings to power its take-off, resulting in a net force of up to 3·7 times its body weight[37].

Small birds correspond to those having a mass between 15g and 90g, with a wingspan between 15cm to 25cm. Earls describes the sequence for the common starling (*Sturnus vulgaris*) as shown in Fig. 12. It starts with a crouching countermovement, more exaggerated than that made by the hummingbird. This step is followed by an extension of the bird's hindlimbs, while maintaining the wings against the body. When the animal is about to fully extend its feet, the wings are drawn out. The feet are completely off the ground at about the same time as the first upstroke is completed. Force measurements show that, as with tiny birds, both legs and wings are used to power the jump. The contribution of the wings, however, is much lower meaning that starlings have a high dependence on their feet to take off. The total jumping force can be up to 5·4 times the bird's body weight[38]. This take-off technique has also been observed in the zebra finch (*Taeniopygia guttata*) and the diamond dove (*Geopelia cuneata*)[39].

Medium birds vary in mass from 100g to 1·5kg, with a wingspan range 30cm to 1·2m. Within this group is the common pigeon (*Columba livia*), whose take-off technique is fully described by Heppner and Anderson. The first step, instead of consisting of a countermovement, generally starts with a squat. Then the animal extends its legs and starts positioning its wings for an initial downstroke right before leaving the ground. It was also observed that the pigeon used the clap and fling mechanism to enhance lift. Most likely this is done to contribute to initial support of weight, which is higher for these animals in comparison to those previously mentioned[40]. Research on the contributions from the limbs to the take-off force show that in this case, all the take-off force came from the legs as no wing flapping is performed while in contact with the ground[41]. Another study shows that during take-off the wingtip of the pigeon followed a figure-of-eight pattern[42]. Similar observations have been made in other species like the European migratory quail (*Coturnix coturnix*) whose take-off sequence is shown in Figs 13[38] the blue-breasted quail (*Coturnix chinensis*)[43], the northern bobwhite quail (*Colinus virginianus*), the chukar (*Alectoris*

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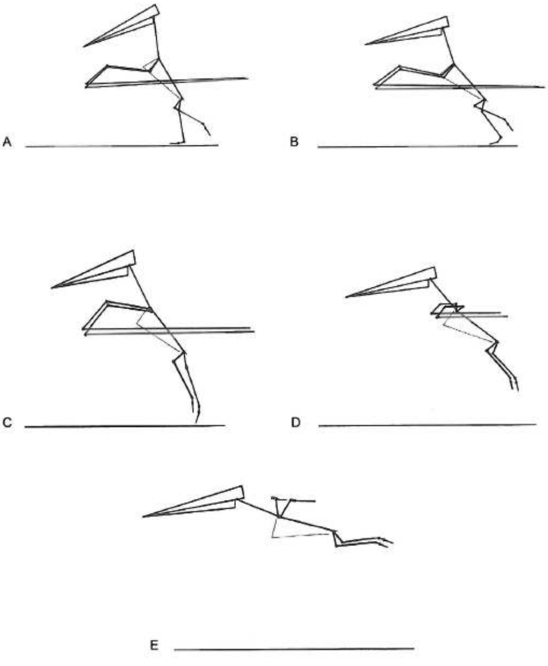

Figure 10. Pterosaur take-off sequence[32] Reprinted from *Posture, locomotion and paleoecology of pterosaurs*, by S. Chatterjee and R.J. Templin, 2004, Geological Society of America, Special Paper No. 376, p 50.

chukar), the ring-necked pheasant (*Phasianus colchicus*), the wild turkey (*Meleagris gallopavo*) [44]. and the guinea fowl (*Numida meleagris*)[45]. Maximum take-off force within these species was 8·4 times the animal's body weight.

Large birds consist of those who have a mass between 2kg and 15kg, with a wingspan between 1·5m and 3·5m. McGahan performed a very detailed analysis of the flight of the Andean condor (*Vultur gryphus*), including its take-off phase. According to his findings, the condor always makes several wing beats before actually jumping into flight in order to generate vortices that aid take-off procedure. Usually they jump from a tree branch or a cliff; however, they are also capable of launching from the ground. Take-off from high grounds is advantageous as it exploits gravity. The flapping frequency before launch is variable and is higher when launching from the ground than when doing so from a tree. This ensures the animal can obtain the additional power required to initiate flight. Initial wing beats are also of lower amplitude, but this is in order to avoid collisions that may harm the wings. The downstroke is measured to take longer that the upstroke. Total take-off force was never above six times the weight of the animal[46].

