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ABSTRACT
In this paper, we report a novel experimental study to examine the response of a soft capsule bathed in a liquid environment to sudden external impacts. Taking an egg yolk as an example, we found that the soft matter is not sensitive to translational impacts but is very sensitive to rotational, especially decelerating-rotational, impacts, during which the centrifugal force and the shape of the membrane together play a critical role in causing the deformation of the soft object. This finding, as the first study of its kind, reveals the fundamental physics behind the motion and deformation of a membrane-bound soft object, e.g., egg yolk, cells, and soft brain matter, in response to external impacts.

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I. INTRODUCTION

Soft matter in a liquid environment widely exists in nature. Some examples include the soft brain matter that is bathed in the cerebrospinal fluid (CSF) inside the hard skull, a soft egg yolk that is bathed in the fluidic egg white inside the eggshell, and red blood cells in our circulation system. Deformability is one of the most important features of soft matter. For instance, the deformability is an indicator to decide whether red blood cells should be kept in the circulation system or cleared by the spleen. Traumatic brain injury, on the other hand, is caused by large brain deformation as the head is exposed to a sudden translational or rotational impact.

The deformation of soft matter in a fluid environment is a result of a series of fluid–structure interactions. Different flow conditions and configurations could cause different types of deformation. Extensive studies have been performed to examine the deformation of soft capsules under shear flow, spinning flow, or through small channels. In many applications, an active breaking of soft matters is needed. Hence, a significant amount of work has been done to examine the break-up mechanism of droplets and bubbles in a micro-T-junction or a cross-junction, in a pre-mix membrane, through a narrow constriction or a permanent obstruction. These studies demonstrate that large deformation of soft capsules in a liquid environment is induced by a fast change in the fluid field, such as the velocity gradient (e.g., the shear flow and the spinning flow) or velocity boundary conditions (e.g., sudden change in the flow pathway).

For a soft matter bathed in a liquid environment and enclosed in a rigid container, an interesting yet fundamentally important question is “How can one damage or break the soft matter without breaking the container?” To answer this question, we did a simple experiment using a Golden Goose Egg Scrambler, in which we used rotational forces to scramble an egg inside of the eggshell. It is puzzling to notice that the egg yolk was deformed and broken while the egg shell remained intact. This experiment inspired us to study the fundamental flow physics governing the motion and deformation of the soft matter in a liquid environment, using an egg yolk as a sample system. The insights obtained from this study could shed some light on the understanding of problems such as concussive brain injury.

II. EXPERIMENTAL SETUP

To damage or deform an egg yolk, one would try to shake and rotate the egg as fast as possible. Hence, two experimental setups,
a translational impact setup, as shown in Fig. 1(a), and a rotational impact setup, as shown in Fig. 1(b), have been developed.

The egg yolk and the egg white used in the experiment are obtained from fresh eggs bought from a grocery store. As our goal is to deform the egg yolk without breaking the eggshell, the eggshell is replaced by a transparent rigid container. For the translational impact, a 1.77 kg hammer [(c) in Fig. 1(a)] falls freely along a vertical guide rail [(b) in Fig. 1(a)] from 1 m above the container to create the impact. At the bottom, a spring base [(d) in Fig. 1(a)] allows the container to move vertically. The acceleration of the container was measured by an accelerometer [Analog Devices, model ADXL 1004Z, with a bandwidth of 24 000 Hz, (e) in Fig. 1(a)]. For the rotational impact setup, the container [(a) in Fig. 1(b)] is connected to an electric motor [(g) in Fig. 1(b)] that drives the container to rotate. The motion of the container is monitored and controlled by the motor controller. The motion and the deformation of the egg yolk are recorded through the transparent container by a high-speed camera (Phantom® Miro® C110) with a sample rate of 1000 fps.

### III. EXPERIMENTAL RESULTS

First, the densities of the egg yolk and the egg white of six eggs have been obtained by using a graduated cylinder and a scale to measure the volume and the weight. According to the calculation, the density of the egg yolk is 1.045 ± 0.020 g/ml, while the density of the egg white is 1.033 ± 0.014 g/ml. It confirms that the density of the egg yolk and egg white is very close to each other.

