Hold on tight!

8/4/16

Beetles have thousands of slender and flexible hair-like structures located under their feet. These structures enable them to adhere to any surface thanks to a miniscule quantity of liquid present on their tips. This is what the Microfluidics Lab of the University of Liege has been able to demonstrate by studying the dock beetle. The scales at play are so tiny that no consensus had been reached up to the present, either in terms of the quantity or the role played by this systematically present liquid. Using a method of interference reflection microscopy, the researchers were able to observe the deformations of these microstructures in vivo. They then verified that a simple theory based on the influence of capillary forces could predict the level of adhesion reached by the insects. They calculated the quantity of liquid necessary: it is of the order of a femolitre (the equivalent of a cube with one micrometre long sides) per structure! These results were obtained with the help of researchers from ULB and the University of Cambridge (UK) and have just been published in the ***Journal of the Royal Society Interface*** (1)

The study of adhesion mechanisms developed by animals is not new. The adhesion methods of mussels or other molluscs have been abundantly studied, so were those of the gecko, a small lizard which is characterised by an astonishing ability to rapidly climb a wide variety of surface. The gecko uses dry adhesion, a phenomenon involving the Van der Waals forces (low-intensity electric interactions which occur at short distances between atoms or molecules). This mode of adhesion has been studied for several years and has resulted in the production of glues and even small robots whose functioning is based on this principle.

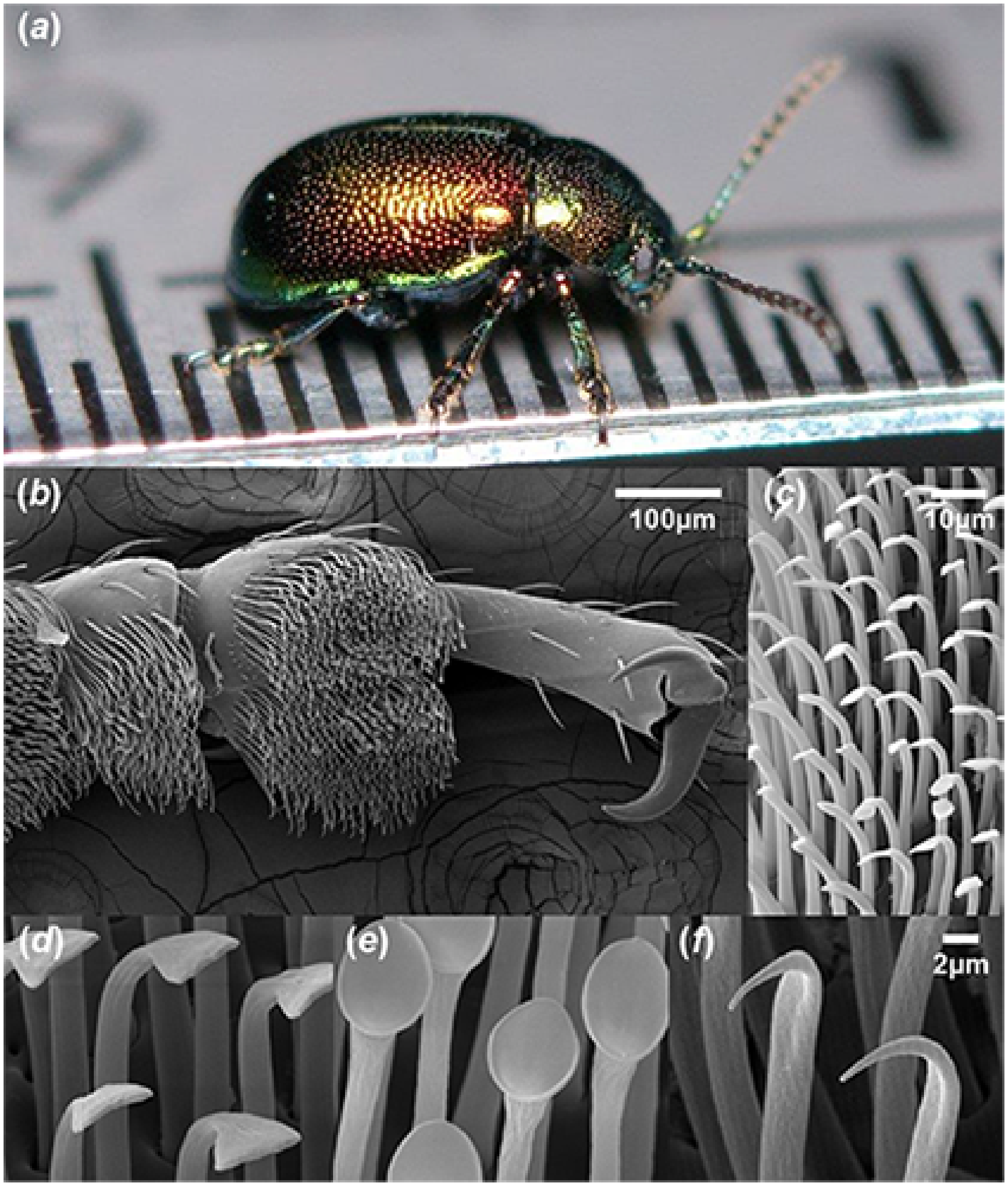
The mechanism developed by insects is very different because it is based on **capillarity**.   It is implemented in two different ways. Firstly, smooth capillary adhesion is used by insects such as ants or stick insects which adhere to surfaces by means of pads which are a few tenths of a millimetre in width and are entirely covered in liquid. Secondly, other insects developed a system known as hairy capillary adhesion. In this case the adhesion relies on very fine structures with a diameter in the order of a micron coupled with many liquid menisci instead of only one per feet such as described above. This applies to flies but also to beetles such as the ladybird for example.

