INTERFACE

rsif.royalsocietypublishing.org

Research

Cite this article: Wu J, Zhao Y, Zhang Y, Shumate D, Braccini Slade S, Franklin SV, Hu DL. 2018 Elephant trunks form joints to squeeze together small objects. *J. R. Soc. Interface* **15**: 20180377.
http://dx.doi.org/10.1098/rsif.2018.0377

Received: 24 May 2018
Accepted: 25 September 2018

Subject Category:
Life Sciences–Physics interface

Subject Areas:
biomechanics

Keywords:
elephant trunk, joint, force regulation

Author for correspondence:
David L. Hu
e-mail: hu@me.gatech.edu

Electronic supplementary material is available online at https://dx.doi.org/10.6084/m9.figshare.c.4257323.

THE ROYAL SOCIETY PUBLISHING

Elephant trunks form joints to squeeze together small objects

Jianing Wu[1], Yichao Zhao[1], Yunshu Zhang[1], David Shumate[1], Stephanie Braccini Slade[3], Scott V. Franklin[4] and David L. Hu[1,2]

[1]School of Mechanical Engineering, and [2]School of Biology, Georgia Institute of Technology, Atlanta, GA 30332, USA
[3]Zoo Atlanta, Atlanta, GA 30315, USA
[4]School of Physics and Astronomy, Rochester Institute of Technology, New York, NY 14623, USA

DLH, 0000-0002-0017-7303

Wild African elephants are voracious eaters, consuming 180 g of food per minute. One of their methods for eating at this speed is to sweep food into a pile and then pick it up. In this combined experimental and theoretical study, we elucidate the elephant's unique method of picking up a pile of food by compressing it with its trunk. To grab the smallest food items, the elephant forms a joint in its trunk, creating a pillar up to 11 cm tall that it uses to push down on food. Using a force sensor, we show the elephant applies greater force to smaller food pieces, in a manner that is required to solidify the particles into a lump solid, as calculated by Weibullian statistics. Elephants increase the height of the pillar with the force required, achieving up to 28% of the applied force using the self-weight of the pillar alone. This work shows that elephants are capable of modulating the force they apply to granular materials, taking advantage of their transition from fluid to solid. In the future, heavy robotic manipulators may also form joints to compress and lift objects together.

1. Introduction

Wild elephants browse and graze for up to 18 h per day [1,2], consuming over 200 kg of vegetation per day [3]. Thus, on average, an elephant eats 180 g of food, or the weight of two corn cobs, per minute. Even in captivity, elephants (figure 1) continue to consume food at up to half this rate [3]. To eat at these high rates, an elephant uses its trunk to pick up as much food as possible each time it reaches out. This behaviour is analogous to using a fork to pick up as many noodles as possible before each bite. Picking up multiple objects at once requires practice and physical intuition as to how piles of materials behave under applied forces [4,5]. While little is known how elephants perform this feat, there is a growing interest in robotics in conducting similar tasks. For robotic manipulators to work in the real world, they will have to deal with multiple objects in cluttered and unpredictable environments [6,7]. The goal of this study is to elucidate how elephants manipulate multiple objects at once.

We focus here on piles of granular materials, collections of discrete, solid, macroscopic particles. Examples include construction material, such as sand and gravel, as well as food items, such as flour and chia seeds. Sand and gravel are often pushed with bulldozers and grabbed using construction cranes with an end attachment called a clamshell [8]. In both cases, a dustpan-like device is slid underneath the pile of materials in order to lift it up. Elephants use a different mechanism: they squeeze the particles together, jamming the grains which cause the pile to solidify. Such a mechanism might be used to help soft robotic grippers to pick up multiple objects together [9–12].

The elephant trunk is similar to other boneless organs in nature such as the octopus arm, and the human tongue and heart. These organs are composed of a tightly packed array of muscle and connective tissues. They are known as muscular hydrostats and are composed of interdigitated muscle fibres arranged in three dimensions. They thus lack the discrete muscles of rigid skeletal support systems

Figure 1. The indoor enclosure where experiments are conducted. During experiments, the elephant turns to face the force plate and video cameras and protrudes its trunk through the enclosure. (Online version in colour.)

[13]. The elephant trunk is the largest muscular hydrostat on land, making it subject to substantial gravitational forces.

In this study, we investigate the behaviours used by elephants to pick up multiple items simultaneously. We begin in §2 with our experimental methods for filming and measuring the forces applied by elephants. We proceed in §3 with our mathematical models for the squeezing force applied to the food and the granular physics of jamming. In §4, we present our experimental results, focusing on the forces applied to pick up different sized food items. In §5, we discuss the implications of our work and suggest directions for future research, and in §6 we state our conclusions.

2. Material and methods

2.1. Elephant training and husbandry

All experiments are performed on a 34-year-old female African elephant *Loxodonta africana* over several weeks in the summer of 2017. The elephants are trained to perform a number of routines for visitors, including a demonstration of basic movements of the body, and reaching for food using the trunk. All experiments are supervised by the staff at Zoo Atlanta.

2.2. Measuring trunk density and trunk weight

Using an elephant trunk that is cut into four sections, all of which are stored in a freezer with a temperature of − 20°C, we are able to collect length and mass data. While the trunk is in the shape of a frustrum, the last 23 cm can be approximated as a hollow cylinder using the equation:

$$m_{\rm v} = \rho_{\rm trunk}\pi(r^2 - 2r_0^2)H, \tag{2.1}$$

where $\rho_{\rm trunk}$ is the density of the trunk, and r is the trunk outer radius, H the height, and r_0 the inner radius of each of two nostrils. We measure the mass of the frozen trunk section as $m_{\rm v} = 2.35$ kg and its height $H = 23$ cm. The trunk section has an outer radius r of 52 mm, and an inner radius r_0 of 15 mm. Thus the volume of the trunk can be calculated as $V_{\rm trunk} = \pi(r^2 - 2r_0^2)\, H = 1990\ {\rm cm}^3$. Using equation (2.1), and the weight of the trunk section, we calculate the average density of the trunk tip as $\rho_{\rm trunk} = 1.5\ {\rm g\ cm}^{-3}$. This value is above the density of lean boneless cow muscle, $\rho_{\rm steak} = 1.2\ {\rm g\ cm}^{-3}$, possibly because of desiccation in the sample [14].

