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Superb autorotator: rapid decelerations in impulsively launched samaras

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Autorotation of botanical samaras, with a consequent reduction in their rate of descent, increases dispersal range in the presence of horizontal winds. Samaras in initial free fall from rest pass through a brief transitional phase prior to reaching their minimum rate of descent and stable autorotation. By contrast, intense wind gusts and elastic recoil of tree branches can produce impulsive samara detachment and accelerate them rapidly through the air. Here, we investigate the autorotation of maple samaras when launched with a high initial impulse. Norway maple seeds catapulted either vertically or horizontally at approximately 9 m s^{-1} exhibited remarkably high and rapid decelerations (10–15g) and reached a near-zero translational speed in less than 150 ms. The initial rotational frequency of catapulted seeds was up to four times greater than that ultimately reached during steady-state autorotation. These helicopter seeds thus transiently produce very high lift forces (at Reynolds numbers near approximately 10^4) that act to enhance aerial transport. These findings are relevant to the modelling of long-distance seed dispersal in unsteady flows, as well as to the design of deceleration mechanisms based on lift generation, rather than drag-based devices such as parachutes.

1. Introduction

Samaras during free fall, as well as isolated animal wings, can significantly increase their time of descent by producing large aerodynamic forces while maintaining rotationally stable motion around their centre of mass [1–5]. Maple samaras initially accelerate under gravity when in free fall following downward release and then decelerate until the seed reaches a constant downward translational speed of descent [6,7]. In nature, however, samara detachment will not necessarily occur in still air, but rather will be forced by winds, which can reach speeds of up to 24 m s^{-1} [8]. Turbulent environmental flows will also increase the number of detached seeds, in comparison with laminar flows at the same mean speed [9]. Moreover, seed detachment can be elicited by elastic recoil of plant branches caused by wind gusts [10,11], thereby catapulting them through the air. Most botanical samaras are connected, in pairs, to a thin flexible stem which can act as a whip during branch recoil. The consequences of such rapid launches on samara autorotation are, however, unknown, and effects of both high deceleration and increased Reynolds numbers may compromise their aerodynamic performance. Here, we evaluate the performance of maple seeds when launched at speeds an order of magnitude higher than their equilibrium translational speed during free fall, and demonstrate a rapid and effective deceleration. This mechanism of enhanced lift production could significantly decrease descent velocity under certain wind conditions and can be as effective as the classical drag-based force used to decelerate objects in the air.

2. Material and methods

Mature Norway maple seeds (*Acer platanoides*) were collected from a single tree in Portland, Oregon. We carried out experiments using five seeds with values (mean \pm s.d.) for mass m , wing length l , mean wing chord c and wing area S of $130 \pm 10 \text{ mg}$,

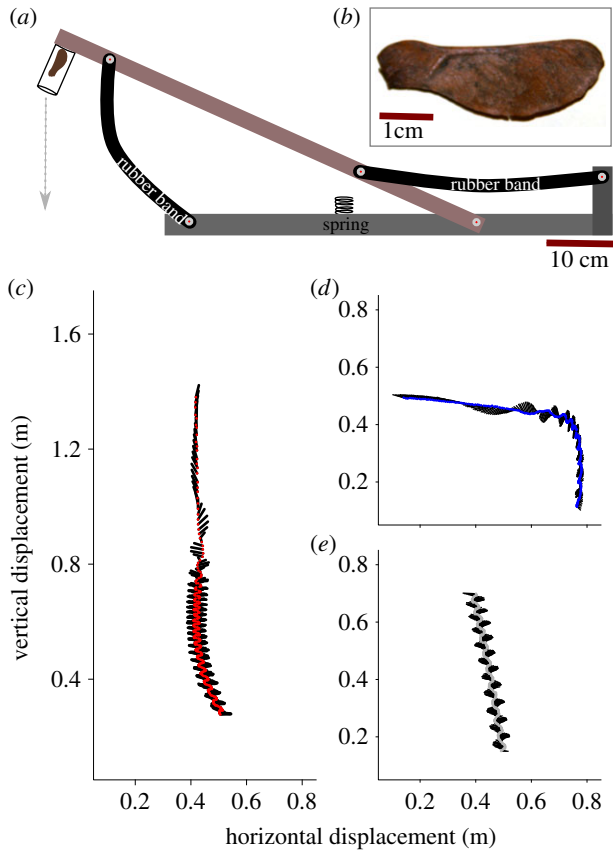


Figure 1. (a) Launching apparatus, (b) Norway maple seed, (c) trajectory followed by a seed during a downward vertical launch, (d) trajectory followed by a seed during a horizontal launch and (e) trajectory followed by a seed during unforced free fall. Red, blue and grey colours indicate position of the seed-root for vertical launches, horizontal launches and free fall conditions, respectively; the black line indicates the tip of the seed.

