Contact Layer as a Propelling Advantage in Throwing

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The ability to throw objects is important to hominid evolution and has been central to many technological innovations in human history. The conditions for optimal throwing performance, however, are in general unknown. Here we present ejection experiments of projectiles composed of a rigid and a soft layer. The optimal performance is achieved when the soft layer of the projectiles matches the acceleration dynamics of the throwing engine. Compared with a fully rigid projectile, a bilayered projectile with a small soft elastic layer can achieve a more than 300% increase in translational kinetic energy. Our study emphasizes the importance of not only designing projectiles to optimize the stability in flight, the aerodynamic profile, and the spin, but also to carefully match the mechanical impedance of the projectiles and their thrower.


I. INTRODUCTION

In humans and animals, the release of energy stored inside elastic fibrous structures, like tendons, can produce power outputs far beyond the capability of mere muscles [1]. In fact, elastic tissue structures recoil faster than muscles can shorten, which is used, for example, when jumping [2–5], running [6,7], or throwing [8,9]. The ability to throw objects has offered an evolutionary advantage to primates [10] and in particular humans [11–13], and is tightly coupled to the elasticity of the shoulder [8]. The mechanical work produced in a throw starts with a motion of the hips, is followed by a loading of the elastic elements in the shoulder, and ends with a rapid kinetic energy transfer to the arm and projectile [9]. Underlying these steps, different muscles (in the legs, hips, torso, shoulder, elbow, and wrist) are activated sequentially and the optimal throw happens when the different joints are put into motion with carefully timed delays [14–17]. The timing and activation of successive segments is an active subject of research in the field of robotics, biomechanics, sports, and human evolution [8,9,18–24]. The idea of precise synchronization and timing in throwing is also important in plants and fungi, which use throwinglike mechanisms to release and disperse spores and pollen [25,26]. For example, the sporangia—the spore ejection units in ferns—take advantage of two different time scales to maximize the ejection [27]. Finally, throwing experiments with soft elastic objects have shown that the transfer of energy can be optimized, up to 250%, when the ratio of the time scale of acceleration to the projectile eigenperiod takes a particular value [28].

Inspired by these mechanisms, we design a projectile that delays the release of elastic energy and optimizes the energy transfer within a chain of elastic elements. Specifically, we consider bilayered projectiles thrown by an ejection engine. We show that the throw efficiency of rigid objects, which is generally low, can be drastically improved by more than 300% by adding an extra soft layer between the engine and the rigid object.

II. MATERIALS AND METHODS

A. Ejection setup

The experiments are performed with the ejection engine illustrated in Fig. 1(a). From \( t = 0 \), the engine plate performs a uniaxial harmonic motion described to a high precision by the function \( z_p(t) = A[1 - \cos(2\pi ft)] \). The frequency \( f \) of the engine can be varied in the range 20–80 Hz and the amplitude \( A \) is approximately 1 mm. The maximum velocity of the engine, \( V^* = 2\pi fA \), is around 0.5 m s\(^{-1}\) and the maximum acceleration is around 25 g, where g is the acceleration of gravity. Moreover, the weights \( m \) of the projectiles are negligible relative to the weight of the engine and therefore do not influence the engine motion. We use cylindrical projectiles with a diameter of 12 mm and a length \( L \) of 15 mm. The projectiles consist of a soft and a rigid material superposed. The rigid elastic material is made of a hard plastic (polyether ether ketone, Young’s modulus \( E_r = 3.6 \) GPa, and density \( \rho_r = 1300 \) kg m\(^{-3}\)) and the soft elastic
The experiments are supported by numerical simulations of the deformation dynamics. For the sake of generality, we consider the wave propagation in both the soft and rigid layers. In cylindrical coordinates and assuming axial symmetry of the projectiles, the displacement \( \mathbf{u} = (u_r, u_\theta, u_z) \) has the components \( u_\theta = 0 \), \( u_r = u_r(r, z, t) \), and \( u_z = u_z(r, z, t) \). We do not expect the longitudinal displacement \( u_z \) to depend significantly on the radial coordinate \( r \), so we approximate \( u_r(r, z, t) \approx u(z, t) \). The dynamics is therefore driven by the propagation of longitudinal elastic waves inside the projectile. The waves are described by the one-dimensional momentum balance equation