To estimate the weight of the trunk, we photograph the elephant when its trunk is in a relaxed position (electronic supplementary material, figure S1). We measure by hand the tip diameter $d_1 = 12$ cm, and so infer from the photograph that the trunk has a length $L_{\rm trunk} = 1.9$ m and is widest proximally, with a diameter of $d_2 = 38$ cm. Approximating the trunk as a frustrum with two nostrils, its volume is $V_{\rm frustrum} = (\pi/3)L_{\rm trunk}((d_1/2)^2 + (d_2/2)^2 + d_1d_2/4) - 2\pi r_0^2 L_{\rm trunk} = 0.1\ {\rm m}^3$. The total mass is $m_{\rm trunk} = \rho_{\rm trunk}V_{\rm frustrum} \approx 150$ kg (see details in the electronic supplementary material).

2.3. Grabbing force measurement

To prepare food for the elephant, we cut by hand rutabaga and carrot into cubes of side length 10 mm, 16 mm and 32 mm. We also scoop wheat bran with grains of characteristic size $L \sim 2.0 \pm 0.5$ mm, and volume $V \sim L^3 = 0.008\ {\rm cm}^3$. The food is arranged by hand into a small pile in the centre of a force plate (Accugait, AMTI, USA) for each trial. We separate the food into piles of approximately the same size: this means 50 g of bran and 100 g of cubes in sizes of 10 mm, 16 mm and 32 mm. Since wheat bran has a density of $\rho = 0.17{-}0.25\ {\rm g\ cm}^{-3}$, then $M = 50$ g of bran has approximately $N = M/(\rho V) \sim 40\,000$ particles in it. Thus, the number of particles that we test varies over four orders of magnitude, from four particles to 40 000.

Figure 1 shows the location where experiments are conducted. The elephant stands behind the bars of an indoor enclosure and extends its trunk through the bars to reach food. Food is placed on the force plate, whose edge is a horizontal distance of 46 cm from the enclosure. Two video cameras (Sony Handycam, Japan) are placed in the bird's-eye view and side view of the force plate. An indicator light (Massimo Retro LED, USA) activated by remote control is used to synchronize the force plate and cameras.

We start every experiment in the morning at 9.30 EST and finish it within an hour. First, the force plate, indicator light and cameras are installed. The force plate is zeroed and the indicator light is turned on. Each trial begins by the curator instructing the elephant to retrieve the food. The elephant

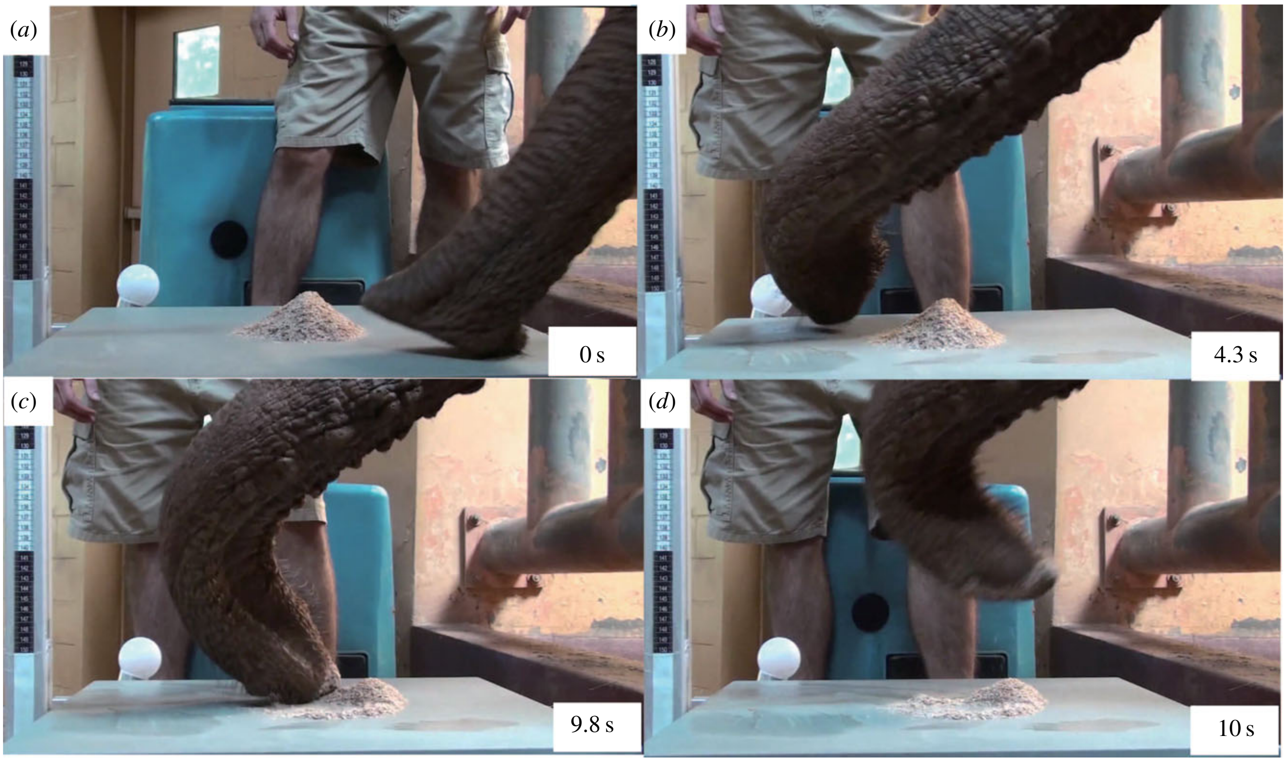

Figure 2. Time sequence of elephant trunk sweeping and grabbing a pile of wheat bran. (*a*) The trunk locates the force plate. (*b*) The trunk tip sweeps for about 5 s to compact the bran. (*c*) The trunk tip pushes downward to jam the bran using both finger-like extensions on the trunk tip. (*d*) The trunk detaches from the force plate, carrying food to the mouth. (Online version in colour.)

draws close to the force plate and stretches its trunk to grab, as shown in figure 2. The two cameras start to record the scene and the indicator light is turned off to synchronize both cameras. The real-time contact force data are captured at the same time. For each of these food sizes, we conduct six trials, providing a total of 24 trials, of which 16 were analysed. The remaining eight trials were not analysed because the elephant performed a trunk wrapping rather than a jamming motion. The rest time between experiments is about 2 min.