This section is closed with aquatic birds, which are those who have the ability to swim. Norberg and Norberg present a study of the take-off sequence carried out by the red-throated loon (*Gavia stellata*). The loon is usually found in lakes and ponds with few trees nearby. Once the bird has decided to take-off, it raises is body over the water surface and accelerates with its wings sweeping only through the air and its feet paddling inside the water. During this phase, the tail is lowered and is contributing to the generation of lift. Once it obtains sufficient speed, the tail is raised and the body reduces its inclination, after which it leaves the surface of the lake. If there are trees around, the loon will circle around the pond until sufficient altitude has been gained for it to fly over them[47].

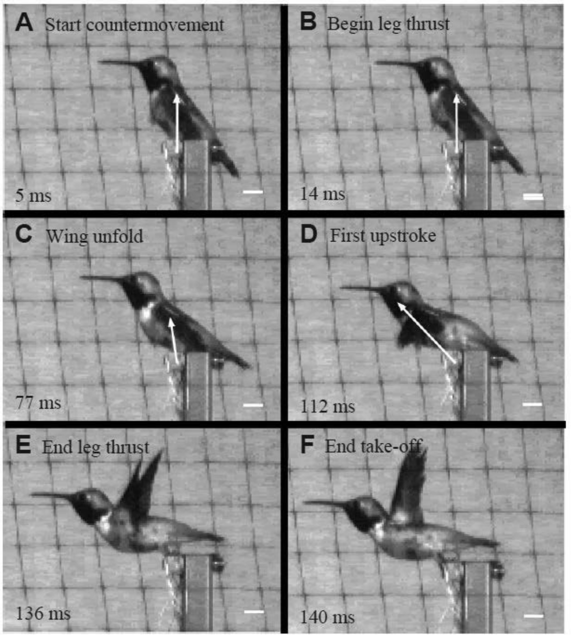

Figure 11. Take-off sequence of the roufus hummingbird[37]. Reprinted from 'Take-off mechanics in hummingbirds (Trochilidae)', by B.W. Tobalske, D.L. Altshuler and D.R. Powers, 21/01/2004, *Journal of Experimental Biology*, **207**, (8), p 1348.

5.0 TAKE-OFF IN MAMMALS

In this section two types of mammals will be analysed; those that have powered flight and those with the ability to glide. The study will start with the first – bats. Bats usually hang inverted from a cave ceiling or from a tree branch. Because of this, its most straight forward take-off technique is to let itself fall and take advantage of the gravitational acceleration in order to gain the necessary speed to generate lift[48]. Some bat species, however, have the need to take-off from the ground or other surfaces because of their specific type of food source. Bats can make these types of jump-initiated take-offs because their flight power requirements are enough as to allow these jumps to be performed; jumping is a secondary locomotive ability in bats as they have had no ecological pressure to adapt to it[49].

Several bat species need to land on the ground to acquire their food. One of them is the vampire bat (*Desmodus rotundus*) whose diet consists solely in blood. Because of this, vampire bats must be able to land upon land creatures to feed. After feeding, the bat must drop to the ground and take-off from a quadrupedal stand[50]. Other insectivore bats must also be able to take-off from the ground as they obtain their food by flying over their prey and landing directly over them. After being fed, these bats must also launch from a quadrupedal stance. Amongst the bat species that are known to do this are the common bent-wing bat (*Miniopterus schreibersii*), the lesser mouse-eared bat (*Myotis blythii*), the long-fingered bat (*Myotis capaccinni*) and the mouse-eared bat (*Myotis myotis*),[49] as well as the blasius's horseshoe bat (*Rhinolophus blasii*), the mediterranean horseshoe bat (*Rhinolophus Euryale*) and the mehely's horseshoe bat (*Rhinolophus meheleyi*)[51].