\[
\rho(z) \partial_z^2 u(z, t) - \partial_z [E(z) \partial_z u(z, t)] = 0, \tag{1}
\]

where \( z \) measures the distance from the bottom part of the cylinder along the symmetry axis, \( E(z) \) is the local Young modulus, and \( \rho(z) \) is the mass density. For our bilayered projectiles, the material parameters are constant in each layer and we recover the classical wave equation with two longitudinal wave velocities, \( c_s = \sqrt{E_s/\rho_s} \) and \( c_r = \sqrt{E_r/\rho_r} \), inside the soft and rigid layers, respectively. We use the subscripts \( s \) and \( r \) to denote physical quantities of the soft and rigid materials, respectively. For the numerical simulations, we used a basic semi-implicit (symplectic) Euler finite difference scheme. The point of contact with the plate is assumed to be fully rigid such that the end of the rod upon starting immediately assumes the speed of the plate. The dynamics is subject to the boundary conditions

\[
u(0, t) \geq A[1 - \cos(2\pi ft)], \tag{2a}\]

\[
u(z, 0) = 0 \quad \text{for } z > 0, \tag{2b}\]

\[
\partial_z u(z, 0) = 0 \quad \text{for } z > 0, \tag{2c}\]

\[
\partial_z u(z, t) \xrightarrow{z \to L} 0. \tag{2d}\]

In our simulations, the projectile is released from the throwing engine as soon as the strain crosses from positive to negative at \( z = 0 \). Note that it is possible for a projectile to reconnect to the engine after takeoff, that is, the engine can catch up with the trailing edge and thereby result in successive stages of ejection and reconnection.
C. Spring-mass model

We derive here the results obtained with a simple spring-mass projectile—a point mass \( m \) on top of a massless spring of stiffness \( k \) and free length \( L \)—to give insights about the role of inertia and elasticity in throwing experiments. This system has an eigenfrequency \( f_0 = (1/2\pi)^2 \sqrt{k/m} \). We denote by \( z_m \) the position of the point mass:

\[
\ddot{z}_m = -(2\pi f_0)^2(z_m - z_p - L).
\]

Here \( z_p = A[1 - \cos(2\pi ft)] \) measures the position of the engine plate. The solution of this forced harmonic oscillator equation, with \( z_m(0) = L \), is

\[
z_m(t) = L + A + \frac{A}{f^2 - f_0^2} [f_0^2 \cos(2\pi ft) - f^2 \cos(2\pi f_0 t)].
\]

The projectile takes off when \( z_m - z_p = L \), at time \( t_e = 1/(f^2 + f_0^2) \). The velocity ratio at takeoff \( V_e/V_p \) is predicted to be

\[
V_e/V_p = \frac{\dot{z}_m(t_e)}{2\pi fA} = \frac{f_0/f}{f_0/f - 1} \sin \left( \frac{2\pi}{f_0/f + 1} \right).
\]

In Fig. 2, we show that the energy transfer factor \( \alpha = (V_e/V_p)^2 \) reaches the maximum 3.13 for \( f_0/f \simeq 1.62 \). We interpret that this peak efficiency results from a particular match between the acceleration time of the engine (proportional to \( 1/f^2 \)) and the typical time of the projectile deformation (proportional to \( 1/f_0^2 \)). Finally, we point out that this projectile has a maximum energy transfer factor 3.13, even higher than the maximal value 2.5 obtained with a homogeneous linear projectile [28].

III. RESULTS

We study configurations where the rigid layer is on top and where the soft layer is on top, and we vary the ratio \( x = L_s/L \) between the length of the soft layer \( L_s \) and the projectile length \( L \).

A. Rigid-on-top configuration

We first consider the rigid-on-top configuration. In Figs. 3(a) and 3(b) we present the height reached by various projectiles for \( c_s = 3.4 \text{ m/s} \), for several \( x \) values and two different engine frequencies, 34 and 76 Hz, leading to ratios \( c_s/Lf \) equal to 6.5 and 2.9, respectively. In all cases, there is a very good agreement between the experiments and simulations. For both frequencies, the expected rigid behavior, \( \alpha = 1 \), is recovered when \( x \) equals 0. For intermediate values of \( x \), we observe a peak in the energy.
transfer factor. It is particularly pronounced for \( c_s/L_f = 2.9 \). In this case, \( \alpha \) reaches values close to 3 for both the simulations and experiments.