2.4. Image analysis to locate the trunk joint

The location of the joint is found using image analysis, which is discussed in detail in the electronic supplementary material. We begin with a guess, by estimating by eye the location of the joint, defined as the point at which the elephant begins to form the distal end of its trunk into a distal pillar. We binarize the image using Matlab and then use image analysis tools to extract the points characterizing the most distal and proximal ends shown in the image (electronic supplementary material, figures S2–S6). Two lines, shown in red dashed lines in figure 3, are fit to each of these series of points, and their point of intersection is calculated. This intersection point is the new location of the joint, and it often falls quite close to the initial guess. The coordinates of the joint are used to measure the height of the trunk pillar. In figure 3, the joint is shown by the white point and the height of the pillar by the yellow dotted line. In the next section, we present our mathematical modelling tools which we use to rationalize the shape that the elephant trunk takes to grab each object.

3. Mathematical modelling

3.1. Forces by the trunk pillar

To pick up granular materials, horizontal squeezing forces must be applied to the pile. While humans can use two hands to squeeze the pile, elephants are constrained by the anatomy of their appendage. African elephants like the ones in our study have two finger-like appendages at the tip of their trunk. These fingers push on food as shown in figure 4*a*,*b*. Because the fingers are oriented at a non-zero angle α relative to the vertical, it allows the elephant to transduce downward forces into horizontal forces that contract the pile together allowing it to be picked up. The idea is similar to scooping flour up from a table by squeezing it between the fingers and palm of one hand.

Rather than consider the mechanics of the food–finger interaction, we consider a force balance on the entire trunk pillar as control volume as shown figure 4*a*. Forces arise from the following three components: applied force F_m, the plate's reaction force F_{plate} and the weight of the trunk itself $m_v g$ where m_v is the mass of the trunk and g is gravity. The vertical force balance may be written as

$$m\ddot{y} = F_{plate} - F_m - m_v g = 0. \tag{3.1}$$

In other words, $F_{plate} = F_m + m_v g$: the force on the force plate is equal to the self-weight of the pillar plus any forces the elephants apply. We proceed by presenting a model for the force required to solidify the food particles.

3.2. Mathematical model of jamming force

We create an ansatz model interpretation of these results that take into account the fundamental granular nature of the food. Unlike continuum solids, force is propagated through granular materials in discrete chains, which can be deflected due to oblique particle contacts. In order for a collection of granular food to be lifted as a solid, a stable arch must span the entire two-dimensional area at the base and be of sufficient strength to withstand the weight of the particles

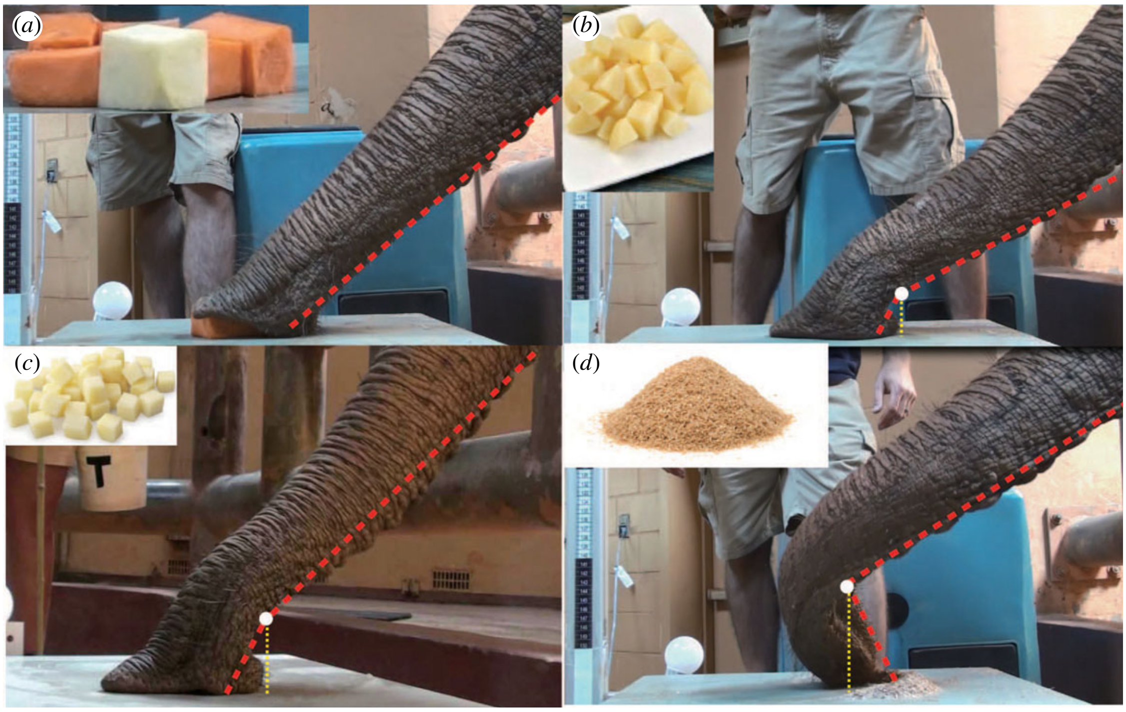

Figure 3. Trunk configuration when jamming food for (*a*) 32 mm cubes, (*b*) 16 mm cubes and (*c*) 10 mm cubes and (*d*) bran granules of diameter 2 mm. Note the carrot cubes are orange and the rutabaga cubes are red. The red dashed line is tangential to the top 50% of the trunk above the joint. Note that the trunk is straight when grabbing cubes with a side length of 32 mm, but then forms a joint when grabbing smaller pieces. When grabbing bran, the vertical part is the longest, reaching up to 11 cm. (Online version in colour.)

