Effect of the granular material on the maximum holding force of a granular gripper

Julián M. Gómez–Paccapelo1 · Angel A. Santarossa1,3 · H. Daniel Bustos1 · Luis A. Pugnaloni1,2

Received: 8 June 2020 / Accepted: 15 October 2020 / Published online: 23 November 2020
© Springer-Verlag GmbH Germany, part of Springer Nature 2020

Abstract
A granular gripper is a device used to hold objects by taking advantage of the phenomenon of Reynold’s dilatancy. A membrane containing a granular sample is allowed to deform around the object to be held and then vacuum is used to jam the granular material inside the membrane. This allows to hold the object against external forces since deformation of the granular material is prevented by not allowing the system to increase its volume. The maximum holding force supported by the gripper depends on a number of variables. In this work, we show that in the regime of frictional holding (where the gripper does not interlock with the object), the maximum holding force as a function of the penetration of the object in the membrane does not depend on the granular material used to fill the membrane. Results for a variety of granular materials can be collapsed into a single curve if maximum holding force is plotted against the penetration depth achieved. The results suggest that a robotic arm capable of sensing the penetration depth can use this master curve to estimate the maximum holding force at each gripping operation.

Keywords Universal gripper · Jamming · Dilatancy

1 Introduction
The handling of objects is a regular task in the industry. Holding objects of well defined size, shape and hardness can be done by robotic arms that present a gripper with a matching shape that fits the object to hold (e.g., hooks). Also, magnets can be used with ferromagnetic objects, and suction systems with objects presenting smooth surfaces. However, matching some of the gripping characteristics of the human hand is always desirable. Fingered grippers have been developed systematically over decades to provide a more universal (any shape, size and hardness) gripping ability (for a recent review see Ref. [1]). However, these hand-like grippers require complex auxiliary systems to asses the gripping problem and take multiple decisions on how to handle each finger (time and amplitude of aperture, time of closure, applied pressure to hold, etc.). These auxiliary systems require complex hardware and software.

More than 30 years ago, there were new proposals to tackle the gripping problem by using some unique properties of dense granular matter [2–4]. The “granular gripper” consists in a flexible impermeable bag partially filled with a granular material and connected to a vacuum pump. When the interior is at atmospheric pressure, the bag (and its material inside) can be easily deformed and reshaped. Simply pressing the bag against an object makes the bag to deform, partially conforming to the object shape. When vacuum is applied inside the bag, this contracts the membrane and confines the granular sample, which becomes rigid. If an object had been partially wrapped by the bag, the new solid state of the bag will cause the object to be gripped. There are three properties of the granular material inside the bag that allow this technology to work. First, the flowability of the grains when there is no vacuum applied [5], then the jamming of the granular sample which sustains the external pressure when vacuum is applied [6], and finally the frustrated dilatation [7] which causes the sample to become hard to deform.
since the external pressure prevents the volume increase
needed by the grains to pass each other during shear.

During the process of evacuating the air from the gripper
bag the granular sample is taken through the jamming tran-
sition [6]. This means that the sample can bear the external
pressure imposed. This, in turn, renders the sample hard
to deform under shear since the dilation necessary for the
material to flow is frustrated. This phenomenon is connected
with the so-called Reynolds dilatancy [10]. Reynolds dilat-
cancy implies two different responses of a dense granular
system, depending on the external constrains. On the one
hand, if the total volume is not restricted, shear will induce
a volume increase. On the other hand, if the total volume is
constrained and not allowed to increase the system cannot be
deformed since shear is prevented unless dilation is allowed.
These two conditions where described by O. Reynolds as:
A strongly compacted granular material placed in a flex-
ible envelope invariably sees its volume increase when the
envelope is deformed. If the envelope is unbreakable but
deflatable, no deformation is possible until the applied
force breaks the envelope or fractures the granular mate-
rial [10]. When the target object is being pulled out of the
ripper, one effectively intends to shear the granular sample
in the bag. However, since the gripper bag cannot increase
its volume, deformation is prevented and the gripper holds
the object.

