MECHANICS OF VENUS' FLYTRAP CLOSURE

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Summary   We investigate the snapping closure of the carnivorous plant Venus flytrap (*Dionaea muscipula*), which exhibits one of the fastest motion in the vegetable kingdom (typically 100 ms). From experimental measurements using a high-speed camera, we propose that the very fast closure of the trap results from a mechanical instability, based on the change of curvature of the leaves. A simple poroelastic model for the snapping of a spherical cap is written, which allows to explain the main experimental observations.

INTRODUCTION

The quick, snapping closure of the carnivorous plant Venus flytrap (*Dionaea muscipula*) was described by Darwin as 'one of the most wonderful [plant] in the world' [1] and there has been much speculation as to what is the underlying mechanism. Rapid closure ($\sim 1/10$ second) of the trap is initiated by the stimulation (by an insect or any mechanical stimuli-see figure 1) of trigger hairs acting as mechanosensors. Many studies have focused on the response of the trigger hairs to stimuli and shown that upon stimulation an action potential spreads quickly across the leaves. However, the mechanism of the rapid closure itself is still badly understood and is the object of contradictory explanations [2]. Here we aim to reconsider the mechanism of Venus' flytrap closure from a mechanical point of view and ask whether such a rapid motion may results from an elastic instability, by analogy with the buckling of plates and shells.
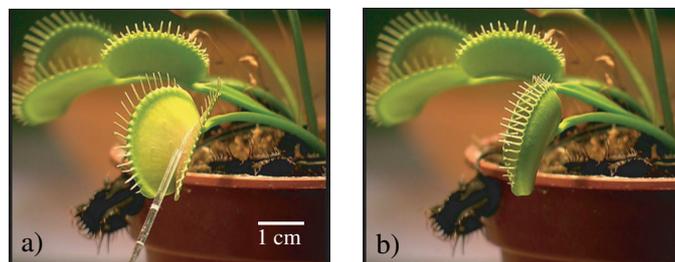

Figure 1. Pictures showing the carnivorous plant 'Venus flytrap' in the open (a) and closed (b) states. In (a) the plant is in the process of being triggered by a tiny glass rod. Note the change of curvature of the lobes before and after closure.

EXPERIMENTS

We have first studied the dynamics of the closure using a high-speed camera (400 frames/s). Small fluorescent dots are painted on the external face of one leaf of the trap (figure 2a) and the closure is filmed simultaneously under two different view angles using a set of mirrors. It is then possible to reconstruct the full 3D shape of the leaf using triangulation. Figure 2a presents a typical sequence of the leaf dynamics during the trap closure. As already noted by Darwin, the leaf is curved outward (convex) in the open state and curved inward (concave) in the final state. The motion itself is characterized by a phase of rapid acceleration ($\leq 1/10$ sec.), which corresponds to the change of sign of the mean curvature, followed by a phase of damping of the system as shown in figure 2b (left). In plate mechanics, changes of curvature are usually associated to differential strains across the thickness. For Venus' flytrap closure, it has been shown that the curvature results from an extension of the outer surface while the inner surface remains unchanged [2]. Using microscopy techniques, we have precisely measured the strain field of the outer surface between the open state and the closed state: the direction of extension (max. 10 %) is observed to occurs mainly in the direction perpendicular to the hinge of the trap (called transverse direction in the following), which corresponds to the main direction of the cells. This suggests that closure is driven by the change of natural curvature of the system only in this direction. We have confirmed this result by cutting in a closed leaf thin strips in different directions. One observes that strips cut in the transverse direction keep their inward curvature whereas strips cut in the longitudinal direction bend spontaneously outward, i.e. the natural curvature is this direction is the same as in the open state.