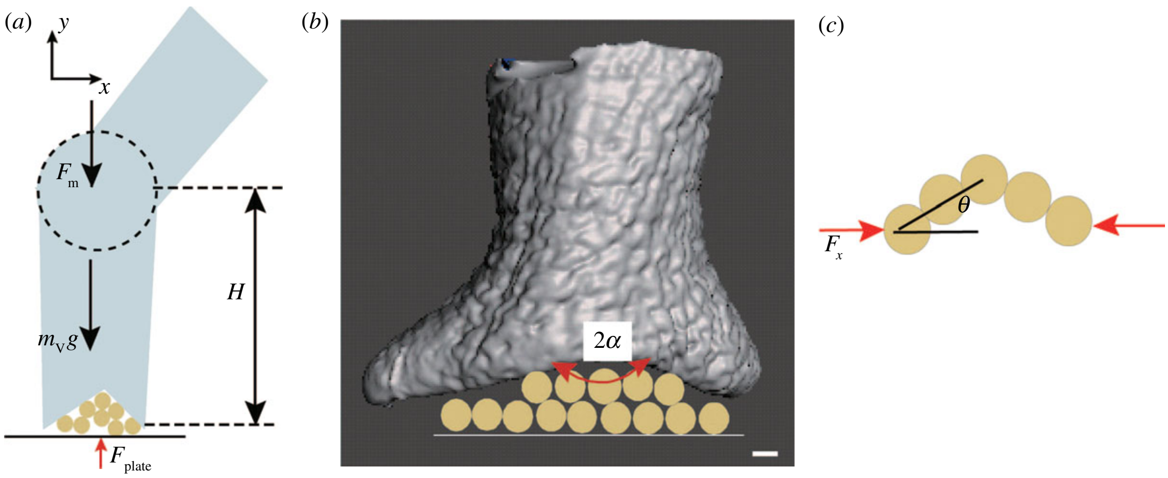

Figure 4. Schematic of forces applied to the force plate and to the food. (*a*) Schematic of the elephant trunk, with pillar weight $m_V g$, applied force at the joint of F_m. The force plate responds with a force F_{plate}. (*b*) Schematic of forces applied to the food pile. (*c*) The food is able to lift off the ground because of lateral forces F_x. Here is a jammed arch of granular particles due to the application of the horizontal force of F_x. (Online version in colour.)

above. The statistics of arch formation have been studied in two-dimensional [15] and three-dimensional [16] hoppers, with two important findings. First, the relevant length scale is the particle size; this means that spanning arches in small foods can be thought of as 'longer' than those in larger foods in that they span more particles. Second, weakest link theory explains the intuitive finding that longer arches are weaker, and therefore less common, than shorter arches. The various statistics involved in arch formation and destruction can be quantified through random mean-field approximations of particle location. Here we apply a related Weibullian weakest link analysis [17], to rationalize why the elephant applies greater forces to pick up smaller food particles.

Weakest link statistics were developed in 1939 by Weibull to explain the strength of continuum materials [18]. The analysis builds on the single assumption that a long sample comprises many smaller elements that are statistically independent. It was subsequently [17] applied to explain the stick–slip yielding of geometrically cohesive granular materials under extensional strain. Here, the key idea is that each particle contact has a probability of failing that is independent of the state of the other particles. In order for an arch or pile to be stable, all contacts must independently be stable. A review of the entire model, including its extensions to identify failure location and time-dependent failure can be found in the previous literature [19].

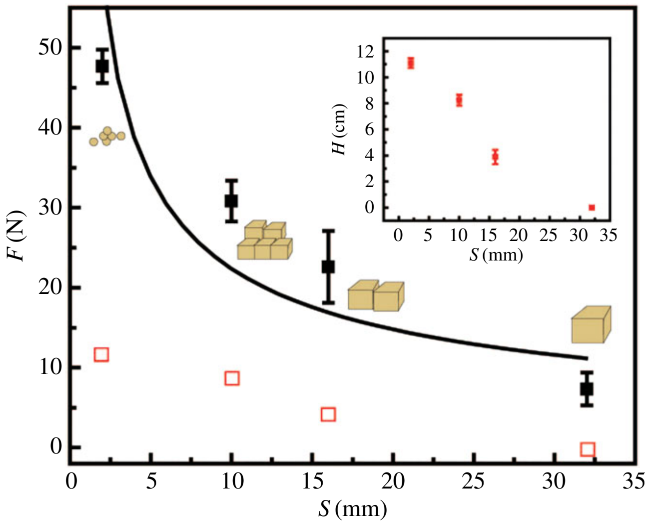

Figure 5. The relationship between applied force and food size S. The solid points represent the applied force recorded by the force plate, and the open points represent the self-weight of the trunk pillar, defined as the region below the joint. The trend line is the power-law fitting of the applied forces. The inset shows the relationship between the height H of the trunk pillar and food size S. Error bars show the standard deviation of the measurement. The self-weight of the pillar has a standard deviation of 0.5 N, which is too small to see in the graph; for that reason, the inset is shown. (Online version in colour.)

We relate by analogy the failure probability with the force needed to prevent an arch break-up. Granular contacts must support vertical forces at least equal to the pile weight. Consider four grains forming an arch supporting the weight of a particle above, as in figure 4*c*. As the angle becomes more oblique, the normal force required to sustain the weight diverges as $1/\sin\theta$. In real grains, the normal force is supplemented with a frictional force, both of which increase with confining (lateral) forces applied by the elephant. In this interpretation, if the force is not large enough to maintain the arch, then the elephant can re-establish stability by applying a larger force, i.e. weaker piles are stabilized by larger applied forces. We now show that the mean force at failure decreases as a power law with the particle size, S.