In recent years, the interest in granular grippers has
increased significantly, partially due to the study about the
gripping mechanisms and their connection to the mecha-
nical strength of the gripper by Brown et al. [7]. In that paper,
the authors describe three gripping mechanism: (i) friction,
(ii) suction, and (iii) interlocking. Interlocking requires the
gripper to wrap the object (or some protrusion of it) to the
extent that detaching the object would require a large de-
formation of part of the rigidized bag. Interlocking is the most
effective gripping mechanism, but is not achieved in most
objects by simply pressing the fluid bag against the object.
Therefore, this mechanism is far from being universal in prac-
tice. Suction is caused by the formation of a sealed cav-
ity between the object and the gripper while the object is
being pulled apart. This mechanism works only if sealing
can readily occur, which is not possible with many rough
surfaces. Friction is in fact the only universal mechanism at
work under all gripping conditions. It is less effective than
the other two mechanism, but more than sufficient to sustain
the weight of objects of moderate size and density [7].

Since the extent of wrapping is essential to achieve a
high maximum holding force, some simple techniques can
be used to aid this process. One such technique is to partially
inflate the bag before approaching the object [11]. This gives
more available volume to the granular sample, which eases
the flow around the object. This so-called “positive pressure
gripper” can conform to an object applying up to 90% less
force on it. In the same spirit, Nishida et al. showed that
the maximum holding force increases if some extra space is left
in the bag for the material to flow during the conforming
phase [12].

The most straightforward method to enhance wrapping
is pressing the gripper against the target object with higher
forces. This applied force \( F_a \) is called the activation force.
Brown et al. [7] considered the maximum holding force \( F_h \)
(the maximum force that the gripper can support before the
object is detached when pulled axially) as a function of the
maximum contact angle between the object and the bag. The
contact angle is a suitable measure of the extent of wrapping.
However, in industrial applications, the angle of contact is
difficult to measure. A more natural choice is to furnish the
gripper with a force sensor to measure \( F_a \). Therefore, for
practical applications one would require to know the \( F_h - F_a \)
curve of a gripper to be able to predict the necessary activa-
tion force to hold a given weight. The \( F_h - F_a \) curve will
depend on constructive details of the gripper, the granular
material used and the size and shape of the target object.

Brown et al. mentioned that the details of the granular
material seem to have a minor role in the maximum holding
force attained by the gripper as long as the material used
does not interfere with the gripper conforming the object [7].
However, more recent studies seem to show that the holding
force depends on the granular material used inside the bag
[12, 13]. In this work, we revisit this issue by performing
a series of experiments with different granular materials.
We show that for grain sizes below 1/15 of the target object
diameter, the actual material used has an important effect on
the \( F_h - F_a \) curve. However, we find that this is only due to
the flowability of the material while conforming the target
object as claimed by Brown et al. [7]. When \( F_h \) is plotted
against the penetration depth of the object inside the gripper
bag all data collapse into a single curve. We also show that
for larger grains this collapse fails; and we discuss plausible
explanations for such deviation from the collapsing data.

2 Experimental setup

Figure 1 shows a sketch of the apparatus. The granular
gripper is composed of a rubber bag partially filled with a
granular sample. The bag is attached to a Teflon fitting that
connects the interior of the bag to a vacuum pump (Leybold
Vp2, 90 kPa maximum differential pressure) through a flex-
ible pipe. The Teflon part is connected to a force sensor
(CT460B, maximum force ±50 N), which is fixed to a rigid
I-shape beam. The Teflon fitting has a concave conical shape
in the bottom part to which the gripper bag conforms.

Beneath the gripper, the object to be gripped (a glass
sphere of 17 mm in diameter coated in rubber) is attached
to a movable base. The base can be displaced up and down
at constant velocity \((2.8 \pm 0.4 \text{ mm/s})\) by means of a screw connected to a motor (BOSCH FPG). We have tested different velocities and found that this does not affect the results. The motion of the base is controlled by means of an Arduino microcontroller using the feedback from the force sensor that sustains the gripper. The motion of the platform emulates the action of a robotic arm, where the object is handled in a controlled way instead of the gripper, which remains fixed.