The existence of optima in \( \alpha \) is examined systematically with simulations, by varying the values of \( c_s/L_f \) and \( x \) in Eq. (1), and we present the results of this analysis in Figs. 3(c)–3(e). We note the existence of a best ejection performance region with \( \alpha \sim 3.1 \), which follows the curve \( c_s/L_f \sim 10 \sqrt{x} \) from \( x = 0 \) until \( x \sim 0.3 \).

This maximal value reminds \( \alpha = 3.13 \) obtained with the spring-mass model in Sec. II C and we propose insights with simulations, by varying the values of \( \alpha \). The limit 
\[
\alpha \rightarrow 1, \quad x \rightarrow 0 \text{ (i.e., a soft homogeneous projectile)}.
\]

In the Appendix, we demonstrate that we need to add the condition \( E_s/E_r \ll x \) to account for the finite rigidity of the top part and distinguish between \( x = 0 \) and the limit \( x \rightarrow 0 \). Given the values of \( E_s/E_r \) (typically \( 10^{-6} \) in our experiments), this moderately thin soft layer limit \( E_s/E_r \ll x \ll 1 \), hereafter referred to as \( x \rightarrow 0 \), is singular and differs from the rigid case \( x = 0 \): this system gives a best ejection \( \alpha = 3.13 \) for \( c_s/L_f = 10.2 \sqrt{x} \), in very good agreement with the simulations. The case in which \( x = 0 \) implies that \( \alpha = 1 \), as expected, because the projectile can be considered as rigid. The limit \( x \rightarrow 0 \) is of particular interest, because we show that the addition of a thin soft layer can lead to very efficient ejection if the layer properties match the dynamics of the catapult. For larger values of \( x \), the crest follows \( c_s/L_f = 6.8 \) and \( \alpha \) tends to 2.5, as shown in Figs. 3(d) and 3(e); the limit \( x = 1 \) recovers the results obtained with a soft homogeneous material [28].

B. Soft-on-top configuration

The soft-on-top configuration results are shown in Fig. 4. Clearly, the ejection performances are lower than in the previous case: the heights reached by these projectiles are notably smaller than the rigid-on-top experiments, for the two frequencies of the ejection engine, as shown in Figs. 4(a) and 4(b). For \( c_s/L_f = 6.5 \) [see Fig. 4(a)], there is a smooth transition in the transfer factor from a rigid object \( (x = 0) \) to a soft homogeneous projectile \( (x = 1) \), and the highest values in \( \alpha \) are reached near \( x = 1 \), that is, for soft homogeneous projectiles. In Fig. 4(b) we show that, in the case \( c_s/L_f = 2.9 \), there is no clear advantage in using a bilayered projectile over a homogeneous projectile. In order to search the parameter space for the best ejection, we show in Figs. 4(c)–4(e) the numerical predictions of the model, and it appears that the best factor \( \alpha \) is reached for \( x = 1 \) (i.e., a soft homogeneous projectile). The soft-on-top configuration [Figs. 4(c) and 4(d)] seems systematically less efficient than the rigid-on-top configuration [Figs. 3(c) and 3(d)].
C. An optimal dynamics

To summarize, rigid projectiles designed with an additional soft layer at their trailing edge exhibit an “optimal crest” that gives an optimal value for α, whatever the value of x, if c_i/Lf is adjusted correctly; it lies in the range α = 3.1 for x → 0 to α = 2.5 for x = 1.