43 ± 4 mm, 12 ± 1 mm and 5.3 ± 0.7 cm² (mean \pm s.d.), respectively; wing loading ($=mg$ S⁻¹) averaged 2.5 ± 0.2 N m⁻².

Maple seeds were launched into the air using a custom-built catapult apparatus (figure 1a). We use a metal bar (1 m in length), a wooden arm (0.6 m in length), two large rubber bands (3×30 cm; cut from a bicycle inner tube) and a plastic container (2.5 cm in diameter \times 5 cm). The catapult was mounted at approximately 1.8 m height onto a tripod rigidly fixed to the floor. To launch a seed placed in the plastic container, the wooden arm of the device was pulled back by hand to its maximal extension point (as limited by a clamp) and was then released. A metal spring and an antagonistically opposed rubber band were used to limit impact between the wooden arm and the supporting metal bar during seed release. Launches were conducted both vertically downward (figure 1a) and horizontally (with the catapult oriented at 90° relative to the geometry depicted in figure 1a); each sampled seed was initially placed at the bottom of and parallel to the length of the launch container such that the seed-root was oriented toward the container's aperture. For each seed, we also conducted a free fall trial (i.e. without launching) by dropping seeds vertically by hand, with the seed-root oriented downward. The treatment order was vertical launch, free fall and then horizontal launch; repeated trials per seed were not conducted because of minor abrasion of the trailing edge of the seed during launches.

All experimental trials were filmed at either 500 frames s⁻¹ (Phantom-Miro high-speed video camera) or 1000 frames s⁻¹ (Fastec camera) from a lateral perspective nominally perpendicular to the seed's trajectory. The root and the tip of each seed were digitized for each frame using the DLTdv6 program for Matlab (http://hedricklab.bio.unc.edu/isis/digitizing/DigitizingTools_

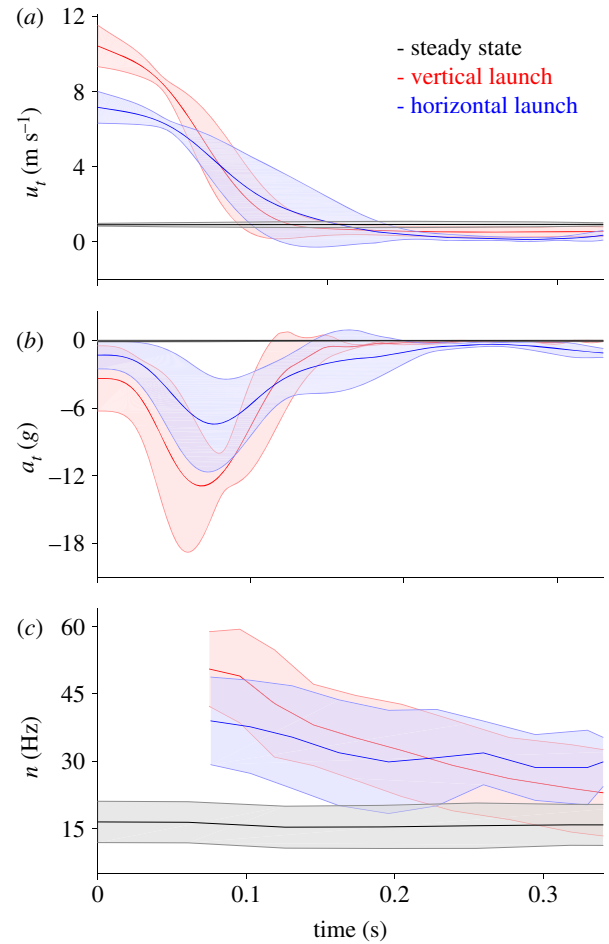


Figure 2. (a) Time course of translational speed u_{ti} , (b) translational deceleration a_{ti} and (c) rotational frequency n for maple seeds ($N = 5$) during vertical launches (red), horizontal launches (blue) and in non-forced free fall (grey). Solid lines represent mean values; shadowed regions indicate ± 1 s.d. The magnitude of acceleration is expressed relative to gravitational acceleration.

