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Actual determination of center-of-buoyancy in *Nautilus*.

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Abstract A new experimental method is presented in obtaining the center-of-buoyancy of *Nautilus*, and its physical reasoning is explained. Before experiment a model of *Nautilus* of uniform density is prepared, the shape of which copied exactly the lateral halves. The experiment starts with finding its balance-line with to explore on the flat plane corresponding to the animal symmetry. After the placement of the model on two isolated sticks, these were slowly brought close to each other. Ultimately these adjoin at the balance-line. Finding additional two balance-lines on the same plane will result in an intersection point, which corresponds to the center-of-gravity of the model. The intersection corresponds to the center-of-buoyancy of *Nautilus*. The validity of the present method is confirmed using another model, the center-of-buoyancy of which is able to explore theoretically.

Keywords: *Nautilus*, center-of-buoyancy, center-of-gravity, plaster model, uniform mass, two sticks

Introduction

One of key prerequisites in evolutionary studies is the understanding of animal locomotion that varied along the evolutionary change in animal forms. In understanding the form-locomotion relationship, it is inevitable to detect how the form and its operation of organisms reflect the physical variables such as gravity, velocity and the surrounding medium condition. A living marine ectocochleate cephalopod, *Nautilus*, is one of the eye-catching targets for locomotory studies because of its unique drifting movement (Chamberlain, 1987).

The outer conchs of *Nautilus* consist of a body chamber and a gas-filled chambered phragmocone to maintain neutral buoyancy. The driving force of the movement of *Nautilus* animal is the jet propulsion generated by momentary contraction of the hyponome that faces anterior-forward, which in turn brings the animal to backward direction. This results in the animal rocking locomotion, because the jet propulsion acts perpendicular to the line of action of buoyancy (*e.g.*, Jacobs and Chamberlain, 1996). This type of locomotion is mainly due to the force of restitution which was obtained by two centers of gravity and buoyancy, as is similar to the problem of ship hydrostatics (*e.g.*, Rawson and Tupper, 2001). In theoretical morphology point of views, number of studies yet reached to a firm conclusion on account of the position of two centers (*e.g.* Trueman, 1941; Raup & Chamberlain, 1967; Okamoto, 1996). Especially experimental study is few, probably because of the complex three-dimensional animal form to deal with. Below is the method we have introduced to obtain the centers of buoyancy of the *Nautilus* animal.

The concept of buoyancy

When an object is submerged in viscous fluids, its surface suffers more or less the pressure from ambient fluids. Since a lower part of the object suffers higher pressure, the upward force acts the object afloat in the fluids, so called buoyancy. The net buoyancy F is defined as $F = \rho Vg$ where ρ is the density of ambient fluids, V is the volume of the object and g is the acceleration due to gravity (Fig. 1). The force of buoyancy is thus equivalent to the weight of the displaced fluids of the object, *i.e.*, the volume of the object, but not the weight and the density of the object (*e.g.*, Hecht, 2005). Practically in obtaining the center-of-buoyancy of *Nautilus* animal, it is required in advance to replicate accurately the animal form using homogeneous material. Due to the uniformity of the model mass, the center-of-buoyancy of the animal can be taken as the center-of-gravity of the model.

Procedure to determine the center of buoyancy

Next step is to determine the center of buoyancy as the center-of-gravity out of the homogeneous model. When an

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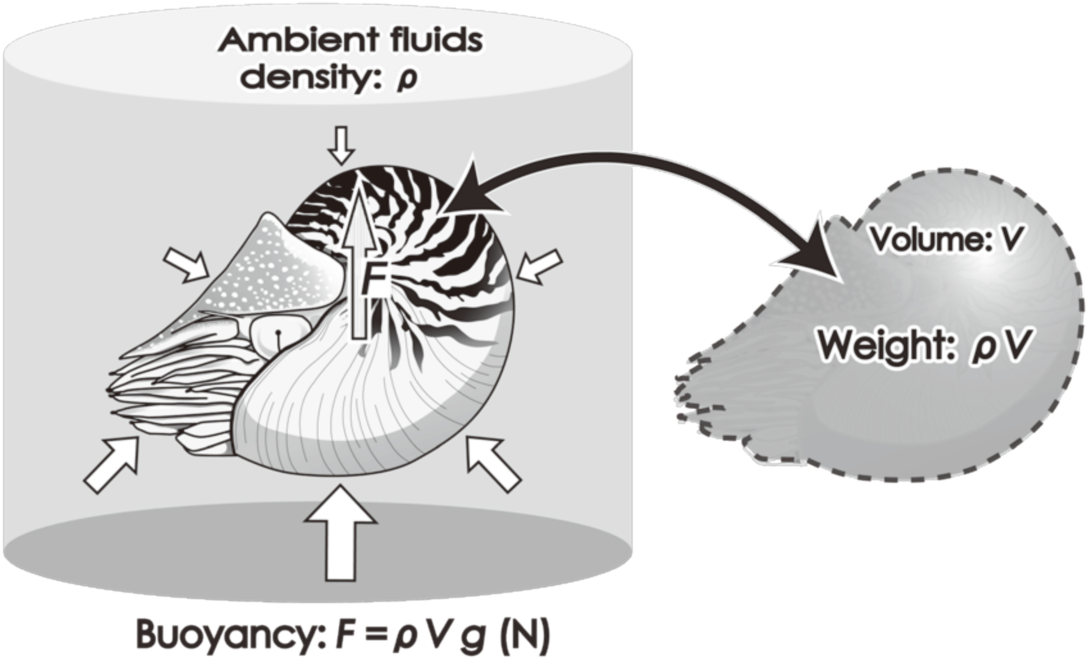

