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# Mechanical Actuation via Resorbable Materials

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Honors Thesis

# MECHANICAL ACTUATION VIA RESORBABLE MATERIALS

by
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# ABSTRACT

## MECHANICAL ACTUATION VIA RESORBABLE MATERIALS

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Resorbable materials—or materials which diffuse into their surroundings— present a promising means of actuating mechanical systems. In current practice, such as in the realm of in vivo surgical devices, resorbable materials are often intended to perform a temporary function and completely dissolve when that function is completed (e.g. resorbable sutures). In this paper, resorbable materials are proposed for use in a different way: as a means for actuating mechanical systems. We create several prototypes which demonstrate that resorbable materials, combined with stored energy, can be used to actuate mechanical systems under several loading conditions and in various applications. We also present force vs. displacement and force vs. time data of the mechanisms. Using the principles illustrated here, resorbable materials offer unique, customizable ways to actuate a variety of mechanisms in a wide range of domains.

# ACKNOWLEDGEMENTS

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# Introduction

A resorbable material is one which dissolves in a specified environment in the way that rock salt or polyvinyl acid (PVA) dissolves in water, polylactic acid (PLA) dissolves in vivo (1), or ice melts into warm water. Resorbable materials have a wide range of material properties and resorption mechanics (2), which makes them desirable for a range of situations and applications. They have been investigated for use in biomedical applications and their success in this area has led to advances in medicine which have greatly helped patients (1,3–8). The main function of resorbable materials in biomedical applications is to dissolve away, such that the entire device— whether it be a pill, sutures, or a stent—dissolves into the body. In these cases, the complete dissolvability of the device is a benefit because it removes the need for additional medical intervention after the device's initial installation.

While this complete dissolution is the most common application for resorbable materials today, they show promise for use as a component of a permanent mechanism. When used in tandem with a non-dissolving apparatus, resorbable materials may provide a method for actuating mechanisms that exhibit unique benefits, including time-delayed response.

# Mechanism Types

The terms "active" versus "passive" distinguish between systems which do or do not require external energy to perform their function. Extending this classification to mechanism actuation is valuable for identifying which types of mechanisms might benefit from actuation through resorbable materials. Thus for a mechanism to be passive, it receives no energy from external sources, and to be active, it relies on energy from an external source. To facilitate understanding of different types of mechanism actuation, we propose a more rigorous categorization enumerating different types of mechanisms. This categorization more clearly identifies which types of mechanisms might benefit from the proposed resorbable-materials-based actuation method by classifying actuation by the mechanism's method of obtaining actuation energy.

Some mechanisms require no stimulus to initialize their activation and utilize no energy. These zero-activation mechanisms either remain static throughout their lifetime (e.g. the Nuss bar for pectus excavatum surgery (9)), or move with a larger mechanism (e.g. a hip (10) or knee (11,12) implant, a durable (non-bioresorbable) coronary stent (13), or an intraocular lens (14,15)).

Other devices require an external stimulus and external energy for activation. They are thus activated from outside the device (e.g. orthodontic braces (16), a palate expander (17), or a cochlear implant (18) (where the exterior speech processor can be removed, thus deactivating the system)). Still others require an external stimulus but use stored internal energy to power the activation. These devices often allow for remote activation without requiring direct physical interaction (e.g. magnetically-controlled growing rods for scoliosis (19,20), programmable palate expanders (21), or remote-controlled implantable insulin pumps (22,23)).

Finally, other mechanisms require no stimulus and use stored internal energy to power the activation and are thus auto-activated (e.g. an implantable cardioverter-defibrillator (24), a pacemaker (25, 26), or multi-stage stent devices (27)). Bioresorbable scaffolds for cardiac stents (28, 29) and controlled-release drug or macromolecule delivery systems (30, 31) are a secondary case of auto-activated medical devices, where the device dissolves (rather than deploying) with time after implantation.