In terms of the dynamics, optimal ejection is provided by a tuned delayed response of the soft layer. To illustrate this idea, we compare in Fig. 5 the temporal evolution of the relevant quantities during the ejection of a rigid projectile (a) and an optimal bilayered projectile (b) given by the spring-mass model with f_0/f = 1.62 (Sec. II C). During the takeoff, the duration of the contact of the projectile with the plate is greatly enhanced in (b) with respect to (a). In the rigid case, the contact force F decreases from an initial maximum towards zero as the plate reaches its maximum velocity V_p^∞. In addition, the maximal force exerted onto the projectile is greater in (b) than in (a). Since the transfer of energy from the plate to the projectile is given by ∫_t_0^te F(t)z_p(t)dt, where z_p(t) = 2πAf sin(2πft) is the plate velocity and F(t)z_p(t) is the instantaneous mechanical power, we infer that the rigid case cannot be optimal since the contact force and the plate velocity are never maximal at the same time. In contrast, the bilayered projectile delays the release of elastic energy and has a contact force in phase with the plate velocity, which ensures an optimal transfer. The nature of the contact force is the key element to discriminate projectiles. If we imagine an ideal engine that could prescribe the same time-dependent force instead of a prescribed engine plate displacement, the motion would be directly dictated by Newton’s second law and the ejection velocity would be identical whatever the projectile.

IV. DISCUSSION

In the light of the results, we can discuss the relevance of such projectiles for human throwing. Following Cross [30], the total kinetic energy provided by our body for an overarm throw is only partially transferred to the (rigid) projectile. In fact, segments of our arm, which can be equated with the throwing engine in our study, are still in motion once the projectile is ejected. Assuming that these segments move with the same velocity as that of the projectile, the throw efficiency (defined here as the ratio of the projectile kinetic energy to the kinetic energy provided by our body) is a function of the mass ratio m/M, where m is the mass of the projectile and M the equivalent mass of the throwing engine, which corresponds roughly to the mass of the forearm and hand, typically M = 1–2 kg [30]. In the case of heavy projectiles, such as shot put, when m/M ≫ 1, the thrower can mobilize most of the kinetic energy for the projectile and the efficiency is close to 1. Conversely, for m/M ≪ 1, this mode of propulsion becomes ineffective and most of the kinetic energy remains inside our body, leading to potential injuries. This could explain the difference between baseball and (American) football overarm throws. Both have very similar throwing sequences, but the difference in the mass of the balls, 140–150 and 400–430 g, respectively, is significant and makes the baseball pitcher more susceptible to injury than his football counterpart [31]. In the same vein, Cohen and Clanet [32] have shown that the mode of propulsion for ball sports (throwing versus hitting) correlates strongly with the mass ratio between the ball and the throwing instrument, which in light of our results can be explained by a pursuit of the maximum energy transfer rate.

Actually, we can experience the effect ourselves with two more extreme throwing examples: try to perform an overarm throw with a golf ball and a handball, 45 and 450 g, respectively, as fast as you can. The throw with the heaviest ball feels smooth, while in the other case you have
a frustrated impression that you cannot mobilize all your strength and that your arm gets overstretched.

Our study is particularly relevant for the inefficient limit $m/M \ll 1$, since the motion of the throwing engine is not influenced by the mass of the projectile, and we see a huge potential in designing projectiles to delay the release of elastic energy and increase the energy transfer by 300%. As a real-life example, we could imagine adding a homogeneous spring, with spring constant $k$, at the trailing edge of the (rigid) golf ball to increase its throw efficiency. Our study predicts that the peak efficiency is reached when $\sqrt{k/m} \sim 10.2$ (Sec. II C). With a typical throw time $1/f \sim 1$ s, this leads to $k \sim 5$ N m$^{-1}$. For heavy objects, we would not expect a large difference in the efficiency of rigid and time-delayed projectiles, although a slight optimization of a few percent may still be relevant in the context of competition.

Finally, it is currently being debated how to regulate footwear in road running [33]. For example, footwear can be optimized to not only conserve energy but also to time the energy release from the sole according to the characteristics of the individual runner. To ensure fairness, it has been proposed to regulate the thickness of the sole [33], and thereby reduce the number of parameters one can use for optimization during the technological development. However, our experiments show [see, for example, Fig. 3(c)] that a limitation on the thickness of the soft layer can potentially be compensated for by a change in the elastic properties.