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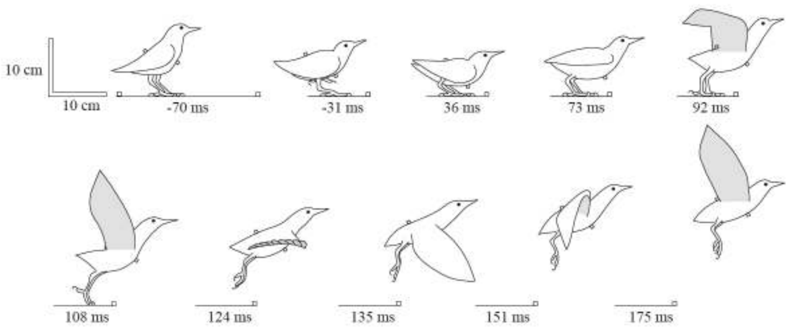

Figure 12 .Take-off sequence of the starling[38] Reprinted from ‘Kinematics and mechanics of ground take-off in the starling Sturnis vulgaris and the quail Coturnix coturnix’, by K. Earls, 26/01/2000, *Journal of Experimental Biology*, **203**, (4), p 728.

The quadrupedal take-off patterns of the bats mentioned previously are very similar and thus, only the vampire bat will be described. Take-off starts with a small countermovement in which the body is inclined backwards, and the knees and elbows of the limbs are completely flexed. After this, arms and legs begin to stretch, imparting a force on the ground. The hindlimbs leave the ground first, followed closely by the forelimbs. Once the bat is off of the ground, the wings are rapidly moved upwards so the flapping motion can begin. Initial wing beats tend to have lower amplitude than subsequent ones. The entire procedure is shown in Fig. 14[52]. Table 1 collects the mass, size and jump force of the vampire bat and other bat species that are capable of jumping into flight from the ground.

Now consideration will be given to those mammals that are capable of gliding. In research carried out by Essner, the launch kinematics of three arboreal mammals, including a gliding 107g southern flying squirrel (Glaucomys volans), are studied. The author distinguishes three phases for the animal’s take-off. Initially, the squirrel performs a body movement that locates the hindlimbs on the edge of the surface from which the launch will take place. Secondly, the

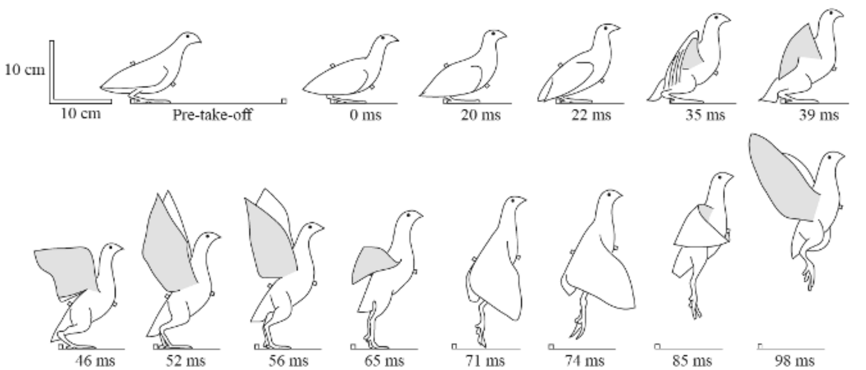

Figure 13. Take-off sequence observed in medium-size birds[38]. Reprinted from ‘Kinematics and mechanics of ground take-off in the starling Sturnis vulgaris and the quail Coturnix coturnix’, by K. Earls, 26/01/2000, *Journal of Experimental Biology*, **203**, (4), p 729.

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Table 1
Physical and dynamic measurements of bat species during take-off

Species	Mass (g)	Wing length (mm)	Jump force (N)
Desmodus rotundus	23·1	183	1·47
Miniopterus schreibersii	11·5	155	0·48
Myotis blythii	26·3	NA	1·21
Myotis capaccinni	8·7	NA	0·29
Myotis myotis	26·4	192	1·18
Rhinolophus blasii	10·5	144	0·36
Rhinolophus Euryale	12·3	143	NA

squirrel carries out a counter movement in which the knees and ankles are positioned such that the take-off speed will be maximised. In the third and final phase, the squirrel rapidly extends its legs to launch itself from the edge. It also bends its tail backwards and protracts its forelimbs so the patagium is stretched and gliding can begin. Squirrels generally prefer to launch horizontally. The complete process can be seen in Fig. 15 in which the total take-off time is 128ms[53]. No dynamic measurements are reported.