Following Weibull's original weakest-link analysis, we first assume that for small values of applied force F, the probability of a differential length δL to fail depends linearly on δL and increases with applied force F as some undetermined power law, $\delta Y \equiv F^m \delta L$; the probability for that differential length to *not fail* is $1 - \delta Y$. For a longer sample composed of i multiple units to not fail, each individual sub-unit must not fail. The probability that *all units* simultaneously will not fail is

$$\prod_i (1 - \delta Y) = \prod_i (1 - \beta F^m \delta L), \tag{3.2}$$

where β is a constant introduced for dimensional reasons and the product is over all i units. We assume that the probability of an individual unit yielding is small compared to 1, in which case we can make the approximation

$$\ln\left[\prod_i (1 - \beta F^m \delta L\right] = \sum_i \ln[1 - \beta F^m \delta L] \approx \sum_i -\beta F^m \delta L. \tag{3.3}$$

The sum of the differential lengths is just the total sample length, $\sum_i \delta L = L$. In experiments, the elephant trunk is picking up samples of approximately the same length; as the food size S decreases, more particles are needed to span that space. The index i increases as $1/S$, and so we can rewrite equation (3.2), which gives the probability that the chain will not break, in terms of the applied force F and the grain size S as

$$\prod_i (1 - \delta Y) \approx e^{-\beta F^m/S}. \tag{3.4}$$

The probability that the chain of particles of size S will fail at the applied force F is then equation (3.4) subtracted from unity, or

$$P(F, S) = 1 - e^{-\beta F^m/S}. \tag{3.5}$$

We now reproduce the calculations from [17] to find the average yield force as a function of grain size. Equation (3.5) is the probability that a chain of particles of size S will fail at the applied force F. Piles are not subjected to instantaneous forces, however. For failure at a *particular* force F to be observed, the pile must not fail at the lesser forces applied. The total probability to observe failure at force F and size S is therefore the product of equations (3.4) and (3.5):

$$P_{\mathrm{obs}}(F, S) = CS^m e^{-\beta F^m/S}(1 - e^{-\beta F^m/S}), \tag{3.6}$$

where the prefactor CS^m is included for normalization so that $\int_0^\infty P(F, S)\,\mathrm{d}F = 1$. The mean force observed $\bar{F}_{\mathrm{obs}}(S)$ is then

$$\bar{F}_{\mathrm{obs}}(S) = \int_0^\infty F P_{\mathrm{obs}}(F, S)\,\mathrm{d}F = CS^m \int_0^\infty F[e^{-\beta F^m/S} - e^{-2\beta F^m/S}]\,\mathrm{d}F \propto S^{1/m}. \tag{3.7}$$

$\bar{F}_{\mathrm{obs}}$ is the average force required to break a chain of particles of size S. Our hypothesis is that when the pile weight exceeds this force, the elephant stabilizes the pile by applying a larger lateral force that increases the friction forces within the pile. For simplicity, we assume that the applied force F needed is first order inversely proportional to the pile strength $\bar{F}_{\mathrm{obs}}$, and so we arrive at the conclusion that $F \propto S^{-1/m}$ shown in figure 5.

4. Results

We filmed 24 trials of the elephant grabbing food. In a third of the trials, the elephant curled its trunk around the food to

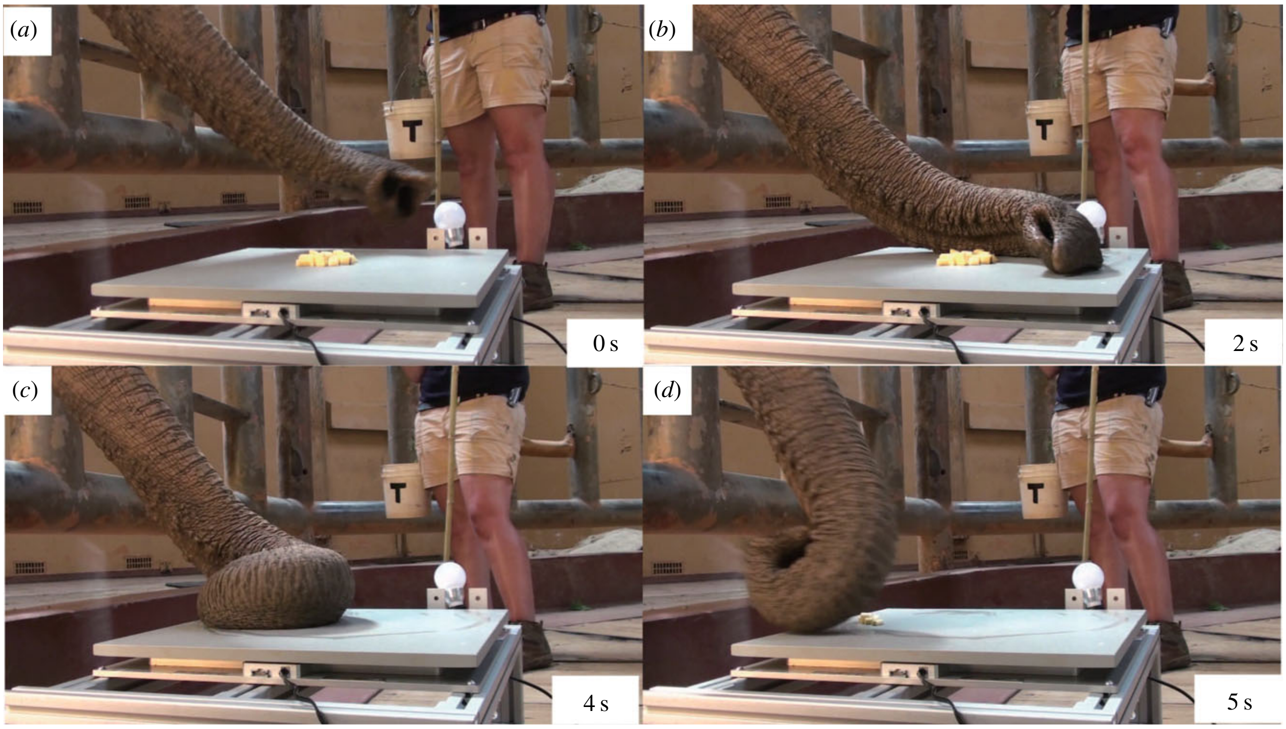

Figure 6. Food grabbing by curling the trunk. (*a*) The trunk curls and sweeps the food together. (*b*) The trunk carefully squeezes the food in a loop to carry it to the mouth. (*c*) The trunk loop holds the food. (*d*) The food is picked up by the trunk. (Online version in colour.)

