EPJ Web of Conferences **340**, 06022 (2025) https://doi.org/10.1051/epjconf/202534006022
*Powders & Grains 2025*

# Influence of brush fibers on sand ejection by a pendulum swept

*Yuto* Ochi[1,*], *Takumi* Akeda[2], *Shin-ichi* Fujiwara[3], and *Hiroaki* Katsuragi[1]

[1]Department of Earth and Space Science, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka, 560-0043, Japan
[2]Graduate School of Environmental Studies, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8601, Japan
[3]Nagoya University Museum, Furo-cho, Chikusa-ku, Nagoya, 464-8601, Japan

**Abstract.** Some birds rapidly move their wings or feet to toss sand into the air for the sake of self-maintenance by sandblasting. This behavior is called “dust bathing”. Although dust bathing is an important factor for the health of birds, its physical mechanisms have rarely been studied. Mechanics of sand tossing induced by a sweep of soft feather is intriguing also in terms of granular physics. In this study, we experimentally investigate the fundamental physical process of dust bathing. Specifically, a pendulum with a brush at its tip is used to sweep the surface of a sand bed, and the resulting sand ejection behavior is observed. In particular, we systematically vary the sweeping velocity $v_0$, sand particle size $D_\mathrm{p}$, and measure the ejection mass $M$, the ejection speed $V$, and the ejection angle $\theta$ of the center of mass of splashed sand cluster. As a result, we find that $M$ decreases with increasing $v_0$. However, $V$ increases with increasing $v_0$. At a high $v_0$ regime, $V$ is faster than $v_0$. The ejection angle $\theta$ gradually saturates as $v_0$ increases. We also find that the ejection behavior (characterized by $M$, $V$, and $\theta$) is independent of the sand particle size $D_\mathrm{p}$ under the experimental conditions of this study.

## 1 Introduction

Sparrows can often be observed moving their bodies and flapping their wings on sandy spots. This behavior is known as “dust bathing”. The purpose of dust bathing is to eliminate parasites and regulate body oils [1]. While dust bathing is an important factor in the living activities of some birds, its physical mechanisms have rarely been examined particularly in the realm of granular mechanics.

There are many phenomena relating to dust bathing and soil excavation. For example, Zhang et al. attempted to optimally design a robot leg by modeling the force in granular media using the Resistance Force Theory (RFT) [2]. This work was inspired by the digging ability of moles’ front legs. By considering a similar setup, Yang et al. applied the slip-line theory to develop a model for ground reaction force against a robotic leg rotation in granular media [3]. These studies have mainly focused on the excavation of granular media by a rigid body motion. However, animal tissues used for dust bathing are not rigid. Rather, they are soft. For instance, ostriches toss sand by flapping their wings. Obviously, wings consisting of feathers are very flexible and soft. Dust bathing by the sweeping impact of such a highly deformable impactor has not been systematically studied yet.

Therefore, in this study, we aim to understand the fundamental physical processes of dust bathing induced by soft impact experiment, as observed in dust bathing by birds. Specifically, the goal of this study is to clarify how sand is ejected by a sweep of a soft brush (collection of hairs or fibers). Although the actual dust-bathing behavior is complex, we simplify the model setup. Namely, this study focuses on the fundamental aspect of dust bathing as a first step in characterizing the phenomenon. To reduce complexity, we develop a simple experimental setup using a pendulum and a brush. As a target, we use roughly mono-disperse glass beads to form a relatively homogenous sand bed. Glass beads are spherical and much different from actual sand. However, dry glass beads have been used as a standard granular matter in various studies to avoid complex effects. Thus, we follow this convention. We also employ a rigid-body pendulum with a brush (fiber bundle) attached to the pendulum. The brush we use is an industrial channel brush (bristles are held by a metal cramp) with relatively uniform fiber density. The brush sweeps the glass beads surface by using a pendulum mechanism, and the resulting sand ejection behavior is analyzed.