Paskins, Bowyer, Megill and Schiebe take the study of gliding animals further by analysing the take-off of a northern flying squirrel (*Glaucomys sabrinus*), with mass around 200g, from tree branches. The authors observe that the amount of energy required for launching from a narrow branch can be dramatically increased. As branches will be flexed by the weight of the squirrel, it is observed that the elastic energy stored by it could be used by the animal to aid its launch by properly timing the jump. Another important contribution of this investigation is that the force required to jump will be directly proportional to the desired travel distance, varying between 5·0 N and 17·8 N[54].

Another gliding mammal of interest is the Malayan colugo (*Galeopterus variegatus*), also known as the Malayan flying lemur, whose mass can vary between 750g and 1·40kg. To get an idea of the take-off technique of the colugo, a review of data reported for jumping lemurs was analysed. Demes, Franz and Carlson observed the jumping technique and recorded the forces used by two species of lemurs, the *Lemur catta* and the *Eulemur fulvus*. Even though they do not fly nor glide, these two species are similar in size to the colugo. According to the authors, the animals usually took an initial run before jumping. Once ready to launch, the animal pushed off the ground using all four limbs. The forelimbs always left the ground first, followed by the hindlimbs. Once again, force production depended on the forward distance the animal wanted to jump and it varied between 7·4N and 178·5N[55].

6.0 TAKE-OFF IN REPTILES

In the introduction it was mentioned that Draco lizards were known to glide. No information on their take-off mechanism was found, other than they extend their ribcage in order to form the lifting surface. Tree frogs, from the *Hylidae* and *Rhacophoridae* families, are also known for having gliding abilities. Their webbed feet allow them to produce aerodynamic forces in order to enhance their performance while airborne. Similar to the Draco lizard, no specific information of haw they jump into gliding state has been published. Information of another type of gliding reptile, however, was reported by Socha: the flying snake (*Chrysopelea paradisi*). Two different take-off methods were identified: the looped and non-looped take-off. In looped take-offs, the snake's posterior

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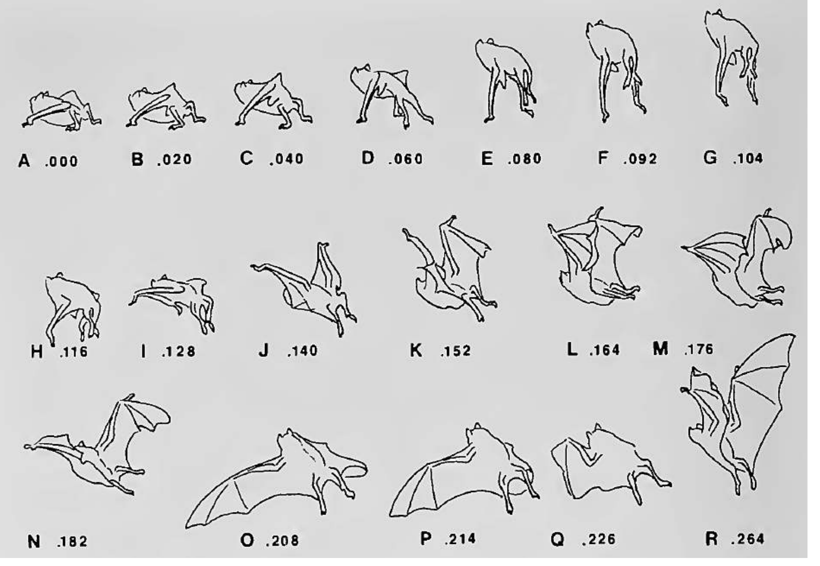

Figure 14. Ground take-off procedure of the vampire bat[52] Reprinted from 'Locomotor morphology of the vampire bat Desmodus rotundus', by S. Altenbach, 22/08/1979, The American Society of Mammalogists, Special Publication No 6, p 22.