The dock beetle

This second type of adhesion is studied by **Sophie Gernay**, a doctoral student in the **Microfluidics Laboratory** of the University of Liege, directed by Professor **Tristan Gilet**.

"*There are of course many ways of studying insects", explains Sophie Gernay. "In our case, we try to create physical models. We do not only observe the structures or materials but also try to examine how these correspond to physical laws and mathematical models. It allows us to simplify and get some idea of how they work with a view to reproducing in the laboratory what we have observed about the insect".*

The insect chosen by the researchers from Liege is the dock beetle *Gastrophysa viridula*, thus named because this particular plant is its only food source! About five mm in length, it shows great levels of adhesion. But more importantly, it is easily bred in a laboratory, does not need to hibernate, does not fly and is correctly documented by biologists including Professor Walter Federle's team from Cambridge, who also participated in the study. In a nutshell, this little animal is absolutely ideal for the laboratory!



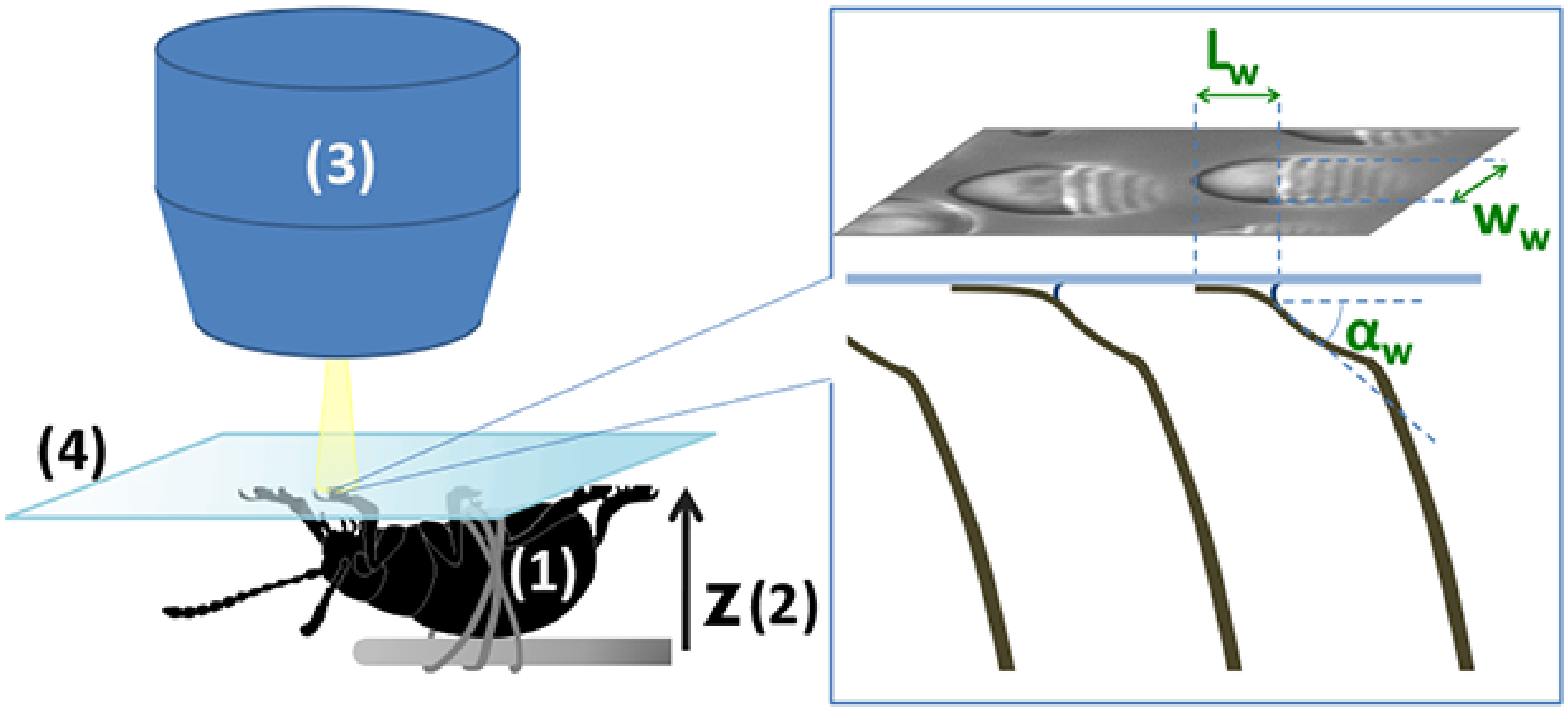
The feet of the dock beetle (photo from above, in colour) are covered at their tips by a set of hair-like structures (microscope view middle left).

A few tens of microns in length, (microscope view middle right), each of these hairs has a differentiated tip which enters into contact with the surface the insect walks on.

A miniscule amount of liquid is necessary to enable adhesion (bottom microscope view).

This liquid cannot be seen in the microscope views.

As the above microscope views show, we already knew that the feet of beetles featured flexible structures that enabled forward movement and adherence and that this was achieved, at least in part, by means of a liquid as tiny droplets had been observed. But what were the underlying mechanisms at work here? Could they be represented by an equation? These questions were answered by the researchers from Liege, beginning with a very practical difficulty: *"The issue*", remembers Sophie Gernay, *"is that the mechanism must be studied in vivo, while the living insect is moving. This is a real challenge because the field of view of the microscope is only a few millimetres, therefore the insect quickly moves away from it. We had to attach the insect to a prop and then bring the insect's foot into the field of vision via an artificial movement. We thus did not observe the natural walk of the insect, which is difficult to obtain under a microscope, but a 'robotic' movement* *(see diagram). We bring its foot in contact with the glass slide of the microscope then we detach it and that gives us images of the hair-like structures as they adhere and detach themselves".* The microscopic images show the tips of the hairs that touch the slide. There is therefore a multiplication of liquid contacts which occur during the walk because the liquid is present on the tip of each 'hair'.



