Evaluation of manipulation probes for expanding the range of capillary force

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ABSTRACT

In order to perform reliable micromanipulation, we need to use a force that is both controllable and greater than the adhesional force. We have proposed a manipulation method based on capillary force. For reliable micro-manipulation, a wide range of capillary force is required to pick/place a micro-object. This paper evaluates the capillary force generated by a liquid bridge between a spherical object and a manipulation probe with a concave tip. As the radius of the concavity being close to the object, the capillary force can be increased drastically, and it can also be controlled through a wide range by means of the liquid volume. There is a drastic decrease of the capillary force with the liquid volume when the hemline of the meniscus is on the brim of the concave, and it can be shifted by means of the depth control of the concavity. The mechanism of this increase of the capillary force, the capillary force curve, and the profile of the liquid bridge are also presented.

Keywords: micromanipulation, capillary forces, adhesion, numerical methods

1 Introduction

It is difficult to manipulate a micro-sized object precisely with conventional tools, *i.e.* tweezers can pick up the micro object but the object still adheres to any of the fingers even if the tweezers opens for releasing it(1). In the micro world, the gravity effect becomes extremely small compared to the adhesional one. Therefore, in order to perform reliable micro-manipulation, we need to use a force that is both controllable and potentially greater than the adhesional force. Saito *et. al* have analyzed the mechanical force required to slip and roll an object by considering adhesional effect, under a scanning electron microscope, and proposed a method of manipulation using a needle shaped tool. If the required force is compressive and larger than the strength of the object, their method might break a brittle object(2; 3). Takahashi *et. al* have evaluated the force generated by Coulomb interaction and estimated the voltage required to detach an adhered particle(4). If the required voltage is too large, Takahashi's method might cause electric discharge and melting of the object(5).

Our group has analyzed the capillary force generated by a liquid bridge between a spherical object and a plate, and has proposed the micro-manipulation method based on the regulation of two liquid bridge volumes(6). The first liquid bridge is formed between a manipulation probe and the object to pick up it, and the second bridge between a substrate and the object is provided in order to collapse the first one during the place manipulation. We have pointed out these critical volumes required to pick/place the object in the previous paper. To remove the spherical object from the substrate, the applied force must be greater than the adhesional force. The adhesional force can be obtained from JKR theory(7);

$$F_{\mathrm{adh.}} = \frac{3}{2}\pi R\Delta\gamma, \tag{1}$$

where R is the radius of a spherical object and $\Delta\gamma$ is the work of adhesion. Experimentaly, the value of $\Delta\gamma$ is highly depending on the surface condition. Therefore, for reliable manipulation, the capillary force should be greater than adhesional force even if $\Delta\gamma$ is on the order of 1 Nm^{-1} and also should be regulated to be smaller than the second capillary force in order to collapse the first bridge (see figure 1(V) and (VI)).

In this paper, a manipulation probe with a concave tip, as shown in figure 1, is introduced in order to expand the capillary force range. The concavity is expected to generate a greater capillary force. The capillary force would remain small when the liquid overflow into the flat surface. A numerical analysis of sphere-concavity-plate model is presented to evaluate the capillary force. Note that we are not concerned here with any mechanical ways or problems of the liquid flow to the surface of the manipulation probe or substrate.

2 Analysis of the liquid bridge

Figure 2 shows an axisymmetric model for the analysis of a liquid bridge between a spherical object and a concave shaped probe, where X and Z are cylindrical coordinates of the profile of the meniscus, which have the origin at the bottom of the concavity, R is the radius of the object, R_{p} is the radius of the concavity, D is the distance from the probe to the object, φ is the filling angle of the object, F is the attractive force acting on

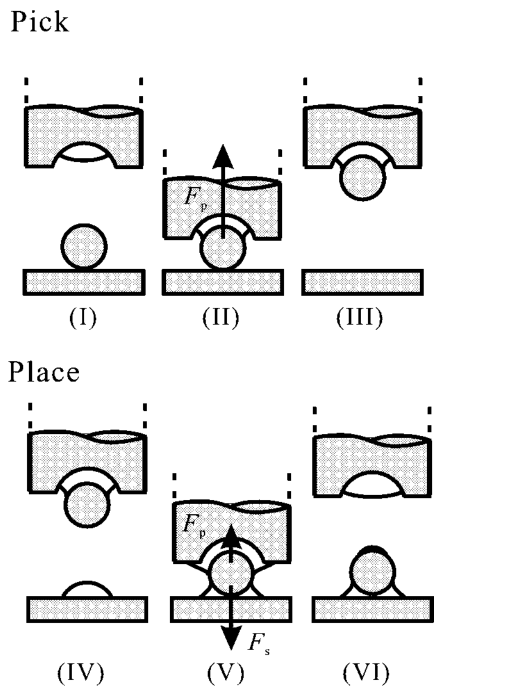

Figure 1: Schematic illustration of pick/placing procedure: (I)positioning (II)lowering (III)picking up (IV)positioning (V)lowering (VI)placing.