20180828.zip) [12]. We used those digitized points to calculate the mean rotational frequency n_{mean} and the mean cone angle θ_{mean} , where the latter is the maximum projected angle between the vector formed by the seed-root tip and the vector perpendicular to the seed's trajectory. For catapulted launches, seeds only began to rotate at approximately 0.09 s (see figure 2c), and mean values for rotational frequencies and cone angles refer to all filmed cycles after the first full rotation (free fall: 13 ± 1 cycles; vertical launch: 18 ± 7 cycles; horizontal launches: 9 ± 2 cycles). The maximum rotational frequency n_{max} observed in the trajectory was also calculated. Translational speed u_{ti} and deceleration a_{ti} through time were obtained from the first and second derivatives of the MSE quintic spline function of the displacement of the seed's root [13]. For the horizontal and vertical catapult trials, we also calculated the time for the seed to reach its minimum descent speed, t_{min} , following complete exit from the catapult's container. A Reynolds number (Re) based on the maximal translational speed $u_{t\text{max}}$ attained during each treatment was calculated as $c(u_{t\text{max}}^2 + u_{\text{tip}}^2)^{1/2}/\nu$, where c is the mean wing chord, $u_{\text{tip}} (=2\pi n_{\text{max}} l_e)$ is the rotational speed of the seed tip, $l_e = 0.75 l \cos(\theta_{\text{mean}})$ and ν is the kinematic viscosity of the air (1.51×10^{-5} m² s⁻¹). The Strouhal number St at maximum translational speed was calculated as $2l_e n_{\text{max}} / (u_{t\text{max}}^2 + u_{\text{tip}}^2)^{1/2}$.

Paired t -tests were used to compare values of n_{max} , θ_{mean} , $u_{t\text{max}}$ and $a_{t\text{max}}$ between horizontal and vertical launches. Linear regressions were used to assess relationships between $a_{t\text{max}}$ and t_{min} and between $u_{t\text{max}}$ versus n_{max} . All statistical analysis was

performed in R v. 3.4.4 (<https://www.r-project.org>). Data are presented as mean values ± 1 s.d.

3. Results

Equilibrium autorotation in freely released maple seeds was characterized by a descent rate of $1.0 \pm 0.1 \text{ m s}^{-1}$, decelerations of $0.1 \pm 0.1g$, rotational frequencies of $16 \pm 5 \text{ Hz}$, and cone angles of $12 \pm 5^\circ$ (figures 1e and 2a–c; table 1). By contrast, seeds thrown either vertically or horizontally at initial speeds from 7 to 10 m s^{-1} then decelerated at values greater than $10g$, and reached their minimum descent speeds in 140–150 ms (figure 2a,b; table 1). Initial rotational frequencies for launched seeds were three times higher than the equilibrium value for free fall autorotation (figure 2c), but average cone angles in all three cases were similar (table 1; electronic supplementary material, video VS1). Moreover, the rotational frequency of launched seeds diminished quickly with time (figure 2c). Vertical launches were characterized by significantly higher values of n_{max} ($t_4 = -3.2$, $p = 0.03$), $u_{t\text{max}}$ ($t_4 = -8.9$, $p < 0.001$) and $a_{t\text{max}}$ ($t_4 = -3.6$, $p = 0.02$) relative to horizontal launches; average cone angles were, however, indistinguishable between the two launching conditions ($t_4 = 0.57$, $p = 0.6$). Pooling data from all trials ($N = 15$), maximal translational speed and maximum rotational frequency were positively correlated ($u_{t\text{max}} = 0.2 n_{\text{max}} - 2$, $R^2 = 0.88$, $F_{1,13} = 95$, $p < 0.001$; figure 3a), and whereas maximal deceleration and time to attain minimum translational speed were negatively correlated ($t_{\text{min}} = -0.0004 a_{t\text{max}} + 0.2$, $R^2 = 0.58$, $F_{1,8} = 11.2$, $p = 0.01$; figure 3b). The mean Reynolds numbers in the rotation were three to four times higher in launched seeds relative to those freely dropped; Strouhal numbers (see definition above) were, however, comparable (i.e. 0.2–0.3) among the three experimental conditions (table 1).