## 2 Materials and methods

We develop an experimental apparatus to observe the sand ejection behavior (Fig. 1(a,b)). The pendulum, with a brush at its tip, swung down from a certain angle sweeps the surface of the glass beads bed. Then, the sweeping brush tosses glass beads. The ejected glass beads are collected by a vessel placed at the bottom of the setup. Then, the mass of ejected glass beads $M$ is measured by an electronic balance (A&D, EK-300i). The length of the pendulum excluding the brush is 0.21 m and its mass is 0.82 kg. The pendulum is initially held by an electromagnet and released, i.e., the pendulum motion is driven by gravity. The held angle measured from the vertical direction is varied

---

[*] e-mail: y.ochi@ess.sci.osaka-u.ac.jp

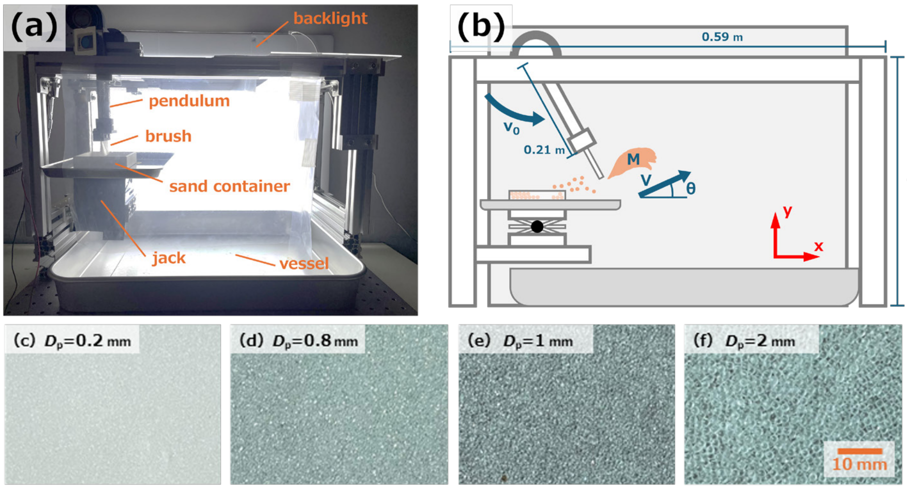

**Figure 1.** Experimental setup, coordinate system, controlled and measured quantities, and glass beads used in this study. (a) Photograph of the actual experimental setup. (b) Schematic illustration of the apparatus. Motions of glass beads and brush pendulum are captured with a high-speed camera using a backlight illumination. The sweeping velocity of the brush onto the sand surface, $v_0$, is systematically varied. The amount of ejected glass beads $M$, ejection speed $V$, and ejection angle $\theta$ in the forward direction ($x > 0$, $y > 0$) are measured. (c-f) Photograph of glass beads used in the experiment: particle diameter (c) $D_\mathrm{p} = 0.2$ mm, (d) $D_\mathrm{p} = 0.8$ mm, (e) $D_\mathrm{p} = 1$ mm, and (f) $D_\mathrm{p} = 2$ mm.

from 45° to 135°. This release-angle variation results in the sweeping-velocity variation ranging from 1.4 m/s to 3.1 m/s. Five experimental runs with identical experimental conditions are performed to ensure reproducibility. The coordinate system is defined as shown in Fig. 1(b).

The motions of the pendulum and ejected glass beads are captured by a high-speed camera (Photron, FASTCAM SA5) equipped with a lens (Nikon, NIKKOR 28–85 mm f/3.5–4.5), by using a panel LED illumination as a backlight. The frame rate of the image acquisition is fixed at 2,000 fps. The size of the acquired image is 1,080×1,080 pixels with a spatial resolution of 0.47 mm/pixel. By measuring the pendulum motion, we confirm that the pendulum rotation speed does not vary before and after sweeping. This means that the mass of the pendulum is large enough to neglect the deceleration due to the sweeping.

The sand beds used in this study consist of glass beads (Fig. 1(c-f)). The representative particle size $D_\mathrm{p}$ is varied as, 2 mm, 1 mm, 0.8 mm, and 0.2 mm (AS-One: BZ-20, BZ-10, BZ-08, and BZ-02, respectively). The sand bed is prepared in a 100 mm × 100 mm × 20 mm container. The height of the container is adjusted by the jack to fix the swept thickness of the target sand bed at 1 mm. The brush used in this experiment is made of Nylon 6 (Young's modulus: 1.8 GPa. This value is close to an actual bird feather [4]), and its dimensions are as follows: length, $3 \times 10^{-2}$ m; thickness, $5 \times 10^{-3}$ m; width, $5 \times 10^{-2}$ m; and bristle diameter, $2.0 \times 10^{-4}$ m (MISUMI, BRUSN5-0.2-30-50).