MODEL

From the experimental results, we propose the following mechanism for the Venus' flytrap closure. Upon stimulation, the closed state becomes the stable state of the system due to the change of the natural curvature in the transverse direction. We
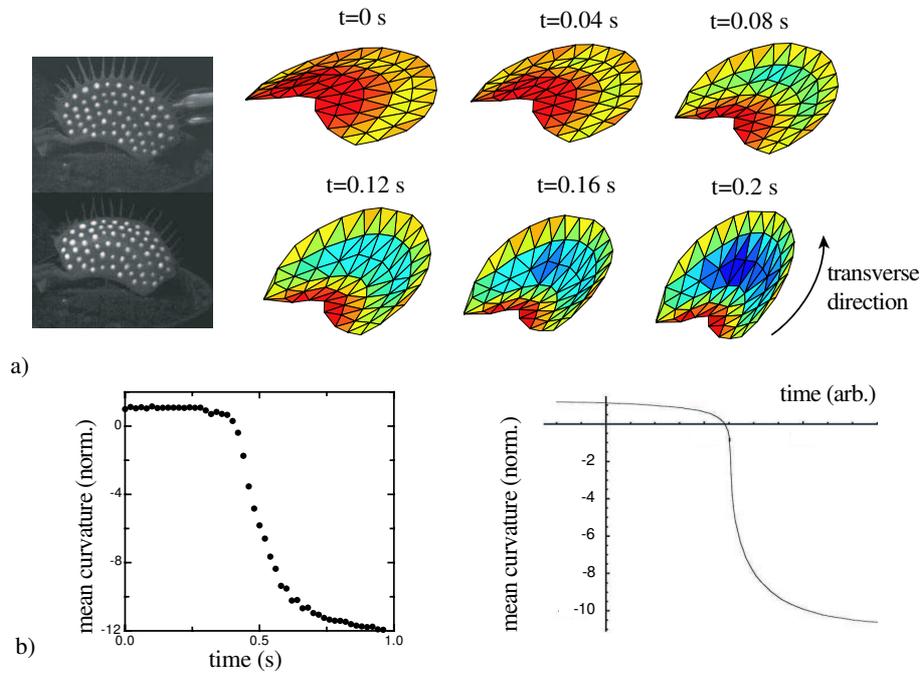
Figure 2. a) Left: pictures of the open and closed states showing the experimental method. Right: 3D reconstruction of the dynamics of the trap closure. The colour gives the local mean curvature (red: convex, blue: concave). b) Mean curvature as a function of time. Left: experiment, right: model.

do not pretend here to explain this natural curvature change, which involved a complex physiological process. However, in order to reach the stable closed state the system has to overcome an energy barrier, which corresponds to the stretching elastic energy needed to change the curvature of the leaf (more precisely the Gaussian curvature). Once this barrier is crossed, the system snaps via a buckling-like instability, which is damped by the diffusion of water inside the leaf. This mechanism is supported by observations of highly curved traps for which the delay between the triggering and the closure may exceed 30 seconds before a violent snap occurs. In order to test the proposed mechanism, we have written a simple mechanical model of the snapping of a poroelastic spherical cap. The elastic energy of the leaf E_{el} involves a bending term and a stretching term, and the control parameter is the natural curvature in the transverse direction. A first result is that there exists a critical geometrical parameter $\alpha = L^4 \kappa^2 / 3t^2 \sim 1$, where L is the size of the leaf, t its thickness and κ its initial curvature, above which the system undergoes an elastic instability and snaps from one state to another. Note that for a typical leaf $\alpha \sim (1\text{cm})^4 (0.2\text{cm}^{-1})^2 / 3(0.1\text{cm})^2 \sim 1$, which roughly corresponds to the smooth/snapping transition. To model the dynamics during the snap, we use the fact that the system is overdamped and balance the variation of energy to the poroelastic dissipation: $dE_{el}/dt = P_d$. The time scale of the snap is then controlled by the poroelastic time $\tau \sim t^2/(EK)$ [3], where E is the Young modulus and K is the water permeability. A typical dynamics predicted by this model is presented in figure 2b (right). For realistic parameters: $E \sim 10$ MPa, $K \sim 10^{-12}$ m^{2}Pa^{-1}s^{-1}, one obtains $\tau \sim 0.1 - 1$ sec., which is consistent with the experimental observations.

CONCLUSION

Our model of Venus' flytrap closure implies that the closure is actually composed of an 'active' part, which builds the stress necessary to overcome the stretching barrier, followed by an elastic 'passive' snapping of the trap. It is interesting to note that this transition occurs in the biological range perhaps implying something about the optimality of the design of the Venus flytrap. On the one hand the plant wants to have a violent and fast snap to catch insects, while on the other hand a violent snap requires more energy to be put before the snap occurs, which may cause a longer period of delay before the snap occurs. In this study, we have only considered the mechanical part of the closure and not the 'active' process by which the natural curvature change. An important future work would be to measure some physiological parameters at the cell scale, such as turgor pressure, in order to better understand this 'active' process and other rapid motions in plants [4].

References

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