We define the activation force as the maximum force exerted in the vertical direction by the object onto the gripper while deforming the bag around it. The upward motion of the object can be stopped for any prescribed value of the activation force. The maximum holding force is defined as the critical force at which the object is detached from the gripper during the downward motion.

The protocol for any single measurement is as follows. (i) The bag is inflated for a few seconds using a small positive pressure to allow the granular material to relax and loose memory of previous manipulation of the bag. (ii) The bag inner pressure is let to equilibrate with ambient pressure. (iii) The object is elevated at constant velocity and pressed against the gripper bag until the vertical force between the object and the gripper reaches the desired activation force. (iv) The movable base is held static during 10 s for the granular material to relax. (v) Negative pressure \((86 \pm 7 \text{ kPa})\) is applied to the gripper so that the granular material becomes rigid inside and the object gets gripped. This pressure is held for 36 s while the material relaxes. (vi) With the vacuum pressure fixed, the object is moved downward by the base until it is detached from the gripper. We measure the depth that the object has dipped into the bag in each case using a digital image of the configuration right after applying the vacuum pressure [i.e., after step (v)].

During the entire experimental run, the force in the force sensor is registered at 100 samples/s with a resolution of 0.05 N. In Fig. 2 we show an example of the force exerted on the target object during one experiment. Each phase in the protocol described above is indicated in the figure. During phase (iii) we observe the increase of the force on the object in the downward direction (negative forces) until the prescribed value for \(F_a\) is achieved. In the relaxation phase (iv) we observe a small decrease and rapid saturation of the absolute value of the force. In phase (v) the applied vacuum induces a slight increase in the absolute value of the force on the target object. When the object is pulled back down by the platform in phase (vi) the force on the object rapidly decreases in absolute value and becomes positive until the object detaches from the gripper and the force relaxes to zero. The maximum holding force \(F_h\) is extracted from the maximum in Fig. 2. For any given activation force, we carried out between 5 and 10 realizations of the experiment. The standard deviation of the maximum holding force is usually below 5% of the mean in all our experiments.

![Fig. 1 Sketch of the experimental apparatus](image1)

![Fig. 2 Force exerted by the gripper onto the target object during one experiment. The phases of the protocol are indicated in the figure: (i,ii) the bag is inflated for a few seconds and then the pressure is let to equilibrate with ambient pressure, (iii) the object is pressed against the gripper until the desired activation force, (iv) the object is held at its position for 10 s, (v) negative pressure is applied for 36 s, (vi) the object is pulled downward and detached from the gripper at constant speed. \(F_h\) indicates the maximum holding force and \(F_a\) is the activation force.](image2)
We have tested different granular materials (see Fig. 3 and Table 1). Since material density and packing fraction varies, we used in all cases the same apparent volume (60 cm$^3$) of material inside the gripper bag. The apparent volume was measured before pouring the material in the bag by filling a graduated tube with a funnel taking care of using always the same funnel position and filling speed. The materials chosen cover a wide range of particle sizes, material densities and stiffnesses.

As we mentioned, the target object is a glass sphere (17.0 mm in diameter) coated in the same rubbery material as the membrane used for the gripper bag. During each gripping experiment we take images with a CCD camera to measure the penetration depth $D$ of the target object into the gripper bag. This is measured after the vacuum has been applied and before pulling back the object. We measure the vertical distance $D'$ from a reference point marked on the bottom part of the target object to the lowest part of the gripper bag. We calculate $D$ by subtraction of $D'$ from the known distance measured from the top of the target object to the reference point. The relative vertical position of object and gripper is measured with 0.1 mm resolution. In total, 100 experiments were carried out including several realizations for different materials and different activation forces.