4. Discussion

Autorotation by samaras has traditionally been investigated during non-forced free fall. Samaras falling vertically from rest experience a brief transitional phase before smoothly entering into equilibrium rotation, according to their initial attitude during release [6,7]. For example, maple seeds released from 2 m reach a maximal speed of approximately 2 m s^{-1} and a maximal deceleration of approximately $1g$ and enter into stable autorotation in 500 ms [7]. By contrast, maple seeds launched at fairly high speeds (9 m s^{-1}) quickly initiate autorotation and reach a near-zero translational speed in only one-third the time required for non-forced free fall. Maximal rotational frequency and translational deceleration were three times and one order of magnitude higher than in free fall, but the ability to generate high lift coefficients (associated with a strong leading-edge vortex on the upper surface of the blade [1,5]) was apparently unimpaired. Moreover, the positive relationship between maximal translational speed and rotational frequency (figure 3a), and the negative relationship between maximal deceleration and the time to attain minimal translational speed indicates that these seeds are producing remarkably high aerodynamic forces over very short intervals. In general, autorotating biological objects are understudied relative to their extremes of performance. For example, an isolated hummingbird wing loaded at 45 times its weight rotates at a

Table 1. Kinematic, morphological and aerodynamic data for five maple seeds (mean ± 1 s.d.) in steady-state autorotation during free fall, and during vertically downward and horizontal launches. See text for further details and calculations.

treatment (N)	n_{mean} (Hz)	n_{max} (Hz)	θ_{mean} (deg)	$u_{t\text{max}}$ (m s^{-1})	$a_{t\text{max}}$ (g)	$u_{t\text{tip}}$ (m s^{-1})	t_{min} (ms)	l_e (cm)	Re	St
free fall (5)	16 ± 5	17 ± 4	12 ± 5	1.0 ± 0.1	0.1 ± 0.1	3.2 ± 0.7	(n/a)	3.16 ± 0.29	2688 ± 308	0.30 ± 0.01
vertical launch (5)	27 ± 4	51 ± 8	6 ± 4	10.4 ± 1.1	15.3 ± 3	8.2 ± 0.9	140 ± 30	3.22 ± 0.30	$11\,374 \pm 1581$	0.22 ± 0.01
horizontal launch (5)	31 ± 8	39 ± 10	7 ± 2	7.2 ± 0.8	9.2 ± 2.2	7.6 ± 1.5	150 ± 10	3.21 ± 0.29	8250 ± 1083	0.23 ± 0.01

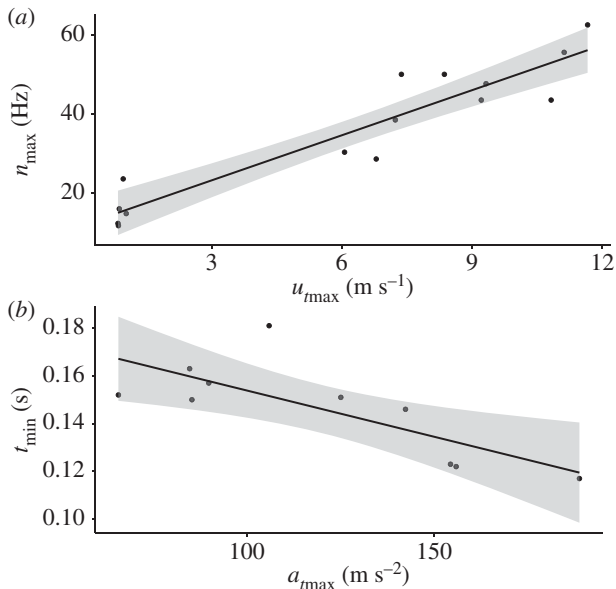


Figure 3. (a) Relationship between rotational frequency n_{\max} and translational speed $u_{t\max}$ for all trials ($N = 15$; $u_{t\max} = 0.2 n_{\max} - 2.0$, $R^2 = 0.88$, $F_{1,13} = 95$, $p \ll 0.001$). (b) For launched seeds, the relationship between the time to attain minimal speed t_{\min} and maximal deceleration $a_{t\max}$ ($N = 10$; $t_{\min} = -0.0004 a_{t\max} + 0.2$, $R^2 = 0.58$, $F_{1,8} = 11.2$, $p = 0.01$). The regression line is given in black, and the shadowed regions represent 95% confidence intervals.

frequency seven times higher in comparison with an unloaded isolated wing, but its rate of descent increases only twofold [5].

For the turbulent flow regimes studied here (i.e. $Re > 10^3$), the optimal propulsive performance of oscillating plates typically occurs at values of St from 0.2 to 0.4 [14], and a similarly constrained range of St is found for variably sized animal fliers and swimmers in characteristic cruising locomotion [15]. Here, launched seeds in turbulent flow regimes are characterized by St ranging from 0.2 to 0.3 (table 1), suggesting similarly efficient aerodynamic force production and concomitant deceleration. Seed deceleration did increase with Re (and thus predictably at greater speeds, given the latter parameter's linear dependence on u_{ti}), but otherwise was independent of St , wing loading and aspect ratio (see electronic supplementary material, figure S1).