The insect is attached to a prop; the researchers bring it close to the slide (4) of the microscope (3) until the hair-like structures present on the lower part of the legs come into contact with the slide and then move away from it and so on and so forth. This movement is represented in a schematic on the right side of the diagram. We can also see, (in the upper section) a microscope picture of the tips of the hairs in contact with the slide as well as the interference patterns (fringed section). Each tip is of the order of 5 microns wide.

The interest of the microscopy technique used resides in the production of interference patterns. A luminous ray is reflected on the microscope slide and the other on the hair surface at a certain distance from the slide thus producing interference patterns. These patterns allow understanding the shape of the hair when it is not in contact. "We therefore have not only a 2D image, explains Professor Tristan Gilet, but also information about the third direction and therefore the deformation of the hair just before it comes into contact with the slide. This is what made it possible to reproduce the deformation of the hairs caused by contact with the surface the insect is "walking" on and the capillary forces of the liquid it secretes".

Optimal formula

From there on, the researchers were able to design a model that takes account of the different forces involved in the movement of the hairs. Each of them was considered by the researchers as a deflected beam subjected to capillary forces that are dominant in the liquid meniscus and to the contact forces with the surface. The researchers then studied the balance between these forces. "*We were then able to deduce information about the flexibility of the hairs, their deformation by the substrate or the quantity of liquid necessary to ensure adhesion, about one femolitre (the equivalent of a cube with sides of one micrometre) per structure",* explains Sophie Gernay.