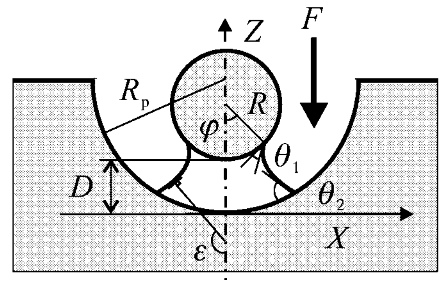

Figure 2: Liquid bridge between a spherical object and a concave shaped probe

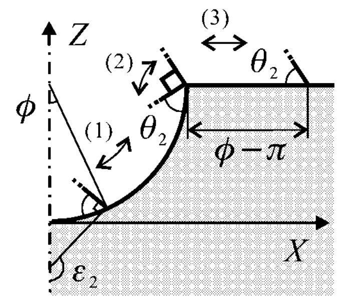

Figure 3: Boundary condition on the concaved probe surface

the object, and V is the volume of the liquid bridge between two solids. The meniscus forms contact angles θ_1 at the object and θ_2 at the probe. We make the following assumptions as simillar as our previous paper (6); 1. The influence of gravity is negligible. 2. The dynamic flow of the liquid is negligible. 3. The volume of the liquid is conservative. 4. The contact angles are determined by Young-Dupré equation (8). 5. The object and the probe are rigid.

Capillary force F can be expressed as the sum of the pressure difference force and the surface tension force:

$$F = -\Delta P \pi {X_1}^2 + 2\pi\sigma X_1 \sin\varepsilon_1, \tag{2}$$

where ΔP is the pressure difference between inside and outside the liquid, X_1 is the radius of the contact circle on the spherical object, σ is the surface tension, and ε_1 is the inclination of the meniscus at the contact circle on the object. According to Young-Laplace equation, the value of ΔP can be obtained from the stability profile of the liquid bridge:

$$\Delta P = 2H\sigma, \tag{3}$$

where H is the local mean curvature. Since ΔP is a constant, the surface of the meniscus has the same mean curvature at any local point. As shown by Orr(9), the value of H in (3) can be expressed by geometrical parameters as

$$2H = \frac{\mathrm{d}}{\mathrm{d}X}(\sin\varepsilon) + \frac{\sin\varepsilon}{X}, \tag{4}$$

where ε is the angle between the normal to the meniscus and the vertical axis. Since the left-hand side of this equation is constant, it can be solved as a two-point-boundary value problem, for which the boundary conditions are the inclinations ε and X coordinates of the menisci on the solid surfaces. These inclinations are determined by the slopes of the solid surfaces and the respective contact angles θ_1 and θ_2 (see figure 2).

Figure 3 shows three boundary states on the probe surface, which appeares (1)on the concavity, (2)at the brim, and (3)on the flat surface. If the hemline of the meniscus is on the concavity (see (1) in figure 3), the boundary conditions can be written as

$$\left.\begin{array}{ll} \varepsilon_1 = \theta_1 + \varphi, & X_1 = R\sin\varphi, \\ \varepsilon_2 = \pi - \theta_2 + \phi, & X_2 = R_\mathrm{p}\sin\phi, \end{array}\right\} \tag{5}$$

where ϕ is the filling angle of the concavity. When the meniscus reaches the brim of the concavity as (2) in figure 3, the boundary condition on the probe surface is

$$\varepsilon_2 = \pi - \theta_2 + (\pi - \phi), \quad X_2 = R_\mathrm{p}, \tag{6}$$

where ϕ shows the increasing angle at the brim of concavity. In the case of (3), the boundary can be shown

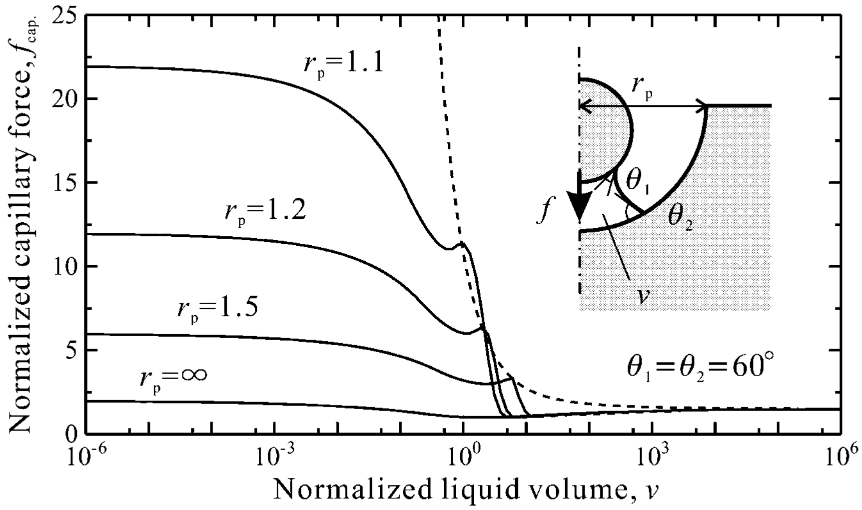

Figure 4: Relation between the maximum capillary force and the liquid volume for each radius of the concavity and for $\theta_1 = \theta_2 = 60°$ ($r_p = \frac{R_p}{R}, f_{cap.} = \frac{F_{cap.}}{\pi R\sigma}, v = \frac{V}{R^3}$). The two broken lines represent the thresholds of the boudary changes on the probe surface. The second boundary change occurs at the bottom of the each solid line (the second broken line is behind the solid lines).

as

$$\varepsilon_2 = \pi - \theta_2, \quad X_2 = R_p + (\phi - \pi), \tag{7}$$

where ϕ becomes the parameter describing X coordinate.