V. CONCLUSION

By modifying the mechanical properties of a projectile, the throw efficiency can be significantly changed. For optimal throws, the key point is to delay the reaction force experienced at the thrower-projectile contact such that the contact force and velocity are in phase during the propulsive phase, thereby maximizing the mechanical power. For a homogeneous projectile or a spring-mass system, this is obtained by matching the throwing time with the eigenperiod of the projectile oscillations. For a bilayered projectile, there is an optimum if the soft part is placed at the trailing edge. In this case, the gain in translation energy is a factor of three larger than for a rigid projectile. From an engineering point of view, massive propulsion engines are not the best choice to propel light projectiles. Actually, the lower the mass of the projectile, the lower the mass of the throwing instrument should be, in order to achieve the best efficiency. If the mass cannot be adjusted, projectiles designed for elastic-assisted throwing seem to be a very good option.

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APPENDIX: DOUBLE SPRING-MASS MODEL

We model each part of the bilayered projectile with a spring-mass system, as depicted in Fig. 6. We approximate the upper part of the projectile with a point mass $m_t$, located at $z = z_t$, and the bottom part with a point mass $m_b$, which is located at $z = z_b$. These two components are connected together with a spring of stiffness $k_t$ and length $l_t$. The engine is modeled through a plate, located at $z = z_p(t)$, which triggers the bottom mass through an elastic spring of stiffness $k_b$ and length $l_b$. The dynamics of this model is described by

$$m_t\ddot{z}_t = k_t(z_t - z_b - l_t),$$
$$m_b\ddot{z}_b = -k_t(z_t - z_b - l_t) - k_b(z_b - z_p - l_b),$$
$$z_p = A[1 - \cos(\omega t)].$$

We have neglected the effect of gravity.

To mimic the continuous medium, we approximate the spring response to the elastic force resulting from a length change in the bulk; hence, $k_{t,b} = E_{t,b}/(L_{t,b})$, where $E_{t,b}$ represents the Young modulus of the material of the upper and bottom parts of the projectile, and $S$ is the transverse area of the projectile. We assume that $l_t = (1 - r)L$, and $l_b = rL$, as well as $m_t = m(1 - r)$ and $m_b = rm$, where $m$ and $L$ are respectively the mass and the length of the projectile. The variable $r$ measures the composition of the projectile: $r = 0$ corresponds to a homogeneous object with a Young
Young’s moduli, there is a general solution:

\[ (1 - r) \ddot{z}_l = -\omega_l^2 \left( \frac{1}{1 - r} (z_l - z_b - l_t) \right), \quad (A1) \]

\[ r \ddot{z}_b = \omega_b^2 \left( \frac{1}{1 - r} (z_l - z_b - l_t) \right) - \omega_b^2 \frac{1}{r} (z_b - z_p - l_b), \quad (A2) \]

where we have introduced \( \omega_{l,b}^2 = SE_{l,b}/ml_{l,b} \). Initially, both masses are at equilibrium: \( z_l(0) = l_b + l_t \) and \( z_b(0) = l_b \).

The projectile will take off from the forcing plate at time \( t_e = t_{e_1} \), for which \( z_b(t_e) = z_p(t_e) = l_b \).

We first study the dynamics of a soft homogeneous projectile. This configuration is reached as \( r \) tends to 1 (the case \( r \) tends to 0 will be discussed later). The inertia of the top mass is neglected and \( z_t \) follows \( z_b \) adiabatically from Eq. (A1): \( z_t = z_b \) as \( l_t \to 0 \). In this limit, we recover the dynamics described by the single spring-mass model where \( \omega_t = \text{now } \omega_b \).

Hence, our model predicts an efficiency peak in the energy transfer factor for a homogeneous soft projectile. Nevertheless, the agreement remains qualitative, since the continuous model anticipates 2.5 as the highest value for \( \alpha \).

We now study the ejection dynamics of bilayered projectiles. For a composite projectile with very different Young’s moduli, there is a general solution:

\[ z_l(\omega t) = l_b + l_t + A[1 - (Z_{11} + Z_{2t}) \cos \omega t]
\]

\[{}\quad{}- (1 - Z_{11}) \cos \omega t - (1 - Z_{2t}) \cos \omega t], \quad (A3)\]

\[ z_b(\omega t) = l_b + A[1 - (Z_{1b} + Z_{2b}) \cos \omega t]
\]

\[{}\quad{}- (1 - Z_{1b}) \cos \omega t - (1 - Z_{2b}) \cos \omega t]. \quad (A4)\]