The egg yolk is enclosed by a thin, fragile, and soft membrane, the stretching of which is associated with the deformation of the egg yolk. Hence, it is crucial to evaluate Young’s modulus of the membrane in order to understand the stress it experiences during the deformation process. The egg yolk membrane was carefully peeled off from a fresh egg yolk and stored in a petri dish filled with water, as shown in Fig. 2(a). The water is used to allow the membrane to naturally spread on the surface without any strain before the test. A tensile test has been performed using a Psylotech µTS test system. As the membrane is very soft and fragile, it was held on the water surface during the test. Five membrane specimens were stretched with a constant velocity of 0.1 mm/s, Fig. 2(b), until the membrane was broken, Fig. 2(c). The tensile force and the stretched length were recorded. Here, we choose a low velocity to achieve a quasistatic state. It should be noticed that if the stretching velocity is too high, the measured elastic modulus will increase correspondingly. A Scanning Electron Microscope (SEM) was used to measure the thickness of the membrane, Fig. 2(d), which indicates that the average thickness of the membrane is 3 μm. The width of the membrane sample is known, which, together with the thickness, provides the measurements of the cross-section area. Hence, the stress of the membrane is obtained. Figure 2(e) shows the stress–strain relationship obtained in five testing cases. It shows that the membranes were linearly stretched before the maximum strain was reached. The membrane began to break as the strain was getting close to its maximum value. The slope of each curve provides the value of Young’s modulus, $E = 2.64 ± 1.45$ MPa, and the average strain when the break happened is 0.46 ± 0.14. It is shown in Fig. 2(d) that the membrane thickness is not uniform, which might bring a relatively high variance in the measured physical properties.
FIG. 3. (a) Reactions of the egg yolk under the translational impact. The shell was impacted by a hammer to achieve the translational acceleration up to 600g, \( g = 9.8 \text{ m/s}^2 \). (b) Reactions of the egg yolk under the rotational acceleration impact. The container was set to rotate instantaneously from 0 rad/s to 400 rad/s within 1 s, after which it was maintained at the constant angular velocity of 400 rad/s. (c) Reactions of the egg yolk under the rotational deceleration impact. The rotation speed of the container was reduced sharply from 400 rad/s to 0 rad/s within 1 s to create a deceleration impact on the egg yolk.

For the translational impact, the acceleration of the container was up to 600g, \( g = 9.8 \text{ m/s}^2 \). As shown in Fig. 3(a), the yolk had almost no deformation. This observation is quite surprising and counter-intuitive because one expects translational impacts would lead to the damage of the egg yolk. The reason behind this phenomenon is that the density difference between the egg yolk and the egg white is very small. Besides, both the yolk and the egg white are incompressible. Therefore, no relative motion was observed, and the whole container moved as a rigid body.

Two types of rotational impacts, acceleration and deceleration, were considered. For the accelerating-rotational impact, the container was set to rotate instantaneously from 0 rad/s to 400 rad/s within 1 s, after which it was kept at the constant angular velocity of 400 rad/s to establish a steady-state. It is shown in Fig. 3(b) that the yolk started from a spherical shape was subsequently compressed slightly in the radial direction at the center and hence stretched horizontally. Within 2 s, it was changed into an ellipsoid. Then, with a constant angular velocity, the egg yolk maintained a stable shape as the one shown in the last panel of Fig. 2(b) for several minutes. The balance between shear stress, the centrifugal force, and the tension force in the membrane determines the slight deformation of the egg yolk.

The rotational speed of the container was then reduced sharply from 400 rad/s to 0 rad/s within 1 s to create a deceleration impact on the egg yolk. The most intriguing result is obtained in the deceleration impact process, where the egg yolk experienced a significant deformation soon after the container started decelerating, which is shown in Fig. 3(c). During the process, the yolk was tremendously squeezed horizontally and expanded radially in the center region. This large deformation obviously could cause severe damages to the yolk. At the end of the test, when the rotation is stopped, the deformed egg yolk slowly resumed its original spherical shape [i.e., Fig. 3(b) at \( t = 0.0 \text{ s} \)], which takes ~1 min.