### 3 Results

We have carried out measurements of $F_h$ for a range of $F_a$. Figure 4 shows the results for all granular materials tested. Measurements are very reproducible with typical error in $F_h$ below 5%. The polymer microspheres, ceramic beads, small glass beads and amaranth seeds show similar results, although with some scatter. However, sand and large glass beads present a significantly lower $F_h$ for any given $F_a$.

As we can see in Fig. 4, $F_h$ increases with $F_a$ and saturates at around 30 N. For some materials we where unable to reach the high values of $F_a$ required to achieve saturation due to limitations in the mechanical system. This saturation occurs because the gripper bag does not wrap the object completely covering it pass beneath the equator so that interlocking is at play. While increasing $F_a$, the target object simply deepens into the bag creating a straight vertical cylindrical channel that does not close beneath the target object. The contact between the gripper and the object only occurs for the upper hemisphere of the object. Therefore, once the bag has covered the upper hemisphere, further penetration does not lead to any additional increase in the contact angle. It is worth mentioning that higher contact angles have been achieved in previous studies only by molding the gripper bag by hand [7]. It seems that proper interlocking cannot be attained without external intervention.

Since it is impractical to measure the maximum contact angle, we used a different measure of the degree of wrapping. This is the penetration depth $D$ defined as the length that the object has penetrated into the bag for the given value of $F_a$. In Fig. 5 we show $F_h$ as a function of $D$. In this representation all data for small grain sizes collapse to a good degree for all materials tested. This result indicates that is in fact the penetration depth that controls the holding force. If a
Effect of the granular material on the maximum holding force of a granular gripper

1 The granular material displays a lower holding force for a given $F_a$, this is simply caused by a less effective penetration. The peculiar behavior observed for the large glass beads is worth of attention. In agreement with the lower $F_h$ observed here for large grains, Amend et al. have reported that smaller mesh sizes for the granular material do lead to lower object retention [5]. We have tested if materials with small grains present an extra contribution to the holding force due to suction that is not present for large grains. We did this by using a perforated target object that prevents the formation of a seal between object and gripper. However, suction seems to be negligible in our system. Interestingly, we have observed that the bag, when vacuum is applied, presents a bumpy surface since it copies the shape of the granular sample inside. For large grains, this is particularly apparent (see Fig. 6). This makes the bag to contact the target object only at the protruding spots since the concave regions of the bag surface are deeper for large grains. Since the rubbery bags present some degree of adhesiveness, the holding force depends partly on the effective area of contact. As a consequence, large grain sizes induce a marked drop in holding force. This is consistent with recent experiments based on pin array grippers that show a clear dependence of $F_h$ on the number of contact points between the gripper and the object [14].

4 Discussion and conclusions

We have shown that the $F_h - F_a$ curve for a granular gripper is sensitive to the granular material used. From a practical perspective, this implies that a robotic arm that senses the activation force while conforming the gripper to the object will require a calibration curve for the particular granular material used. However, if the same penetration of the object is achieved for two different materials, then $F_h$ becomes material independent.

We have observed that the collapse of the data fails for large grains; larger than 1/15 of the target object diameter. This seems to be connected to the fact that large grains create a bumpy surface on the gripper bag that reduces the effective contact area between the bag and the target object. This, in turn, leads to a marked drop in the maximum holding force.

The previous observations are consistent with reports in the literature that seem at first sight contradictory. On the one hand, some workers found that the holding force is material dependent [12, 13]. On the other hand, Brown et al. suggested that the granular material should play a marginal role on the holding force [7]. We have shown that both claims are compatible because, while $F_h$ does depend only on the contact angle (or penetration depth) for many materials as shown in Fig. 5, some granular materials (especially those consisting of large particles) result in incomplete contact between the target and bag due to their large size and so do not achieve the full frictional contact area modeled by Ref. [7]. This explains why large particles have previously been found to result in inferior gripping capabilities [12, 13].