In this study, we analyze the collection of glass beads tossed forward by the sweeping (hereafter referred to as "clusters"). Specifically, a cluster is defined as the beads ejected forward from the tip of the brush. In each experimental condition, the ejected cluster is caught by a trapping vessel to measure the ejection mass $M$. The ejection speed $V$ and the ejection angle $\theta$ of the center of mass of the clusters are computed by analyzing the high-speed images. The center of mass of the cluster was determined by binarizing an image that was trimmed to isolate the cluster. Specifically, a threshold was set to separate the cluster from the trimmed image, and its center of mass was then determined by calculating the centroid of the cluster area. At the same time, the sweeping (impact) velocity between the brush and the target sand bed, $v_0$, is measured by using the time series data of the pendulum motion.

## 3 Results

The raw data examples are shown in Fig. 2. After the cluster detaches from the brush, the cluster experiences free fall due to gravity. From the raw images right after the detaching, we can measure $V$ and $\theta$. Here, we define the time frame $t = t_0$ at which the cluster detaches from the brush. Within a short timescale, the motion of the cluster's center of mass can be approximated by the ballistic motion. As shown in Fig. 3, both the horizontal and vertical components of $V$ can be approximated by linear motions in the range of $0 \leq t - t_0 \leq 10$ (ms). Therefore, the ejection speed $V$ and its angle $\theta$ immediately after the cluster ejection are estimated by calculating the slope of linear approximations of the cluster's center-of-mass positions in $x$ and $y$ directions, $X_\mathrm{G}(t - t_0)$ and $Y_\mathrm{G}(t - t_0)$, as shown in Fig. 3.

Figure 4 shows the measured ejection mass $M$, the ejection speed $V$, and the ejection angle $\theta$, as a function of the sweeping velocity $v_0$ with various particle diameters, $D_\mathrm{p}$. The plots represent the average of five trials, and the error bars indicate the standard deviation. In Fig. 4, the following trends are observed. Regarding the ejection

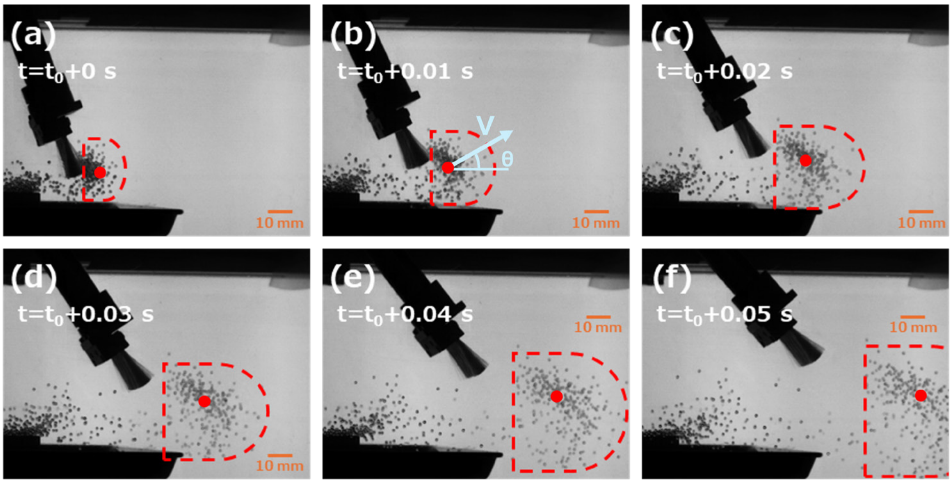

**Figure 2.** Raw data images of the sweeping pendulum with a brush and an ejected cluster. The panels (a-f) show the temporal development of the cluster's motion. The red dots indicate the representative central point of each cluster. The red dashed circles roughly indicate the circumscription of the cluster.

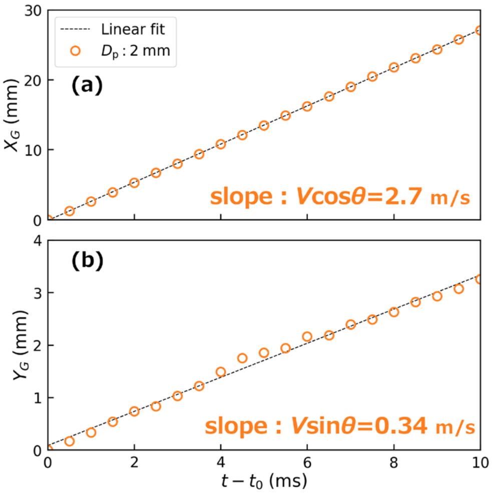

**Figure 3.** Temporal evolution of (a) the horizontal and (b) the vertical position of the cluster's center of mass. The center-of-mass positions of the cluster are tracked over 21 frames from the moment it detaches from the brush, $0 \leq t - t_0 \leq 10$ (ms). By the linear fitting to these data, $V$ and $\theta$ can be computed.