To understand if the phenomenon observed in Fig. 3 is unique to the egg yolk, a biomaterial, we have performed a control experiment using a non-biomaterial. Following a spherification technique,\(^{33}\) we made a soft capsule where a calcium lactate solution is enclosed by a thin spherical membrane made of calcium alginate. To visualize the shape of the capsule, some boron nitride powder was added to the calcium lactate solution. The capsule was bathed in water and exposed to a sudden acceleration/deceleration rotational impact. Similar deformation was observed. It confirms that the dominant mechanism leading to the deformation of the soft matter in a liquid environment is a result of mechanical forces instead of biological responses. We also noticed that the deformation of the calcium alginate capsule is slower and less severe compared to that of the egg yolk. This is because the water is less viscous than the egg white, and the calcium alginate membrane is thicker than the egg yolk membrane. The videos of the egg yolk response to three types of impacts and the calcium alginate capsule response to the rotational acceleration/deceleration can be found in the supplementary material.

To quantify the membrane stretch during the experiments, we estimate the average strain and stress of the yolk membrane. In the beginning, the yolk was in a spherical shape, as shown in Fig. 3(b), at \( t = 0.0 \text{ s} \). Its strain was zero. When the yolk began to deform, its total volume remained unchanged due to incompressibility. Hence, the surface area of the membrane would change during the acceleration/deceleration process. The change in the total surface area with respect to the initial surface area is the average strain of the membrane. Because the yolk established an axisymmetric shape as it picked up the rotational speed during the acceleration phase and remained to be axisymmetric during the deceleration phase, one could obtain the total surface area of the yolk at different instants by surface integration. Figure 4(a) shows the coordinate system and a representative cross-section of the yolk obtained from Fig. 3. The
geometry is axisymmetric about the x-axis. The highlighted region represents an infinitesimal element, which is treated as a frustum. The surface area of this infinitesimal element, $dS$, is

$$dS = \left[ \pi y + \pi (y + dy) \right] \sqrt{dx^2 + dy^2}. \tag{1}$$

By integrating, the total surface area, $S(t)$, a function of time, could be obtained. Then, the average strain of the membrane, defined as $\varepsilon = (S(t) - S_0)/S_0$, is obtained. Here, $S_0$ is the initial surface area of the yolk, as shown in Fig. 3(b), at $t = 0.0\, s$.

The change in the average strain and stress during the deceleration process is shown in Fig. 4(b). The $y$-axis on the left represents the strain, while the $y$-axis on the right is the average stress obtained from multiplying the strain with Young’s modulus. It is shown in Fig. 4(b) that the strain and stress decreased first as the yolk was squeezed in the axial direction into a more spherical shape, corresponding to Fig. 3(c), at $t = 0.2\, s$. Then, as the yolk was deformed more seriously in the axial direction and deviated from the spherical shape, the strain and the stress increased rapidly, corresponding to Fig. 3(c), at $t = 0.4\, s$ and $t = 0.6\, s$. With the further decrease in the angular velocity, the yolk tends to restore its original shape. Therefore, the strain and stress decreased again. The maximum strain is 0.25. According to the tensile test shown in Fig. 2(c), the membrane is still in the elastic region. The maximum stress in the membrane, $\sigma_{\text{max}} = 0.66\, \text{MPa}$, is then obtained for the deceleration process. Since the deformation is relatively small during the acceleration phase, we focus our discussion on the average strain and stress in the deceleration process. The approach developed herein is to provide a rough focus for the discussion on the average strain and stress during the deceleration process, while the y-axis on the right is the average stress obtained from multiplying the strain with Young’s modulus.

IV. DISCUSSIONS

Such an unexpected observation inspires us to investigate the mechanism behind it further. To understand the fundamental physics causing the large deformation of the egg yolk in the deceleration impact process, we would like, as a first try, to examine the response of the velocity and the pressure field when the motion of the outer shell is rapidly altered. As shown in Fig. 5(a), an impermeable spherical membrane is placed at the center of a cylindrical container that is filled with liquid. The container can rotate with angular velocity $\pm \omega_0$. The membrane is very thin, and thus, there is no pressure gradient across it. It divides the container into region I and region II. As an approximation, the membrane uniformly shares the same angular velocity, which is determined by the torque caused by the shear stress on both sides of the membrane. A cylindrical coordinate system $(r, \theta, z)$ is shown in Fig. 5(a). The container has a radius of $R_c$ and a length of $2L$. The spherical membrane has a radius of $R$. Because the problem is symmetric about the $r$ axis and axisymmetric about the $z$-axis, only the first quarter is quartered.