body was coiled around the tree branch and the anterior portion of the body, including the head, was suspended from the tree branch forming a loop that looked like the letter J. In some occasions, the animal produced the loop while remaining stationary, a case that the author called anchored J-loop take-off. After positioning itself in the loop the snake stayed motionless for a moment, after which it rapidly accelerated and jumped off the branch in an upward direction, as depicted in Fig. 16(a), which shows upper, side and frontal views. This was the most common launch technique observed. On other occasions, the snake made the jump immediately after positioning itself in the loop. This case is named the sliding loop take-off and is shown in Fig. 16(b). The non-looped take-offs are characterised by the absence of a loop formation by the anterior body of the snake. In some occasions, the animal kept sliding off the branch with continuous movement, with the head pointing in the desired gliding direction, as shown in Fig. 16(c). This technique is called dive take-off. The last observed technique consisted of the snake simply releasing itself from the branch, without producing any forward acceleration; named fall take-off. Looped take-offs usually took longer to complete, however, they gave the animal higher velocity and longer travelled distance. After launching with any of the described processes, the snake would extend its ribcage to form a lifting surface that allows it to glide. No force or mass measurements were performed[56].

7.0 TAKE-OFF IN MARINE ANIMALS

Some marine animals have gliding capabilities. One of them is the fish family *Exocoetidae*, which contains approximately 40 different species. Depending on the species, the animal can have two wings, which are positioned on the enlarged pectoral fins, or four wings, in which both pectoral and pelvic fins are enlarged. The body is elongated with a constant and squared cross-section and has

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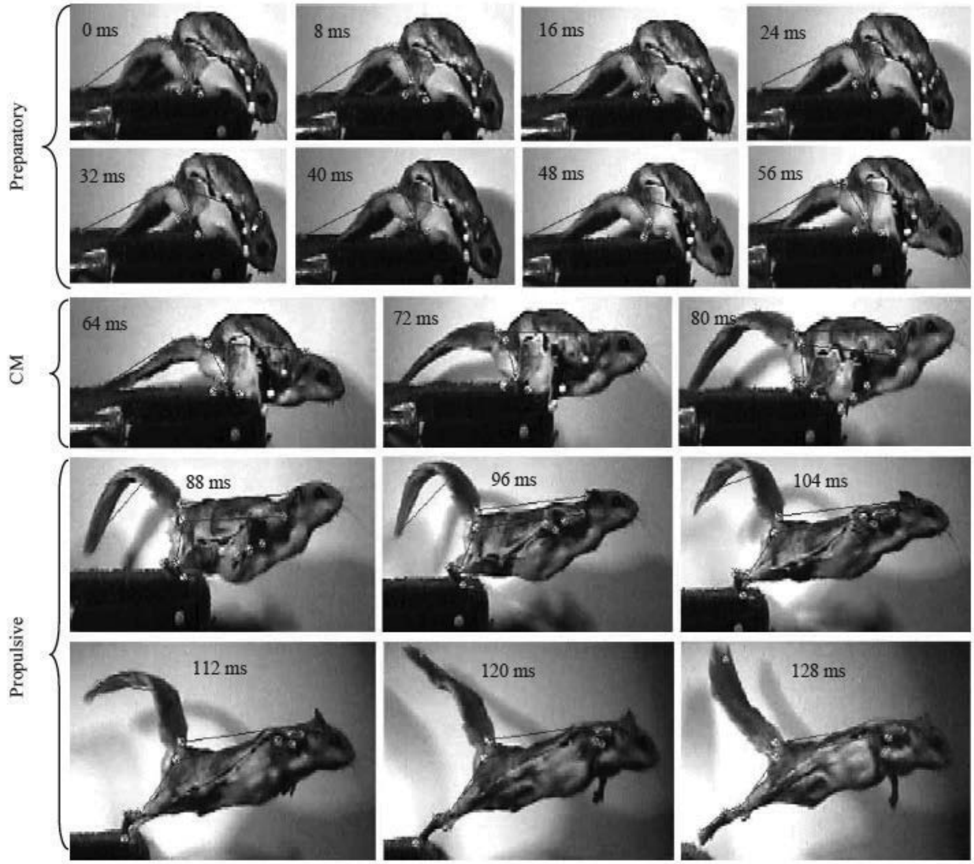