grip and lift it. Figure 6 and electronic supplementary material, video S2 shows the elephant curling to grab an entire pile of 10 mm cubes. This technique is successful at obtaining more than 80% of the food items. The remaining 20% of food items are fetched on a return trip of the trunk. Each curling action takes 6 ± 2 s ($N = 4$). For the remainder of this paper, we focus on the elephant's most typical method for grabbing piles of particles: formation of a joint and downward pushing to jam the particles.

The elephant's method of grabbing bran is shown in figure 2 and electronic supplementary material, video S1. The elephant first extends her trunk to locate the force platform. When this occurs, the food pile is usually missed by 10 cm, which is suggestive of the elephant's poor vision. Once contact is made with the platform, the elephant sweeps the food into a pile with the tip of her trunk. During the sweeping process, she appears to keep the trunk oriented diagonally, aimed directly toward the food. However, grabbing the food requires substantial horizontal forces to stabilize the particles. Thus, once sweeping ceases, she pushes downward while spreading her trunk's two finger-like extensions, as shown in figure 4. Then the food is taken into the mouth by curling the trunk (figure 1).

This sequence of events corresponds to changes in the applied force, which we measure with a force platform synchronized to the video. The time course of the contact force is shown in figure 7, for 32 mm cubes, 16 mm cubes and bran. When the elephant trunk makes the first contact with the plate, a force peak of magnitude 20−40 N is reached for a fraction of a second, associated with impact of the trunk with the plate. We believe this force is large because the trunk is heavy; by tracking the trunk tip when it approaches the force plate, we find that the elephant trunk actually slows in speed by 50% before impact with the plate (electronic supplementary material, figures S7–S10). This reduction in speed suggests that the elephant can anticipate the position of the force plate. After the initial impact, the elephant rests part of her trunk on the scale as she sweeps the food, showing a plateau in force of 10–20 N for a duration of 4–10 s. This force is likely required to ensure adequate contact with the scale to perform the sweeping action. The contact force doubles to 30–40 N for a second when the elephant picks up all objects, except for the 32 mm cubes. In figure 7*a*, the force applied when picking up the 32 mm cubes is only 7 N. By watching our videos synchronized to the force platform, we observed that the onset of peak contact force coincided with the elephant bending its trunk from a straight configuration to one with a kink, or joint.

Figure 3 shows the configuration of the trunk for each food item, at the point where the applied force is highest. The elephant forms joints in all 12 trials except for trials involving the largest food size, 32 mm cubes (figure 3*a*). We characterized the pillar by a height H, shown by the dotted yellow line in figure 3. When picking up bran, the trunk pillar has a height of 11 ± 0.39 cm. In comparison, when picking up 16 mm cubes, the elephant uses a pillar height that is one third as tall, of height 3.9 ± 0.55 cm. Clearly, the elephant has a great deal of control of the height of this pillar. Using the density of a deceased elephant's trunk, we calculate using equation (2.1) in §3.1 the weight of the pillar.

Figure 5 shows the pillar weight (open points) and applied force by the elephant (closed points) as a function of the different food size S. As objects decrease in size, the pillar weight and applied force both increase. When picking up the smallest object, the elephant applies a force of 48 ± 2.1 N and generates a pillar of 11 ± 0.38 N in weight. For all the food items except for the 32 mm cubes, the pillar weight is 20–30% of the force applied. The elephant does not form a pillar, for the 32 mm cubes, but still applies a force of $F_{\min} = 7.3 \pm 2.0$ N. We speculate it is the minimum force resolution that the elephants can sense.

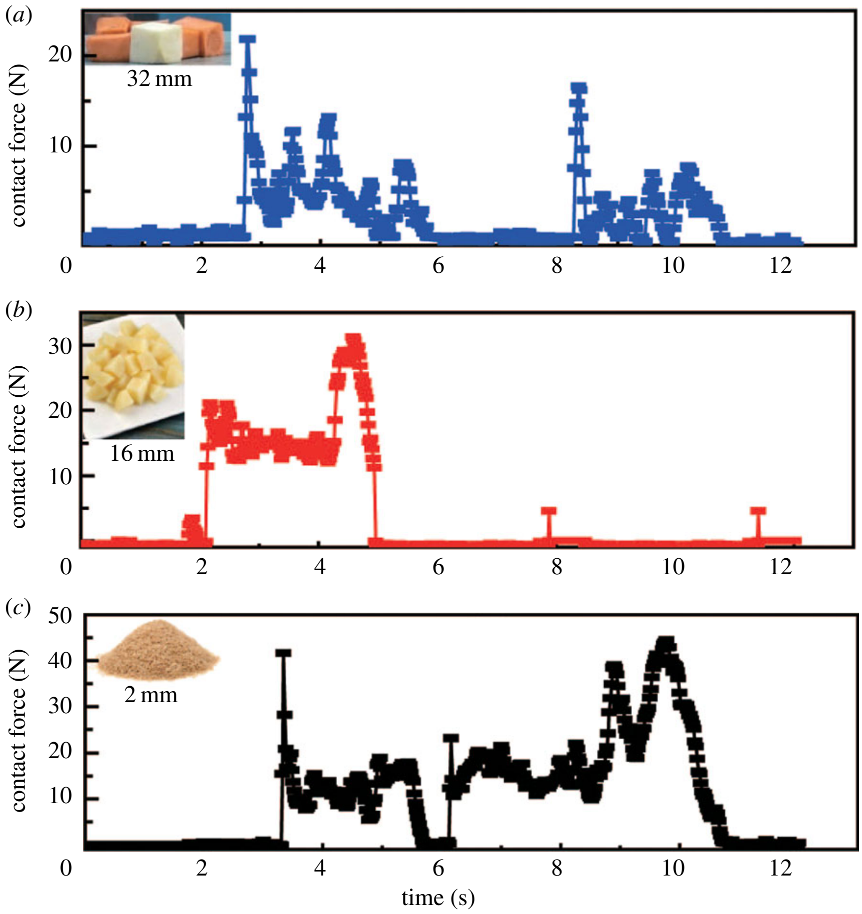

Figure 7. Real-time contact force while grabbing (*a*) 32 mm cubes, (*b*) 16 mm cubes, and (*c*) wheat bran (2 mm in diameter). A force peak of 20–40 N is made when the elephant trunk first reaches the force plate. The force then drops and forms a plateau of 10–20 N. At the moment when the elephant pushes down the food to pick it up, the contact force doubles to 20–40 N. (Online version in colour.)