Fig. 1 Schematic description of parameters of *Nautilus*'s buoyancy. Buoyancy F, which is defined by the multiplication of the density of ambient fluids, the volume of the object and the acceleration due to gravity are represented by ρ, V and g, respectively. White arrows mean ambient fluids pressure. Grey arrow means buoyancy F, which brings the animal vertically upward. The magnitude F is equivalent to the weight of the displaced fluids of the animal form.

object in symmetric form has uniform density, the position of the center-of-gravity always lie on the symmetric line or plane. We therefore prepared the model as to the lateral half of the animal with the flat median plane, and its center-of-gravity was projected on the median plane, termed here as CGM (the center of gravity of model; CGM).

For determining CGM on the median plane, we adopted the method that is based on the frictional and normal forces on two movable supports. Prior to the determination, the smooth median plane is placed on two sticks so as to act as fulcrums of parallel lines. In this configuration, inferred CGM is located in the area between. When the moment is applied on two sticks to make them closer to each other, the movement of stick that has a lower maximum static friction precedes that of one another. Physically, frictional force f is calculated as $f = \mu N$ where μ is the friction coefficient and N is the normal force. Since the normal force N is upward force so that the fulcrum supports the overlying model, it increases toward the CGM. If the kinetic friction of moving stick exceeds the static friction of one another, the former stick stops and alternatively the latter one starts to move at the same time. Slowly bringing the two sticks close to each other finally results the confirmation of the balanced-line of the model, in which CGM is situated (Fig. 2; A to C).

The procedure is repeated at least three times, each of which differs in horizontal angle of stick directions around 60 degrees to the previous experiment (Fig. 2; D). As the CGM of the model must lie along all the balance lines, it is obvious that CGM is at the intersection of three lines (Fig. 2). The position of the point thus represents the center of buoyancy of *Nautilus* animal.

Reconfirming the method introduced in this study

Finally, we adopted the method introduced in the preceding section into the L-shaped plaster object to determine its center-of-gravity (Fig. 3; **Gcal**). The object is in the form of two rectangular parallelepipeds, bounded together. One of the parallelopipeds is 7 cm × 7 cm × 3.6 cm, and the other is 7 cm × 3.5 cm × 2.3 cm. As the L-shaped object is in uniform density, we documented the projection of the center-of-gravity on the L-shaped plane of the object by calculation prior to the experiment. The outcome of the actual determination is identical to the one in the calculation, thereby proving the effectiveness of this technique. The calculated projection is explained in the following procedure.

Firstly, the L-shaped plane is divided into two rectangles. Since there are two ways of dividing, we get two types of rectangle combination. The two diagonal intersections of each combination are connected by a straight line (Fig. 3A, G1 to G2; 3B, G3 to G4). The intersection of the two straight lines for the two rectangle combinations is the