Resorbable materials may be used to actuate any devices which utilize stored internal energy to power their activation; by placing the material in a permanent mechanism so that the mechanism is elastically deformed, the mechanism gains internal energy that is released as the resorbable material dissolves and allows the mechanism to return to its unstressed state. Resorbable materials are additionally primarily conducive for use in mechanisms which would benefit from a zero-stimulus activation. However, with various adaptations from the methods presented here, they are also viable for mechanisms which use instead an internal or external stimulus to trigger activation. Use of resorbable materials is thus primarily beneficial for the final type of mechanism described: one which requires no stimulus and uses stored internal energy to power its activation. In fact, resorbable material mechanism actuation is novel because it is currently one of very few existing cases of this final type of device.

Additionally, if the device's location makes it difficult to actuate remotely or means that it cannot be activated externally, as is the case for many in vivo implants, the auto-activation of resorbable materials becomes particularly attractive. The use of resorbable materials thus provides solutions to previously difficult applications of mechanisms and proves promising viability for devices that must be embedded or implanted out of reach of further manipulation. For example, utilizing bioresorbable materials to actuate medical devices (e.g. self-adapting corrective implants) produces minimally-invasive, gradual, and less painful in vivo corrective procedures. Thus if a mechanism is in a hard-to-reach location, requires delayed or gradual actuation, and needs a single actuation, resorbable materials are of particular interest.

## Methods: Resorbable Mechanism Development

We demonstrate the functionality of resorbable materials as a means of actuation through four different mechanisms. In these four mechanisms, we show that resorbable materials may be used under various stress situations (compression, bending, shear loads), produce different final actuation motions (linear and rotational), and have different actuation speeds (gradual and delayed instantaneous). The four mechanisms and the testing procedure used for each are described below. The objective of each test was to prove the functionality of the resorbable material as an actuation mechanism for each set of unique loading conditions.

## Mechanism 1: Simple Twist

The circular mechanism of Figure 1 is held in place with a torsional spring hidden in the central shaft. The mechanism is twisted, displacing the spring, and a resorbable insert is placed in compression such that the mechanism is held in its deformed position, as shown in Figure 2. As the resorbable insert dissolves, the torsional spring forces the mechanism back towards its initial position. It is thus a gradually actuated mechanism.

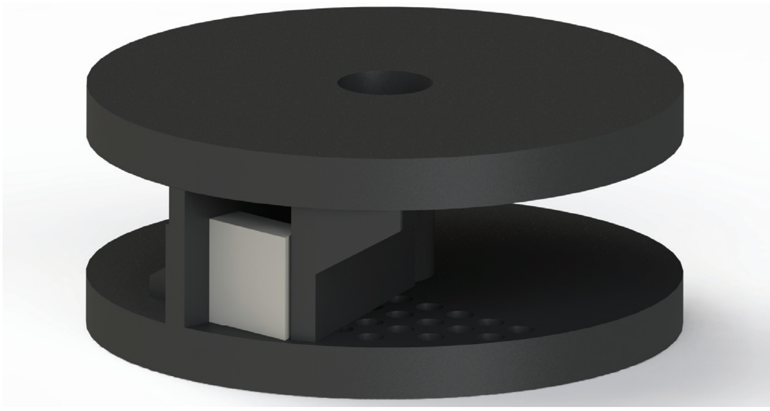
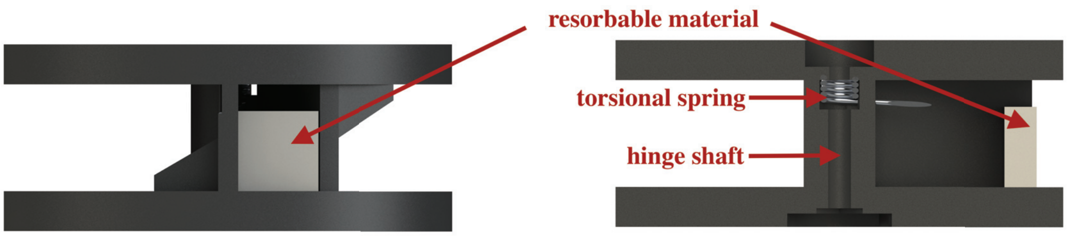


Figure 1: Rendering of an isometric view of the twist mechanism.