The black line in figure 5 is a power law fit to the applied force by the elephant, whose equation is given by

$$\bar{F}_{\text{plate}} = 89S^{-0.60}, \tag{4.1}$$

where S is the food size. Equation (4.1) is a good fit to the experimental measurements ($R^2 = 0.76$). While we cannot predict the exponent nor the prefactor in equation (4.1), the theory in the math modelling section correctly predicts that the exponent has a negative sign. The bran of size 2 mm requires nearly 50 N of force, more than three times the force of the 32 mm carrot cubes. Why do smaller objects require more force to pick up? The difference between the pile of carrot cubes and bran is that the bran involves a far greater number of particles. When the particles are squeezed together to be picked up, each particle has a small chance of failure. Thus, the bran pile requires more applied force to overcome the accumulated failure probability of the large number of grains involved.

5. Discussion

Although the elephant trunk lacks bones, the formation of a joint mimics a common vertebrate strategy to reach out and grab objects. The human upper limb, for example, has seven degrees of freedom. These degrees of freedom make it possible to reach out into arbitrary points in three-dimensional space and grab objects, as well as perform twisting motions in all three directions. An animal with more joints has more degrees of freedom to accomplish tasks. But these joints also provide challenges too, as the animal must search through more potential solutions. This is why appendages without bones, such as the elephant trunk and octopus arm, have both demonstrated the formation of joints. The octopus forms a joint like the elbow only when retrieving food [20,21]. Our study shows that the use of joints might be more common than once thought.

In our study of captive elephants, we prepared cubic food items that the elephant would never find in nature. Nevertheless, wild elephants may still apply the strategies we observed if they need to press downward with their trunk while feeding. Wild elephants eat grasses, small plants, bushes, fruit, twigs, tree bark and roots. To remove the bark from a tree, vertical forces are required, and its possible the elephant may form joints for this task. Now that we have observed the formation of joints, future work will determine how often elephants use this strategy.

Long flexible robots have long been of interest to the robotics community. Such researchers have turned to snakes, octopus and elephants for inspiration. However, even among these animals, the elephant stands out because the trunk can apply the greatest forces. For elephant-inspired robots to apply large forces, they will inevitably become larger. We surveyed four elephant-inspired robots whose weights were reported [6,22,23]. On average, their weight is 5 kg, which is nowhere near the elephant trunk. Nevertheless, a number of elephant-inspired robots have sufficient degrees of freedom that they could be used to generate joints [6,11,24]. In particular, the elephant-inspired robot by Mcmahan *et al.* [7] can perform many of the corresponding motions observed in our work. For example, when this robot lifts an aluminium can, it cradles the can by forming a kink in its trunk, clearly showing that elephant robots have the ability to form joints (see video accompanying the paper) [12].

In our study, we observed the elephant is applying up to 47 N of force in order to pick up the 50-g pile of wheat bran. This means that the elephant must exert 100 times the weight of the pile in order to pick it up. We identified in this study that the weight of the trunk pillar provides up to 28% of the applied force. The remainder of the forces may also come from self-weight of the remainder of the trunk. The entire trunk weighs about 150 kg, or 1472 N. Thus, by simply relaxing just 3% of the weight of the trunk, it might generate enough force to compress the wheat bran. The entire trunk is about 1.9 m long when it is relaxed (electronic supplementary material, figure S1) [25]. We estimate that the 47 N of applied force would require the distal 46 cm of the trunk to be recruited to apply self-weight. In our experiments, the elephant was a horizontal distance of 46 cm away from the force plate, which provided a large constraint to the elephant's grabbing. If the elephant were closer, it might generate a taller trunk pillar to help itself.

6. Conclusion

In this study, we investigate how elephants pick up piles of objects. The challenge in performing this task is that compressive forces must be applied to the objects so that they do not slip away. Using mathematical models, we showed that the greater the number of objects, the more compressive force must be applied. We test this idea in our experiments by providing elephants with food items varying from four to 40 000 in number. Elephants accordingly can vary the forces they apply by a factor of four, from 7 to 47 N. Using synchronized force platforms and video cameras, we show that the application of this force is accompanied by the formation of a kink or joint in the elephant trunk. The distal end of the trunk forms a pillar which provides up to 28% of the applied force. Forming joints may help reduce the energy required to reach for and grab food items, a task they perform for 18 h every day. The joint formation may also have application in elephant-inspired robots.

Ethics. All experiments are approved by Zoo Atlanta's Scientific Research Committee and the Georgia Tech Institutional Animal Care and Use Committee.

Data accessibility. This article has no additional data.

Competing interests. We declare we have no competing interests.

Funding. This work was supported by the US Army Research Laboratory and the US Army Research Office Mechanical Sciences Division, Complex Dynamics and Systems Program, under contract no. W911NF-12-R-0011.

Acknowledgements. We thank N. Elgart and Zoo Atlanta curators for helping us conduct the elephant's grabbing experiments. We thank J. Reidenberg from Mount Sinai School of Medicine, New York for providing the frozen trunk section. We thank the Division of Mammals, National Museum of Natural History, and the Smithsonian Institute for their assistance with the frozen trunk section. We thank Dr Dalen Agnew for working with the frozen trunk section. We thank Sara Ha, Gerina Kim and Dhanusha Subramani for their early contributions.