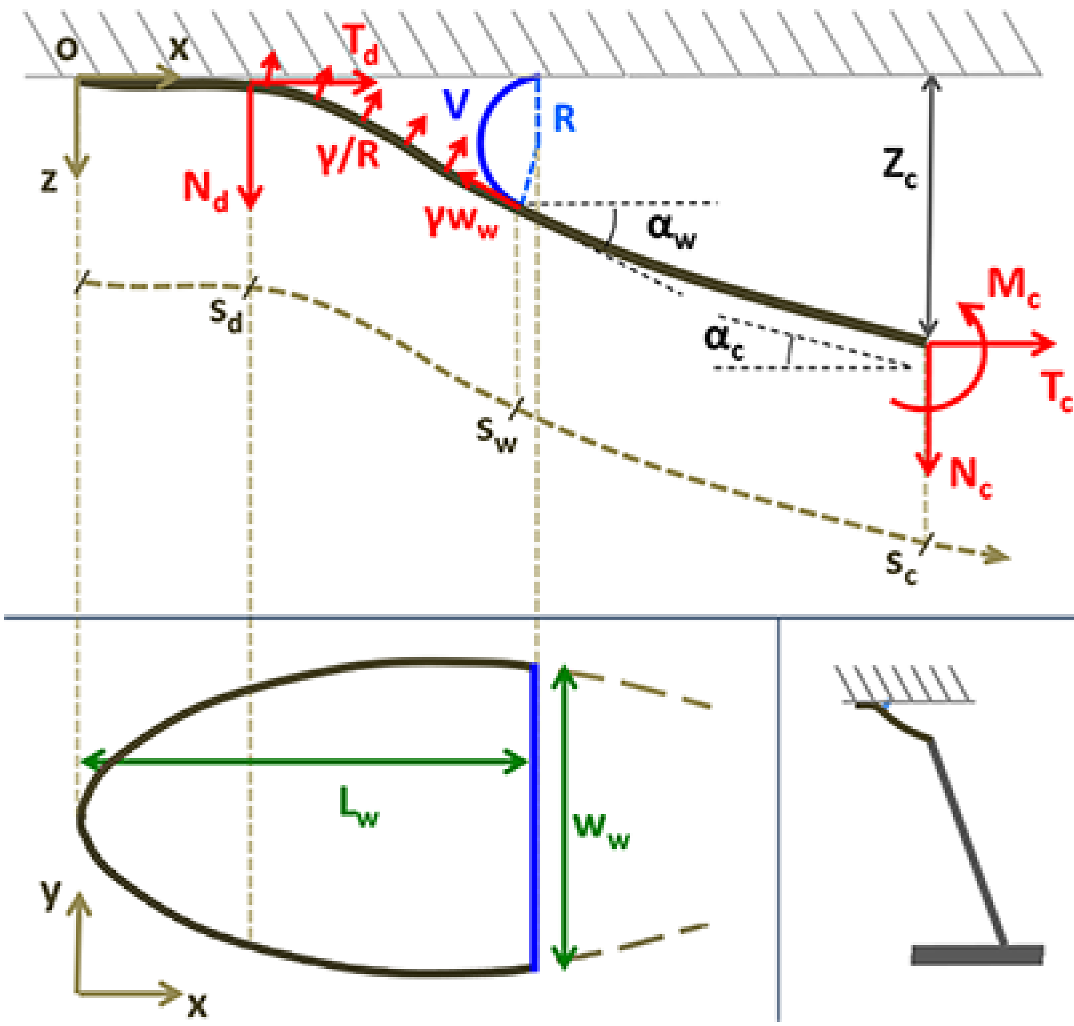


Diagram of the forces applied to the hair tips (dark grey line) located on the feet of the insect.

The liquid mensicus responsible for the capillary forces is the small volume located to the left of the blue line and indicated by the letter V.

This model clearly demonstrates that in addition to the capillary forces, there are also 'dry' contact forces: to the left of the liquid wedge, the hair directly touches the surface without any liquid between the two.

The diagram of the forces shown here above also brings a solution to another problem: It is clear that the liquid is not found everywhere on the pad but mainly in a small wedge, while part of the contact is practically dry. Up to the present, scientists could not reconcile the fact that there was a liquid meniscus and that friction forces could be observed. The model designed by the researchers from Liege shows that these two types of forces actually co-exist. The formula developed by the insect is optimal since the capillary forces and the liquid enable it to adapt much better to the unevenness of surfaces than if there were only solid to solid friction forces. *"The gecko also uses fibrillar structures in the form of hairs"*, explains Tristan Gilet. *"But there is a fundamental* *difference hidden obscured by the sensationalism of the research done on it: the structures of the gecko are arranged in hierarchical form, the smallest ones are as small as a nanometre. The nanohairs of the gecko indeed need to be small enough to come into very close contact with even the slightest bump on the surface. The fact that there is no liquid to "fill in the gaps" has forced the gecko to develop extremely fine surfaces. The insect, on the other hand, has a much more promising strategy from the engineer's point of view because manufacturing hierarchical structures such as those of the gecko is complicated and they are fragile".*

Bio-inspiration

This is the whole point of the research in addition to gaining an understanding of the phenomenon: being able to design a mechanism which can adhere strongly as well as detach rapidly (the insect takes dozens of steps per second and can support up to ten times its own weight!). The goal would be to use such a robotic tool in the field of micromanipulation. Currently the smallest manufactured electronic components are about 200-400 microns in size, not due to a fabrication limitation, but because smaller objects would be impossible to handle. On the other hand insects daily attach and detach structures that are only 5 microns wide (their hairs). What enables them to do so is amongst other? the presence of liquid and precise leg movements that the researchers would like to reproduce with a bio-inspired tool.

This will be the focus of future research in the Liege and Brussels laboratories. A joined project supported by the FNRS aims to study how the liquid is secreted and channelled towards the hairs and how this is optimized by the animal. Indeed, as the insect loses liquid at each step it has to renew it . This represents a lot of energy so it must be used frugally. The researchers therefore suspect that the dock beetle has developed movements aimed at energy saving and moves in such a way that it loses? a minimal amount of liquid!

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(1) *Elastocapillarity in insect fibrillar adhesion, Sophie Gernay et al.* Journal of the Royal Society Interface.