It is reasonable to assume that the fluid velocity in the radial and axial directions is much smaller than that in the circumferential direction. Moreover, because we are mainly interested in the mechanism that causes the deformation of the egg yolk, we chose a small-time scale during which the shape of the membrane has no time to change. The Navier–Stokes equation for the fluid flow is then simplified as

$$2 \frac{v^2}{r^*} = \frac{\partial P}{\partial r^*} + \frac{\partial v_{r^*}}{\partial r^*} = \frac{\text{Str}}{\text{Re}} \left[ \frac{\partial}{\partial r^*} \left( \frac{1}{r^*} \frac{\partial (r^* v_{r^*})}{\partial r^*} \right) + \frac{R_c^2}{L^2} \frac{\partial^2 v_{r^*}}{\partial z^2} \right], \tag{2}$$

where $v_{r^*} = \rho \theta^*, P^* = \rho \theta^* v_{r^*}^2, r^* = \frac{r}{R}, z^* = \frac{z}{R}, t^* = \frac{t}{L}$, $V_0 = \rho \omega_0$, $\nu$ is the kinematic viscosity of the fluid, Reynolds number $\text{Re} = V_0 R_0/\nu$, and Strouhal number $\text{Str} = t_0 V_0/R_0$. Here, $\nu \theta_0(r, z, t)$ is the circumferential velocity, $P$ is the pressure, $\rho$ is the fluid density, and $t_0 = \frac{2\pi}{\omega_0}$ is the characteristic time.

The rotational acceleration of the membrane is determined by the shear stress on both sides of the membrane,

$$\frac{d\omega^*}{dt} = \frac{2\pi R_c^2 \nu v_{r^*}}{I} \left( \frac{R_c}{L} \int \frac{dv_{r^*}}{dz^*} dr^* + \frac{R_c}{R_0} \int \frac{dv_{r^*}}{dz^*} dr^* \right), \tag{3}$$

where $\omega^* = \omega/\omega_0$, $\omega_0$ is the angular velocity of the membrane, $I$ is the inertia of the membrane, and $A$ represents the area of both sides of the membrane.

For the rotational acceleration case, the initial condition requires that when $t^* = 0, v_{r^*}^0 = 0$ and $\omega^* = 0$. While the boundary conditions state that $v_{r^*} = 1$ on $r^* = 1$ or $z^* = 1$, and $v_{r^*} = r^* \omega^*$ on the membrane. For the rotational deceleration case, the initial condition is given as when $t^* = 0, v_{r^*}^0 = 1$ and $\omega^* = 1$, and the boundary conditions require that $v_{r^*} = 0$ on $r^* = 1$ or $z^* = 1$, and $v_{r^*} = r^* \omega^*$ on the membrane.

Equations (2) and (3) have been solved numerically. The solutions of $\omega^*$ during the acceleration and deceleration processes are given in Fig. 5(b). The solutions of the angular velocity, $v_{r^*}/r^*$, and pressure response, $P^*$, at six representative moments during the acceleration and deceleration processes, are given in Fig. 5(c). When the outer cylinder starts to rotate, the momentum is pen-
trated through the viscous fluid gap to the membrane-bound ball, and then to the fluid inside the ball. Thus, at the same axial position, \( z^* \), the angular velocity, \( \omega^* / r^* \), of the fluid near the inner side of the membrane is smaller than that of the fluid near the outer side of the membrane. Hence, the pressure outside the membrane is larger than the centrifugal force of the fluid that is enclosed inside the membrane. This pressure difference will cause the compression of the yolk at the center, leading to the one as observed in Fig. 3(b).

Once the steady state is achieved, the outer shell is suddenly brought to rest while the fluid inside the shell is still moving. This makes the angular velocity of the fluid on the inner side of the membrane larger than that of the fluid near the outer surface of the membrane. Hence, the yolk expands and squeezes out the fluid in the gap between the yolk and the shell, leading to the one observed in Fig. 3(c).