mass $M$, it decreases with increasing sweeping velocity $v_0$ in a large $v_0$ regime. In contrast, the ejection speed $V$ increases with increasing $v_0$. Besides, at large $v_0$ range, the ratio $V/v_0$ increases and exceeds unity (inset of Fig. 4(b)). This implies that the cluster is ejected faster than $v_0$. As for the ejection angle $\theta$, it shows a slight increase with increasing $v_0$. However, this dependence is weak, and $\theta$ saturates around 0.1 rad. Additionally, one can realize that all the measured quantities, $M$, $V$, and $\theta$, are independent of particle size $D_\mathrm{p}$.

## 4 Discussion

These results are now considered in the context of birds' dust-bathing behavior. According to the experimental results, when the sand is tossed from the sand bed using a deformable brush, $M$ decreases with $v_0$. This suggests that birds cannot toss a larger amount of sand simply by flapping their wings faster. However, $V$ has a positive correlation with $v_0$, and $V/v_0$ exceeds unity at large $v_0$ regime. This indicates that the fast flapping of birds' wings during dust bathing mainly contributes to inducing fast particle ejection. To achieve efficient sandblasting, high-speed particle splashing is certainly advantageous. Thus, fast flapping is beneficial for birds dust-bathing. The ejection angle $\theta$ shows a saturation trend at $v_0 \gtrsim 2$ m/s. To cover the wide region of the body surface by the ejected sand particles, a larger $\theta$ is preferred. In this sense, the most efficient flapping speed is around 2 m/s. Namely, these results suggest that an optimal sweeping velocity for creating large and fast cluster splashing with a large splashing angle can be estimated, based on the comparison between actual bird feather properties and the experimental conditions. Quantitative assessment of such actual dust bathing is the most important future work.

Our experiment also reveals that the sand ejection behavior is independent of the sand particle size, $D_\mathrm{p}$. However, this size-invariance is not expected to hold for extremely large or extremely small particles, where different physical effects may become dominant. This implies that for a given sweeping velocity within our experimental regime, the total mass of ejected sand is constant regardless of particle size. Consequently, the bed consisting of smaller particles results in a larger number of ejected particles. This means that the sand beds consisting of smaller particles are better to increase the collision frequency between particles and bird body surfaces. This is consistent with the previous studies reporting that chickens prefer the sand beds consisting of smaller particles for dust bathing [5, 6].

We now discuss the experimental results from the perspective of momentum conservation. Letting $M_0$ be the

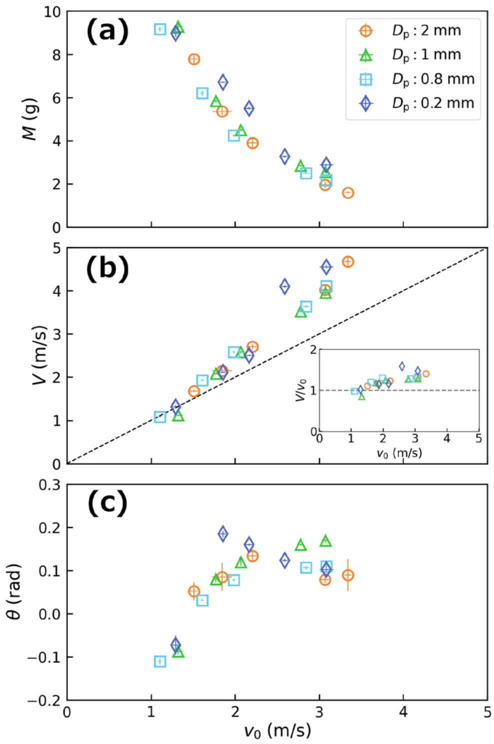

**Figure 4.** (a) Ejection mass $M$, (b) speed $V$, and (c) angle $\theta$, as a function of impact velocity $v_0$. The color indicates the particle size $D_\mathrm{p}$. The inset of (b) shows the $V/v_0$.

mass of sand mobilized by the brush sweep, the momentum conservation can be expressed as $M_0 v_0 = MV$.