Accordingly, our experiments suggest that launched seeds produce very high aerodynamic forces to rapidly decelerate. Lift and drag coefficients (C_L and C_d , respectively) at the moment of maximal deceleration can be estimated as $m(g + a_{t\max})/0.5\rho u_{ti}^2 S$ and $2^{5/2}[m(g + a_{t\max})/\pi l^2]^{3/2} \rho^{-3/2} U_{tip}^{-3} \sigma^{-1}$, respectively (see [2]), where ρ is the air density, u_{ti} is the translational speed of the seed at the time of maximal deceleration (mean value of approximately 6.8 m s^{-1} ; see electronic supplementary material, and figure 2), S is the seed area, l is the seed length and σ is the solidity ($S/\pi l^2$). The term $m(g + a_{t\max})$ incorporates both the seed's weight and the force due to deceleration for vertically launched seeds. Seeds in unforced free fall exhibit a C_L of approximately 0.39 and a C_d of approximately 0.15, whereas vertically launched seeds exhibit both a reduced C_L (approx. 0.15) and a much lower C_d (approx. 0.04). Interestingly, the lift-drag ratio ($=C_L/C_d$) was 4.2 and 2.6 for vertically launched and freely falling samaras, respectively, suggesting relatively

greater use of the lift in the former case. However, these calculations ignore the contribution of unsteady mechanisms, which have been demonstrated to be fundamental for lift production during rotation of samaras at constant angular velocity [1]. To better understand high transient forces on samaras, PIV measurements on accelerating seeds at high rotational frequencies would be required to illustrate how their lift and drag coefficients deviate from those in steady-state autorotation.

Plumed seeds act like parachutes to reduce their rate of descent via drag forces opposing translation [13]. By contrast, the maple seeds studied here are typically two orders of magnitude heavier than plumed seeds (e.g. 100 mg versus 1 mg), but their rate of descent is only four times higher (i.e. 1 m s^{-1} versus 0.2 m s^{-1} ; [16]). Aerodynamic lift produced by autorotation may thus be more effective per unit distance in transporting heavy loads [1,5]. In the case of transient loading, drag-based mechanisms can rapidly reduce high speeds of objects. For example, a large parachute can decelerate a 1 ton payload from 300 m s^{-1} to 20 m s^{-1} in only 5 s [17]. On a much smaller scale, we found that autorotating seeds can decelerate at nearly 15g to near-zero speeds in less than 150 ms. Even more impressively, a maple seed model made of paper (m of 182 mg, l of 5 cm) launched vertically downward at 22 m s^{-1} reached a rotational frequency of 70 Hz, a deceleration of 30g and a near-zero translational speed in only 100 ms (electronic supplementary material, video VS2). Direct comparison between parachutes and samaras is confounded because of the very large differences in speed and size of the two systems. Nonetheless, autorotation has been used in some technological applications [18] but may be more widely relevant for high lift generation and momentum reduction in strongly unsteady flows, with the extra advantage of intrinsic stability.

Extreme weather events are fundamental for the long-distance dispersal of aerial seeds [10,19]. Atmospheric models also predict that turbulence significantly increases dispersal range [19,20], but assume equilibrium descent by seeds, as attained instantaneously following release from the host plant. Our results for maple samaras, by contrast, suggest that sudden changes in upward (or downward) translational speed will elicit increases in spin rate and large vertical aerodynamic forces. Accordingly, such increased rotation may result in sudden height gain within updrafts, increasing the probability of long-distance dispersal. Transient performance of samaras within natural wind regimes, and in fact of all aerially borne seeds, has not yet been studied at the mechanistic level of unsteady aerodynamics, in spite of the ubiquity of environmental turbulence on different scales. The laboratory results presented here suggest that autorotation behaviour of samaras can be dynamically much richer than the classically presented equilibrium condition.

Data accessibility. The datasets supporting this article have been uploaded as part of the electronic supplementary material.

Authors' contributions. V.M.O.-J. conceived the idea. V.M.O.-J. and R.D. designed the experiments. V.M.O.-J. and N.S.-W.K. performed the experiments. V.M.O.-J. and R.D. performed the data analysis. V.M.O.-J., N.S.-W.K. and R.D. wrote the manuscript.

Competing interests. We declare we have no competing interests.

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