This solution takes into account the driving of the moving plate and also the two vibration modes of the system. The frequencies and the amplitudes of the modes are respectively denoted by \( \omega_{1,2,12}, Z_{1,2,12} \). We study the dynamics of bilayered projectiles for which one of the materials is supposed to be much more rigid than the other material (i.e., either \( \omega_l \ll \omega_b \) or \( \omega_b \ll \omega_l \)): in this limit one of the two eigenfrequencies \( \omega_{1,2} \) is much higher than the other eigenfrequency. Let us assume that \( \omega_l \ll \omega_2 \): the effect of the associated eigenmode will be small, and we can show that \( Z_{2t,b} \ll Z_{1t,b} \). The dynamics of the bottom part becomes

\[ z_b(t) = l_b + A[1 - Z_{1b} \cos(\omega t) - (1 - Z_{1b}) \cos(\omega_1 t)], \]

which is very similar to those of \( z_m \) in the single spring-mass model, except that the angular frequency \( \omega_1 \) depends on \( \omega_b, \omega_t, \) and \( x \). This expression predicts the takeoff time \( t_e = 2\pi / (\omega + \omega_1) \), and we can compute the energy transfer factor \( \alpha \), whose functional shape is exactly the same as the single spring-mass model.

In Figs. 7(a) and 7(b), we summarize the behavior of \( \alpha \) as a function of the control parameters for projectiles composed of a soft bottom material and a soft top material, respectively. By comparing the results presented in Fig. 3c and 4c, we conclude that the simple model predicts qualitatively the super propulsive regions in the dimensionless parameter space, namely near \( x = 1 \), for both configurations, and the square-root-like crest for the rigid-on-top projectiles.

For a very thin bottom layer, \( r \) tends to 0, as does the bottom mass: \( z_b \) will follow \( z_t \) adiabatically in (A2) and the model reduces to

\[ \ddot{z}_l + \frac{\omega_l^2 \omega_b^2}{\omega_b^2 + r \omega_l^2} (z_l - z_p - L) = 0, \quad (A5) \]

\[ z_b = \frac{\omega_b^2}{\omega_b^2 + x \omega_l^2} z_p + \frac{x \omega_l^2}{\omega_b^2 + x \omega_l^2} z_l. \quad (A6) \]

For projectiles with the soft part at the top, \( \omega_l = \omega_0 \) and \( \omega_b^2 \gg r \omega_0^2 \): the dynamics of the bottom layer simplifies to

\[ \ddot{z}_l + \omega_l^2 (z_l - z_p - L) = 0. \]

This corresponds to the limit of the single spring-mass model, and justifies the existence of a maximum in the transfer factor near \( x = 1 \) and \( 2\pi \omega_0 / \omega \sim 10.2 \) [see Fig. 7(b)], because we have seen that the most efficient ejection for the single spring-mass model is obtained for \( \omega_0 / \omega \sim 1.62 \).

If the bottom layer is soft, there are two possible behaviors. For an extremely thin layer \( r \ll \omega_0^2 / \omega_l^2 \), the system behaves as

\[ \ddot{z}_l + \omega_l^2 (z_l - z_p - L) = 0, \]

and the projectile can be considered as homogeneous and rigid. Hence, if \( x = r \ll \omega_0^2 / \omega_l^2 \), the transfer factor is equal to 1, as seen in Fig. 7(a), at \( x = 0 \). There exists the
particularly interesting limit \( \omega_2^2 / \omega_1^2 \ll x \ll 1 \), for which the dynamics of the projectile obeys the equation
\[
\ddot{x} + \frac{\omega_0^2}{x} (x - z_p - L) = 0.
\]

Consequently, for a moderately thin soft bottom layer, the bilayered projectile behaves as a single spring-mass model with frequency \( \omega_0 / \sqrt{x} \). Hence, the projectile will be best propelled if \( \omega_0 = 1.62 \omega \sqrt{x} \), which explains the existence of the crest in the continuous model. This square root agrees qualitatively well for both the simple model (see Fig. 7) and the continuous approach (see Fig. 3). Consequently, for a rigid object with a Young modulus \( E_r \), attaching a soft material with Young’s modulus \( E_s \) of thickness higher than \( (E_s/E_r)L \) will achieve the best ejection performance.

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