Figure 15. Take-off sequence of the flying squirrel[53]. Reprinted from *Three-dimensional launch kinematics in leaping, parachuting and gliding squirrels*, by R.L. Essner Jr. 23/05/2002, *Journal of Experimental Biology*, **205**, (16), p 2473,

a hypocercal tail that is highly asymmetrical. Flying fish size also varies within species, ranging from 15cm to 50cm in length and reaching up to 500g in mass. When ready to glide, the fish starts to swim towards the sea surface with a high velocity and the lateral fins retracted. The head leaves the water with a body inclination of nearly 30°. After the body is out of the water, the pectoral and pelvic muscles are engaged to extend the fins which will have a cambered geometry to generate lift. Next the animal enters the taxiing phase in which the tail is beating in the water to propel it to a proper flight speed, presumably with the aid of ground effect. After the proper speed is achieved the animal enters into a fully airborne state, in which it glides for about 50m, before either repeating the taxiing manoeuvre or returning to the ocean. Observations show that the preferred take-off direction is aligned with the headwind, although it is not known how the fish determine this direction while being submerged. Analysis of the animals' muscular structure indicates that their flight capacity depends on anaerobic energy, which leads to questioning of the efficiency of this type of locomotion for fish. It is thought that this might be employed for escaping predators[57].

Another marine animal has been recently discovered to have gliding capabilities. Japanese scientists have photographed for the first time a group of squid from the *Ommastrephidae* family, possibly the *Ommastrephes bartramii* or the *Sthenoteuthis oualaniensis*, jumping out of the water and using aerodynamic surfaces to glide. The take-off procedure commenced when the squid launched out of the water by propelling itself with jetting water. As the body exited the water surface, the animal extended its fins in preparation to glide. The jettison stopped soon after the body was fully airborne, a point at which the animal glided for several metres before diving back into the ocean. No information on the evolution of the animal or its anatomy was given, however, it is suggested that the animal adopts this form of locomotion in order to escape from disturbances caused by boats[58].

8.0 BIO-INSPIRED TAKE-OFF APPLICATIONS

Up to now, the take-off techniques of several flying and gliding animals have been studied. The question now is how to apply that knowledge in order to get bio-inspired take-off mechanisms. To do this, it is necessary to understand the different approaches that can be taken when learning from nature. The first one is learning from the results of evolution. Here, knowledge is obtained from analysing nature's products after they have been optimised by evolution, meaning that a specific natural product or process will be copied. The second approach is related to the evolutionary process itself. In this case, evolution is studied and analysed as an optimisation method that can yield better scientific and engineering solutions. The third and final level is known as learning from the principles of evolution. This level is concerned with the understanding of the basic reasons that lead to evolutionary success, and applying them when problem solving. This will produce results that have lower risks when being implemented, are more beneficial, intelligent, robust, and ultimately safer[59].

The mentioned levels of learning are expected to manifest themselves in the following aspects [59]:

- Lower risk in new solutions.
- Greater possibility of ecological appropriateness.
- Innovative solutions that could not be obtained with non-biomimetic approaches.

From these premises, it can be concluded that aerospace design can benefit from learning from nature as there are several applications that are governed by the same physical laws and follow similar processes. It is important to note, however, that natural processes have taken millions of years to develop under a trial-and-error optimisation processes. These sometimes yield solutions that are inadequate, and thus are rapidly discarded. When developing a new technology via bio-inspiration, it would be a mistake to believe that the obtained solutions are immediately correct. As in all human-produced technologies, biomimetic innovations must be adequately tested and evaluated before being used to avoid serious consequences; humans cannot assume the same risks that nature takes in the evolutionary process[59].

Based on the previous principles, some research has been dedicated to implementing biological take-off techniques to UAVs. One of them, already described in the introduction, consists of a jumping robot with gliding capability whose design is inspired by specialised animal jumpers. Woodward and Sitti develop a similar platform that uses stored elastic energy in the limbs of the aircraft to jump into flight, in a similar fashion to jumping insects. Once it is airborne, the UAV maintains its limbs extended, turning into the required lifting surfaces that allow the vehicle to glide, concept that was mimicked from the vampire bat. The total mass of the system is below 100g[60].