In the low $v_0$ regime, a simple relation $v_0 \approx V$ is satisfied (Fig. 4(b)). This implies the mobilized mass is nearly equal to the ejected mass $M_0 \approx M$. In the high $v_0$ regime, on the other hand, $M$ decreases with $v_0$ (Fig. 4(a)), while $V$ exceeds $v_0$ (Fig. 4(b)). This result is qualitatively consistent with the momentum conservation, $M_0 v_0 = MV$. However, $M$ is quantitatively smaller than the expected value.

Rather, by focusing on the "deformation" of the impacting brush hair, the results in the high $v_0$ regime can be interpreted as follows:
1) The deformation of the brush reduces the effective excavation volume, leading to a decrease in $M$.
2) The elastic energy stored in the deformed brush is transferred to the ejected particles when they are released, thereby accelerating the ejection.

To quantitatively evaluate this model, a reliable estimate of $M_0$ is necessary. However, its direct measurement is not easy. Here, we propose a way to estimate the impulse based on the brush deformation $\delta$. The impulse caused by $\delta$ at time $t$ ($t = 0$ corresponds to the impact moment) can be formulated with the Young's modulus $E$, the area moment of inertia $I$, and the length $L$ of the brush, as:

$$M_0 v_0 = \frac{3EI}{L^3} \int_0^t \delta(t')dt'$$

Therefore, to estimate the moment $M_0 v_0$, the accurate measurement of the brush deformation $\delta$ is a crucial future task.

## 5 Conclusions

In this study, we observe the sand ejection behavior induced by sweeping with a deformable brush. We systematically vary the sweep velocity $v_0$ and the sand particle size $D_\mathrm{p}$. We measure the resultant ejection mass $M$, speed $V$, and angle $\theta$. As a consequence, we find that $M$ decreases with $v_0$, while $V$ increases with increasing $v_0$. In particular, at a high $v_0$ regime, the ratio $V/v_0$ exceeds unity. The ejection angle $\theta$ shows a slight increase followed by saturation with increasing $v_0$. By the combination of these effects, an optimal flapping speed of wings for dust bathing could be estimated from the physical properties of birds' feathers. In addition, under our experimental conditions, $D_\mathrm{p}$ has little influence on ejection behavior. This means that smaller sand is better for dust bathing.

In a future study, more systematic experiments should be conducted using brushes with various bristle thicknesses (bending rigidity) and densities. This will help clarify the effect of impactor (sweeper) deformation. Additional experiments covering a wide range of parameters are the key to developing a comprehensive model for dust-bathing behavior. Finally, a crucial future challenge is to discuss the correspondence between our findings and the actual dust-bathing behaviors.

## Acknowledgements

This work was also supported by JSPS KAKENHI Grant Number JP24H00196.

## References

[1] I. A. S. Olsson and L. J. Keeling, "Welfare of birds in relation to dustbathing behavior," *Appl. Anim. Behav. Sci.*, vol. 93, no. 3–4, pp. 259–282, 2005. https://doi.org/10.1016/j.applanim.2004.11.018

[2] T. Zhang *et al.*, "Bionic mechanism of dust-removal in birds and its application," *J. Bionic Eng.*, vol. 22, pp. 171–180, 2025. https://doi.org/10.1007/s42235-024-00633-0

[3] C. Yang *et al.*, "Modeling and analysis of granular media excavation with rotating rigid bodies," *Mech. Mach. Theory*, vol. 152, 103901, 2020. https://doi.org/10.1016/j.mechmachtheory.2020.103901

[4] R. H. Bonser and P. P. Purslow, "The Young's modulus of feather keratin," *J. Exp. Biol.*, vol. 198, pp. 1029–1033, 1995. https://doi.org/10.1242/jeb.198.4.1029

[5] S. J. Shields, J. P. Garner, and J. A. Mench, "Dustbathing by broiler chickens: a comparison of preference for four substrates," *Poult. Sci.*, vol. 84, no. 12, pp. 1816–1824, 2005. https://doi.org/10.1093/ps/84.12.1816

[6] D. W. van Liere, "The significance of dust-bathing for the well-being of chickens," *Behav. Process.*, vol. 26, no. 2–3, pp. 177–188, 1992. https://doi.org/10.1016/0376-6357(92)90012-3