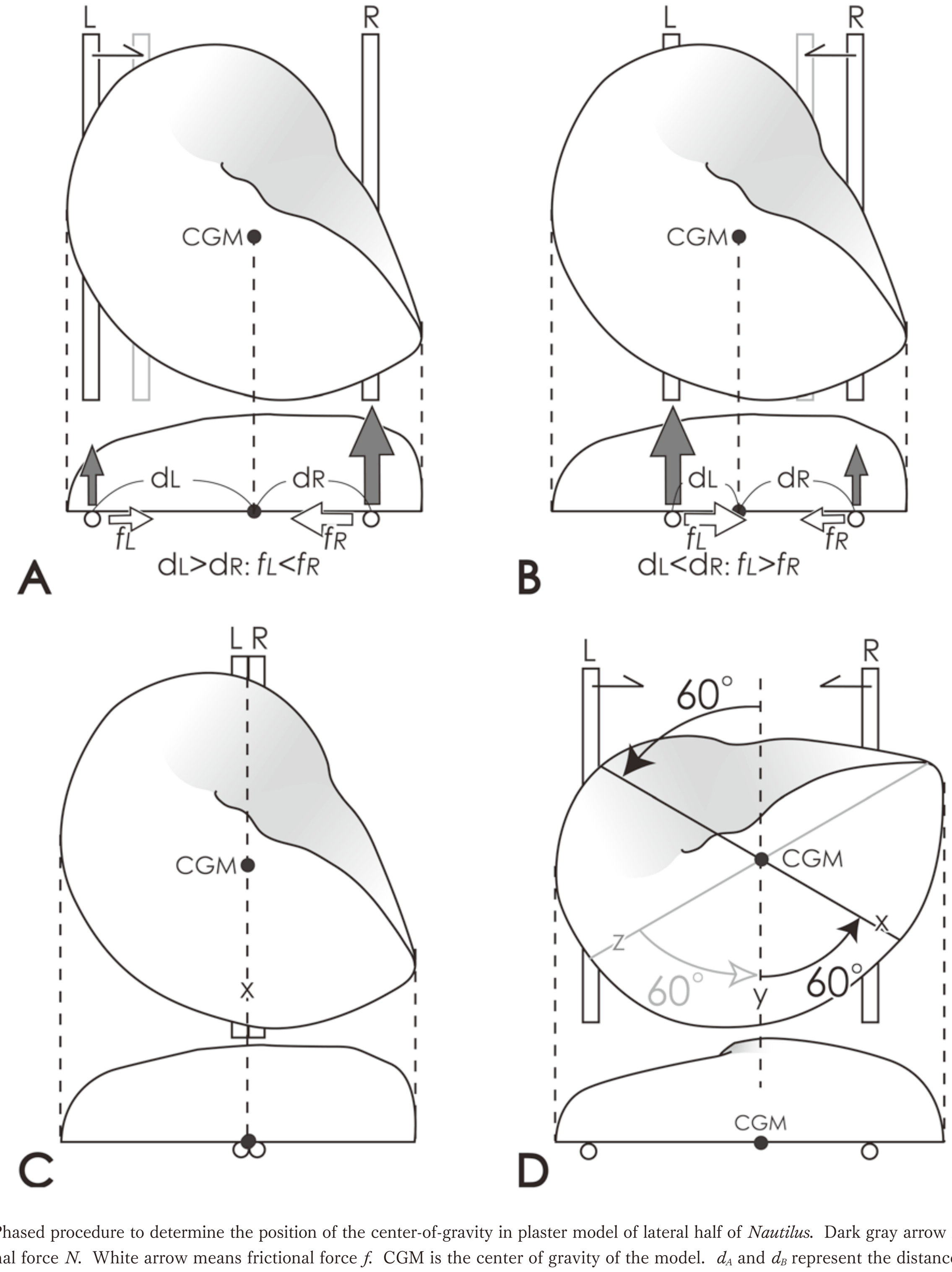

Fig. 2 Phased procedure to determine the position of the center-of-gravity in plaster model of lateral half of *Nautilus*. Dark gray arrow means normal force *N*. White arrow means frictional force *f*. CGM is the center of gravity of the model. d_A and d_B represent the distance from CGM to stick L and R, respectively. (A) When d_L is longer than d_R, f_L becomes smaller than f_R that ultimately brings stick L movable and *vice versa* (the condition shown in B). (C) A joined two sticks on the balanced line (x) where CGM should be situated. (D) Three times repetition of phases shown in A to C results in the intersection of three balance lines (x, y and z), which represents the center-of-gravity on the medial plane.

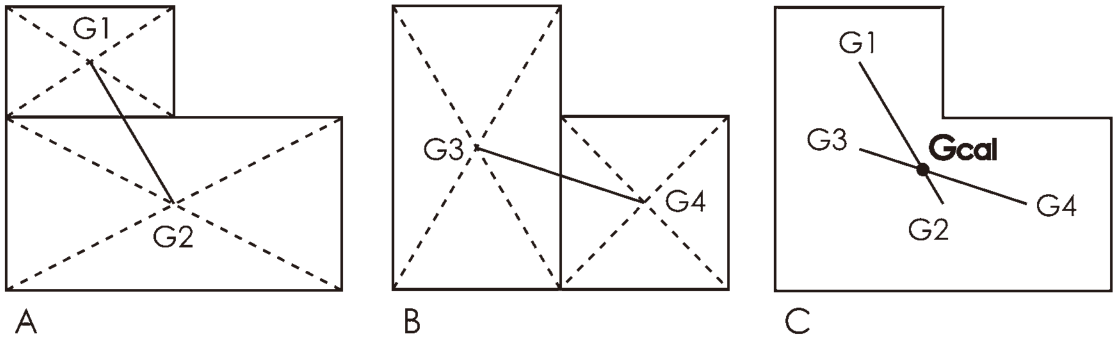

Fig. 3 The projection of the center-of-gravity of the L-shaped plane is calculated from the position of the center-of-gravity of rectangles that constitute the shape. G1, G2, G3 and G4 are the center-of-gravity of each rectangle. **Gcal** is the center-of-gravity of the L-shape plane.