Bio-inspiration has also been used for take-off of UAVs that have powered flight. Lussier, Asbeck and Cutkosky have implemented a novel mechanism that allows a fixed-wing unmanned aircraft to initiate flight from a perching position[61]. When clawed to a wall, the control system

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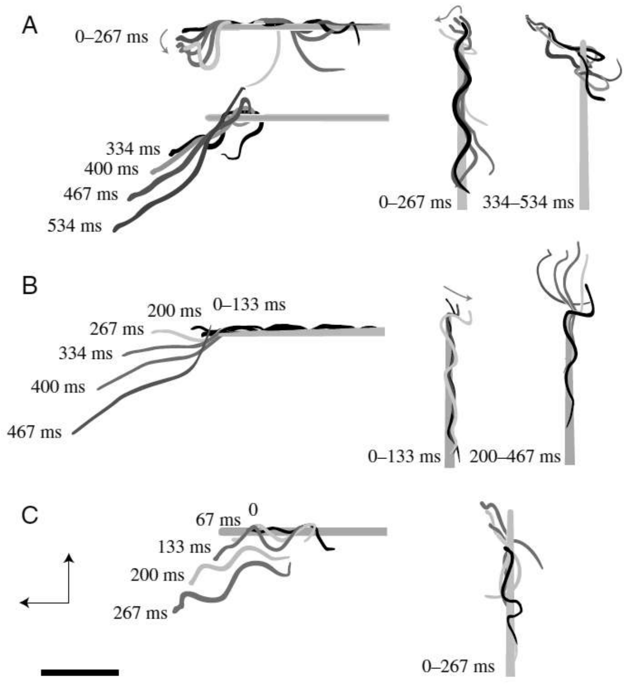

Figure 16. Different take-off techniques of the flying snake[56]. Reprinted from 'Becoming airborne without legs: the kinematics of take-off in a flying snake, Chrysopelea paradisi', by J.J. Socha, 12/06/2006, *Journal of Experimental Biology,* **209**, (17), p 3361.

retracts the claws, making the aircraft fall backwards and gain speed from gravitational acceleration, similar to the way bats do when dropping from an inverted position. While falling, the UAV pitches away from the wall until obtaining a 130° angle from the horizontal. In the process, an electric engine is started which makes the aircraft gain more speed and move away from the wall. After reaching a safe point, the controller will initiate a roll which correctly positions the aircraft so it can continue its flight.

As a final example, Siddall and Kovac propose the design principles for a MAV capable of aquatic locomotion. Their considerations lead them to a take-off system that allows the vehicle to jump into flight from an underwater starting position using a water-jet similar to the one used by the flying squid. To demonstrate the validity of this idea, such a device is constructed and shown to take a 2·6g mass to an altitude of 4·8m. The complete platform is still under design[62].

9.0 CONCLUSION

A wide range of flying animals has been studied and their take-off techniques identified. Table 2 summarises some of the most significant ones. It can be seen that these vary considerably between animal groups as well as between species. For terrestrial-dwelling animals the use of limbs to jump into flight is a common factor. Reptiles and marine animal gliders expand a thoracic structure to obtain the lifting surfaces required for flight; the ribcage in reptiles and fins in marine animals. Differences can also be seen with respect to size. The smaller flyers are seen to depend on the use

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of alternate mechanisms to initiate flight, including stored elastic energy and transient aerodynamic techniques. Animal flyers in the midrange of mass seem to depend solely on their limbs to become airborne, but as size increases the animals once again rely on alternative methods to take-off like anaerobic power and ground effect. Independently of the differences between species, however, it is evident that nature has perfected myriads of take-off strategies for animals of a wide range of mass. These masses and sizes are comparable to modern UAVs, so it should be possible to use biological inspiration for innovative unmanned aircraft design. In fact, as it has been previously shown, by taking careful consideration in the way lessons from nature are applied, several novel technologies have been implemented for UAV take-off. Jumping with stored elastic energy and gravity assisted take-off seem to be the techniques of most interest for researchers as it is easy to implement. Other more complicated strategies, however, are also being explored. Results from these developments show that nature still has the advantage over man-made ones as its high-performance is still far to be achieved. This fact, though, should serve as inspiration for researchers to further explore nature as a source for innovation; in it there is still plenty more to learn and advance.