This problem involves the internal force (or centrifugal force) and the shear stress penetration, and therefore, Re is important. Besides, as shown in Eq. (2), the Sr describes the transient process caused by the sudden change in the shell velocity. A smaller \( Sr \) will decrease the time-dependent effect and the inertial force and slows down the shear stress penetration. Physically, it suggests a slower boundary change or a smaller viscosity. Hence, the yolk deformation will decrease correspondingly. Another important parameter is \( R/R_0 \) (\( R \) is the radius of the yolk at different axial locations), which describes the local gap height for the momentum to transfer from the outer cylinder to the inner object. \( R/R_0 \) takes different values at different axial locations. Hence, the time for the sudden change in the velocity to be felt by the membrane is different. If \( \frac{\partial R/R_0}{\partial z} = 0 \), the deformation would not happen.

V. CONCLUSION

The experimental study presented herein shows that the soft egg yolk is not sensitive to translational impacts, but is very sensitive to rotational, especially deceleration rotational, impacts, during which the centrifugal force plays a critical role. This finding provides a new perspective for understanding the response of a membrane-bound soft object in the liquid environment to sudden external impacts. It is noticed that the phenomena discussed in this paper seem to be similar to a spinning droplet in tensiometer undergoing rotation. \(^{4,37}\) However, the physical mechanisms behind these two phenomena are different. The spinning droplet in the tensiometer is usually analyzed in a static state, which requires a density difference between the droplet and the surrounding fluid. The egg deformation is a dynamic process in which the density difference between the yolk and the egg white is very small. For the droplet spinning problem, the essential physics is the balance between the surface tension and the centrifugal force, while for this study, the centrifugal force is mainly balanced by the pressure force caused by fluid flow. The existence of the membrane separates the two fluids. The momentum transfers from the outer cylinder to the membrane and then to the liquid yolk inside. Since the travel distance is different, the pressure field of the fluid is disturbed, leading to the deformation of the membrane-bound egg yolk and the fluid flow outside of the membrane. The role of the tension force in the membrane is to force the membrane-bound egg yolk and the fluid flow outside of the membrane to rotate at a constant angular velocity and hold the soft matter together.

Why is the brain injured? The brain is an extremely soft matter bathed in the CSF. From the biomimetic study presented herein, we suspect that rotational, especially deceleration rotational, impact is more harmful to the brain matter. The large deformation of the brain matter during this process induces the stretch of neurons and causes the damage. This finding explains why a player in a boxing game will very likely faint out if he is hit on the chin. Considering the chin is the farthest point from the neck, hitting on the chin could cause the highest rotational acceleration/deceleration of the head.

SUPPLEMENTARY MATERIAL

See the supplementary material for: Movie 1. Reaction of the egg yolk under the translational impact. Movie 2. Reaction of the egg yolk under the rotational acceleration impact. Movie 3. Reaction of the egg yolk under the deceleration impact.

FIG. 5. (a) Sketch of the 2-D rotating model. The space inside the container was divided as region I, which is enclosed by the membrane, and region II, which is between the membrane and the container. The change in the velocity of the container would first penetrate into the viscous gap between the membrane and the container, and then influence the velocity of the membrane as well as the fluid inside the membrane. (b) \( \omega^* \) under the rotational acceleration impact and rotational deceleration impact. (c) Distribution of the angular velocity, \( \omega^* / r^* \), and pressure field, \( P^* \), under the acceleration impact and the deceleration impact.
of the egg yolk under the rotational deceleration impact. Movie 4. Reaction of the calcium alginate capsule under the rotational deceleration impact. Movie 5. Reaction of the calcium alginate capsule under the rotational deceleration impact.

AUTHORS’ CONTRIBUTIONS
Q.W. and J.L. conceived of the presented idea, designed the experiment, performed data analysis, developed the model to understand the flow physics, and drafted the manuscript. J.L. and R.N. constructed the experimental setup and performed the experiments. Q.W. approved the final manuscript.

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DATA AVAILABILITY
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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