projection of the center-of-gravity on the L-shaped plane (Fig. 3C; **Gcal**). The processes and result of the actual determination adopting the method herein is shown in Figure 4. Since the result in the calculation (Fig. 3; **Gcal**) and in the actual determination (Fig. 4; **Gx**) coincides with each other, it is adequate to follow the method introduced herein to determine the center-of-buoyancy in *Nautilus* as well as fossil chambered cephalopods.

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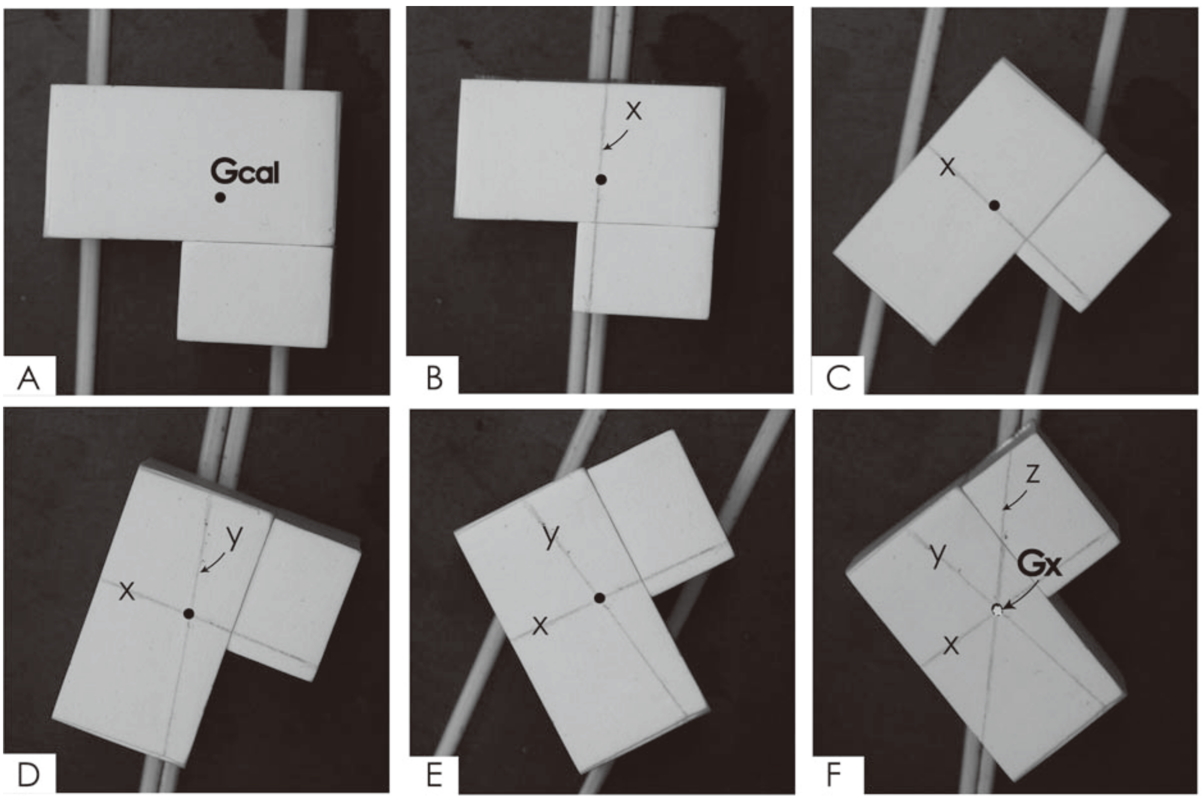

Fig. 4 The projection of the center-of-gravity of the L-shaped plaster object was determined (**Gx**). **Gcal** is the predicted position of the center-of-gravity required in calculation as shown in Fig. 3. Adjoined two sticks on the balanced line (x, y and z) where the projection should be situated. The intersection of the three balance lines is the projection of the center-of-gravity on the L-shaped plane (**Gx**). The position of **Gx** and **Gcal** coincides with each other.

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