After investigating several flying-insects' take-off techniques, it can be concluded that most, including the aquatic ones, initiate flight by jumping off the ground using their legs. In many cases, the preferred legs are those situated in the middle, although some cases show the use of the hindlimbs as well. On the other hand, the assistance of wing movement during take-off varies according to species. The butterfly was the only insect found to have a different technique for launch. The jumping technique, especially that of specialised jumpers, can offer an interesting and simple solution for UAV take-offs that do not require a runway. Although butterfly techniques are inspiring, they seem to be complicated as they require large wings with a low aspect ratio, which would be counterproductive for the cruising stage of the aircraft's flight.

Although the pterosaur take-off mechanisms mentioned above are hypothetical, they would represent a potential biomimetic application for UAV design. It seems, however, that all these launching techniques require very specific characteristics of the take-off site in order to function correctly, if applied to a UAV. This is an unwanted characteristic as it reduces the aircraft's robustness.

It has been observed that small birds have a similar take-off sequence that starts with a countermovement in which the body and legs are pulled back before jumping. When animals reach mid-size, the countermovement is replaced by a squat. Some species start the first downstroke before the feet leave the ground, while others only perform this after completing the jump. Those that do the former usually have higher contribution from the wings to the launch force, although this does not mean that it is always significant. As animals reach large sizes, they are observed to make several wing beats before actually jumping. This is accompanied by high lift configurations involving the wing and tail shape. If the birds are aquatic, it can also include a contribution from paddling feet. Furthermore, some lift could be produced during the upstroke to contribute in the airborne support of animals with high mass. One aspect that is important to highlight is that, regardless of the size, the force produced by the legs while launching into flight always has a significant effect on the take-off speed. It would be prudent to investigate if the elastic energy storage seen in specialised insect jumpers can be efficiently integrated to a bird-like system when developing a new UAV design.

Three different launch mechanisms used by mammals have been identified. The first consists of a launch from a static quadrupedal stance performed by bats; the second is a bipedal launch employed by squirrels and the third a quadrupedal launch with a running start, executed by lemurs. Translating these mechanisms into a UAV, the method used by bats appears to be the optimal option as it can offer the ability to launch vertically or horizontally from any type of surface, giving robustness to the system. Implementing two additional limbs for launch, however, may increase the complexity and weight of the system. The running start employed by lemurs would imply the need of a runway; if this characteristic were to be eliminated the result would be similar to what is seen in bats.

The take-off techniques observed in the flying snake are very restrictive as they require the animal to coil around a branch or other cylindrical object. If they were to be transferred into the design of a UAV, it would put major restrictions on the locations it would use to take off. It seems, however, that this type of take-off mechanism would not require the use of complicated mechanical systems, possibly involving only a system with enough energy storage capabilities to allow the aircraft to initiate flight.

It is interesting to observe how underwater animals have developed unpowered flight capabilities. The mechanism used by flying fish seems to be a simple concept that depends on a swim start and a propulsive device that further propels the animal once it is out of the water. This is very similar to the flying squid; instead of using tail fins to propel, they use a jet of water to get the required speed to become airborne. Both mechanisms seem uncomplicated and easy to reproduce mechanically in an UAV; however they do require a water take-off site as well as a swimming start, which would be similar to a runway.

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Table 2
Summary of take-off techniques of animal flyers and gliders

Animal	Take-off Mechanism	Wing Contribution to Take-off Force (%)	Leg Contribution to Take-off Force (%)
Fruit Fly	Six leg stance, wings extended up, counter movement followed by jump into flight using only middle legs	0	100
Dragonfly	Six leg stance, wings extended up, counter movement followed by jump into flight using only middle legs. Use of stored elastic energy	0	100
Tiger Beetle	Six-leg stance, crouches until touching the floor, exteds wings up and jumps with middle legs	0	100
Butterfly	Clap and peel mechanism	100	0
Pterosaurs	Open wings in wind	100	0
Jumps-off a cliff	0	100	
Tiny birds	Countermovement, followed by jump assisted by flapping wings	40 – 50	50 – 60
Small birds		5 – 15	85 – 95
Medium birds	Squat, followed by jump	0	100
Large birds	Flapping motion prior to squat and jump	30 – 50	50 – 70
Bats	Drops off from an inverted position into flight	100	0
	Quadrupedal launch with hindlimbs leaving the ground first	0	100
Flying squirrel	Counter movement followed by bipedal launch with its hindlimbs. Forelimbs are then stretched into wings.	0	100
Colugo	Quadrupedal launch from branch, usually from vertical position	0	100

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