Reference

1. Shoshani J. 1998 Understanding proboscidean evolution: a formidable task. *Trends Ecol. Evol.* **13**, 480–487. (doi:10.1016/S0169-5347(98)01491-8)
2. Wyatt J, Eltringham S. 1974 The daily activity of the elephant in the Rwenzori National Park, Uganda. *Afr. J. Ecol.* **12**, 273–289. (doi:10.1111/j.1365-2028.1974.tb01037.x)
3. Ullrey DE, Crissey SD, Hintz HF. 1997 *Elephants: nutrition and dietary husbandry*. East Lansing, MI: Nutrition Advisory Group.
4. Hoy M, Matveev AS, Savkin AV. 2015 Algorithms for collision-free navigation of mobile robots in complex cluttered environments: a survey. *Robotica* **33**, 463–497. (doi:10.1017/S0263574714000289)
5. Kitaev N, Mordatch I, Patil S, Abbeel P. 2015 Physics-based trajectory optimization for grasping in cluttered environments. In *2015 IEEE Int. Conf. on Robotics and Automation, Seattle, Washington, 25–30 May*, pp. 3102–3109. Piscataway, NJ: IEEE.
6. Tsukagoshi H, Kitagawa A, Segawa M. 2001 Active hose: an artificial elephant's nose with maneuverability for rescue operation. In *Proc. 2001 IEEE Int. Conf. on Robotics & Automation, Seoul, Korea, 21–26 May*, pp. 2454–2459. Piscataway, NJ: IEEE.
7. McMahan W *et al.* 2006 Field trials and testing of the OctArm continuum manipulator. In *Proc. 2006 IEEE Int. Conf. on Robotics and Automation, 2006. ICRA 2006. Orlando, FL, 15–19 May*, pp. 2336–2341. Piscataway, NJ: IEEE.
8. Miedema S, Vlasblom W. 2006 The closing process of clamshell dredges in water-saturated sand. In *CEDA African Section: Dredging Days 2006 - Protection of the coastline, dredging sustainable development, 1–3 November, Tangiers, Morocco*, pp. 1–3.
9. Amend JR, Brown E, Rodenberg N, Jaeger HM, Lipson H. 2012 A positive pressure universal gripper based on the jamming of granular material. *IEEE Trans. Robot.* **28**, 341–350. (doi:10.1109/TRO.2011.2171093)
10. Kim S, Laschi C, Trimmer B. 2013 Soft robotics: a bioinspired evolution in robotics. *Trends Biotechnol.* **31**, 287–294. (doi:10.1016/j.tibtech.2013.03.002)
11. Hannan MW, Walker ID. 2003 Kinematics and the implementation of an elephant's trunk manipulator and other continuum style robots. *J. Robot. Syst.* **20**, 45–63. (doi:10.1002/rob.10070)
12. Holbrook B, Csencsits M, McMahan W, Chitrakaran V, Grissom M, Pritts M, Jones B, Rahn C, Walker I 2006 Field experiments with the OctArm continuum manipulator. In *2006 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems. Beijing, China, 9–15 October*, pp. 10–10. Piscataway, NJ: IEEE.
13. Kier WM, Smith KK. 1985 Tongues, tentacles and trunks: the biomechanics of movement in muscular-hydrostats. *Zool. J. Linn. Soc.* **83**, 307–324. (doi:10.1111/j.1096-3642.1985.tb01178.x)
14. Charrondiere U, Haytowitz D, Stadlmayr B. 2012 FAO/INFOODS Density Database, version 2.0. See http://www.fao.org/docrep/017/ap815e/ap815e.pdf.
15. To K, Lai P-Y, Pak H. 2001 Jamming of granular flow in a two-dimensional hopper. *Phys. Rev. Lett.* **86**, 71–74. (doi:10.1103/PhysRevLett.86.71)
16. Zuriguel I, Pugnaloni LA, Garcimartin A, Maza D. 2003 Jamming during the discharge of grains from a silo described as a percolating transition. *Phys. Rev. E* **68**, 030301. (doi:10.1103/PhysRevE.68.030301)
17. Franklin SV. 2014 Extensional rheology of entangled granular materials. *EPL* (*Europhys. Lett.*) **106**, 58004. (doi:10.1209/0295-5075/106/58004)
18. Weibull W. 1939 *A statistical theory of the strength of materials*. Stockholm, Sweden: Ingeniors Vetenskaps Akademien.

19. Cassenti BN. 2004 *Engineering design reliability handbook*. Boca Raton, FL: CRC Press.
20. Sumbre G, Fiorito G, Flash T, Hochner B. 2006 Octopuses use a human-like strategy to control precise point-to-point arm movements. *Curr. Biol.* **16**, 767–772. (doi:10.1016/j.cub.2006.02.069)
21. Sumbre G, Fiorito G, Flash T, Hochner B. 2005 Neurobiology: motor control of flexible octopus arms. *Nature* **433**, 595–596. (doi:10.1038/433595a)
22. Stoll W. 2011 *Mobile learning flexibly extended*. Festo. See https://www.festo.com/PDF_Flip/corp/Festo_RobotinoXT/en/files/assets/ba sic-html/page-6.html.
23. Katona J, Ujbanyi T, Sziladi G, Kovari A. 2016 Speed control of Festo Robotino mobile robot using NeuroSky MindWave EEG headset based brain-computer interface. In *7th IEEE Int. Conf. on Cognitive Infocommunications (CogInfoCom), Wroclaw, Poland, 16–18 October*, pp. 000251–000256. Piscataway, NJ: IEEE.
24. Cieslak R, Morecki A. 1999 Elephant trunk type elastic manipulator—a tool for bulk and liquid materials transportation. *Robotica* **17**, 11–16. (doi:10.1017/s0263574799001009)
25. Mahajan U, Wainwright S, Croner L. 1991 A continuum model of elephant trunks. *J. Biomech. Eng.* **113**, 79–84. (doi:10.1115/1.2894088)