The boundary-value problem has the solution(9). The meniscus profile (X, Z), the distance D, the liquid volume V, and also the capillary force F can be calculated from given four parameters; contact angles θ_1 and θ_2, the filling angle φ, and the parameter ϕ. If the volume V is given in advance instead of the parameter ϕ, ϕ must be determined so that V could be equal to the given value. Then, the relation between D and F, which has the conservative liquid volume and given contact angles, can be plotted as a function of the filling angle φ.

To generalize the following discussion, all the parameters are normalized as

$$z = \frac{Z}{R}, x = \frac{X}{R}, d = \frac{D}{R}, f = \frac{F}{\pi R\sigma}, v = \frac{V}{R^3}, r_p = \frac{R_p}{R}. \tag{8}$$

3 The shape effect for capillary force

The liquid bridge is treated as static. Thus the capillary force curves are just plotted in its stable equilibrium state. The curves show the value of the external force that would equilibrate the capillary force. If the external force is larger than the maximum value of the curve, the liquid bridge is extended until eventually the bridge collapses. Therefore the maximum capillary force is essential to predict which bridge will collapse. We set the maximum capillary force as $F_{cap.}$, instead of F_{max} used in Ref. (6).

The solid lines in figure 4 shows the relationships between the normalized maximum capillary force $f_{cap.}(\equiv \frac{F_{cap.}}{\pi R\sigma})$ and the liquid volume v assuming $\theta_1 = \theta_2 = 60°$ for example. Each line has a different concave radius r_p. The indication $r_p = \infty$ represents the sphere-plate model used in Ref. (6). As the radius of concavity being close to the sphere radius, the maximum capillary force grows more and more when the liquid volume is relatively small compared to the object. When the volume is close to zero, the capillary force can be written as

$$f_{cap.} = \frac{2r_p}{r_p - 1}(\cos\theta_1 + \cos\theta_2). \tag{9}$$

The increasing ratio compared to sphere-plate model is $\frac{r_p}{r_p-1}$. This represent that we can achieve high reliability of the picking manipulation by means of the design of the probe shape.

If the volume is sufficiently large, the capillary force is almost independent of the concave radius, since the liquid must overflow into the flat surface. Thus, with increasing v, the capillary force reaches equivalent to that of the sphere-plate model as

$$f_{cap.} = 1 + \cos\theta_1. \tag{10}$$

Therefore, we can control the capillary force within the range from (3.2) to (3.1) at least by means of the regulation of the liquid volume.

The broken lines represents the thresholds of the boundary changes on the probe surface as shown in figure 3. The second threshold is on the bottom of the solid lines. If the hemline of the meniscus is on the concavity, the capillary force remains large level. As increasing v, the boundary condition changes from the concavity state to the brim state. In the brim state, the capillary force decreases drastically with v. Finally, in the plate state, the capillary force is equivalent to the sphere-plate model. Therefore, for pick/place manipulation, we can evaluate the required liquid supply by comparing these thresholds. Furthermore, the drastic decrease can be shifted to smaller liquid volume by making the concavity shallower. We can design the probe shape so that a liquid supplying device could make the drastic decrease of the capillary force. In addition, when the concavity is shallower than hemisphere, the local peak of the capillary force can not be observed. It might be one of the characteristics of the hemispherical concavity shape. In the next section, we clarify the mechanism of the increase of the capillary force with showing the capillary force curve.

4 Conclusion

In this study, the probe shape for micro-manipulation was discussed for increasing the range of the capillary force. The capillary force generated by the liquid bridge between the spherical object and the probe with a concave tip was analized to find a proper shape of the probe. As the radius of concavity being close to the sphere radius, the maximum capillary force grew more and more when the liquid volume was relatively small compared to the object. The increasing ratio compared to sphere-plate model was $\frac{r_{\mathrm{p}}}{r_{\mathrm{p}}-1}$, where r_{p} is the concave radius. This represent that we can achieve high reliability of the picking manipulation by means of the design of the probe shape. If the volume was sufficiently large, the capillary force was approximately equivalent as the sphere-plate model, since the liquid must overflow into the flat surface. Therefore, we can control the capillary force with the wide range by means of the regulation of the liquid volume. The capillary force drastically decreased with the liquid volume, when the hemline of the meniscus was on the brim of the concavity. This decrease can be shifted to the other volume area by means of the depth control of the concavity. The object can float even before this drastic change of the capillary force. This would be the great advantage of our method for both supplying liquid and less mechanical damage.

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