These findings suggest that a robotic arm capable of sensing the penetration depth can in fact use the master curve in Fig. 5 to estimate the maximum holding force at each gripping operation. This can be achieved by equipping the arm with a force sensor to detect the first contact with the target object and a displacement sensor to measure penetration from that position on. It is important to mention that the master curve shown in Fig. 5 needs to be obtained for each object size and shape. The universal character of this curve is with respect to the granular material only.

Fig. 5 $F_h$ as a function of penetration depth for various granular materials (see legend). Error bars correspond to the standard deviation.

Fig. 6 Photographs of the surface of the gripper bag while vacuum is applied for large glass beads (a) and for the polymer microspheres (b).
Acknowledgements We thank N. Arce and J. P. Cagnola from Universidad Tecnológica Nacional (La Plata) for their contribution in the design and test of the experimental apparatus. We are indebted to G. Corral and M. Baccin for their help during the experiments. This work has been supported in part by ANPCyT (Argentina) through grant PICT-2016-2658, UTN (Argentina) through grant PID-MAUTNLP-4415 and FCEyN-UNLPam through grant F-55.

Author contributions JMG and AAS have contributed equally to this work.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Shintake, J., Cacucciolo, V., Floreano, D., Shea, H.: Soft robotic grippers. Adv. Mater. 1707035 (2018)
2. Schmidt, I.: Flexible molding jaws for grippers. Ind. Robot. 5, 24 (1978)
3. Perovskii, A.P.: Universal grippers for industrial robots. Russ. Eng. J. 60, 3 (1980)
4. Rienmüller, T., Weissmantel, H.: A shape adaptive gripper finger for robots. In: Burckhardt, C.W. (ed.) Proceedings of the 18th International Symposium on Industrial Robots, pp 241-250. IFS Publications, Springer Verlag, Berlin (1988)
5. Amend, J., Cheng, N., Fakhouri, S., Culley, B.: Soft robotics commercialization: jamming grippers from research to product. Soft Robot. 3, 213 (2016)
6. Jaeger, H.M.: Celebrating soft matter’s 10th anniversary: toward jamming by design. Soft Matter. 11, 12 (2014)
7. Brown, E., Rodenberg, N., Amend, J., Mozeika, A., Steltz, E., Zakin, M.R., Lipson, H., Jaeger, H.M.: Universal robotic gripper based on the jamming of granular material. Proc. Natl. Acad. Sci. 107, 18809 (2010)
8. Reynolds, O.: Experiments showing dilatancy, a property of granular material, possibly connected with gravitation. Proc. R. Inst. BG 2, 354 (1886)
9. Sakaie, K., Fennisten, D., Carroll, T.J., van Hecke, M., Umbanhowar, P.: MR imaging of Reynolds dilatancy in the bulk of smooth granular flows. Europhys. Lett. 84, 38001 (2008)
10. Reynolds, O.: On the dilatancy of media composed of rigid particles in contact With experimental illustrations. Lond. Edinb. Dublin Philos. Mag. J. Sci. 20, 469 (1885)
11. Amend, J.R., Brown, E., Rodenberg, N., Jaeger, H.M., Lipson, H.: A positive pressure universal gripper based on the jamming of granular material. IEEE Trans. Robot. 28, 341 (2012)
12. Nishida, T., Shigehisa, D., Kawashima, N., Tadakuma, K.: Development of universal jamming gripper with a force feedback mechanism. Joint 7th International Conference on Soft Computing and Intelligent Systems (SCIS) and 15th International Symposium on Advanced Intelligent Systems (ISIS), pp. 242. IEEE, Kitakyushu, Japan (2014)
13. Meuleman, S., Balt, V., Jaray, A., Magnanimo, V.: Investigation of particle properties on the holding force in a granular gripper. In: Wriggers, P., Bischoff, M., Oñate, E., Owen, D.R.J., Zohdi, T. (eds.) V International Conference on Particle-Based Methods—Fundamentals and Applications, pp. 508 (2017)
14. Mo, A., Zhang, W.: A novel universal gripper based on meshed pin array. Int. J. Adv. Robot. Sys. 16, 1 (2019)

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.