(a) Front view

(b) Section view (rotated 90°from front view)

Figure 2: Renderings of the twist design. The white piece of resorbable material is visible, as well as the torsional spring which provides the actuation energy

This mechanism was 3D printed out of PLA and tested with both PVA and rock salt as the resorbable material, both of which dissolve in water. Testing of Mechanism 1 was performed as follows: A tank was filled with 5 gallons of 43ºC water. The resorbable inserts were placed in their designated locations in the mechanism. The mechanism and inserts were taped to a weight and set in the tank of water. Pictures of the mechanism's actuation were taken once every six minutes.

## Mechanism 2: Folded-Beam Suspension

A folded-beam suspension allows the central translating shuttle to be displaced through its attachments to compliant members (32, 33) (see Figure 3). As the central beam is displaced downwards, the compliant members gain strain energy, which forces the central translating shuttle back to its initial position. In the absence of something prohibiting the central shuttle's motion back to the initial position, it will return immediately to its initial position. Placing a resorbable insert in compression between the central translating shuttle's displaced and final positions allows the shuttle to gradually return to its initial position. If the resorbable insert is thinned such that it will fail catastrophically, the beam can alternatively be made to return instantaneously to its initial position.

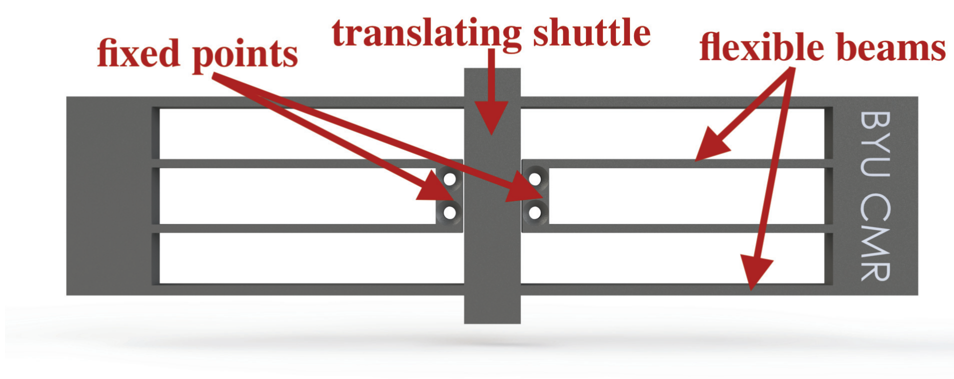



Figure 3: Rendering of the folded beam suspension.

This mechanism was 3D printed out of PLA and tested with both rock salt in water and ice in air. Testing of Mechanism 2 was performed as follows: The mechanism was affixed to a vertical surface. A known weight (0.1 kg) was attached to the bottom of the central beam of the mechanism. The central beam of the folded-beam suspension was forcibly displaced. The resorbable insert was then placed in its designated location in the mechanism. Video was taken of the mechanism as the ice dissolved to record the actuation time, force, and displacement. A ruler was placed behind the mechanism to measure its displacement over time.

## Mechanism 3: Corrective Bar

This mechanism acts as a medical device that can be placed in the chest cavity to correct a pectus excavatum deformity. Pectus excavatum is a deformity of the breastbone where the sternum is recessed into the chest cavity. In some cases, the deformity can be severe enough that it restricts healthy activity of the heart and lungs. The current procedure to correct pectus excavatum involves the placement of a curved metal bar inside the chest cavity, which forces the deformed sternum immediately into the corrected location (9).

The novel version of the corrective bar described in this work (and shown in Figure 4) utilizes resorbable inserts allows for a gradual—and presumably less painful—correction of the deformity. Placing the resorbable inserts in compression in prescribed locations throughout the bar, as shown in Figure 10, allows the bar to initially conform to the deformed shape of the sternum. As the materials dissolve, the stored strain energy in the bar forces the bar towards its initial configuration and redirects the force onto the sternum, so that the sternum is gradually corrected. Use of resorbable materials to activate this device allows for a gradual correction without requiring an external stimulus, as might be otherwise obtained through additional surgeries or in-patient visits.

(a) Isometric view (b) Front view

Figure 4: Rendering of the corrective bar similar to the one used in testing. While this render does not show the resorbable inserts, they would be placed in the slots visible between the bar and the offshoots.

This mechanism was first tested in PLA and with PVA inserts. However, PLA stress relaxes significantly over time, and PVA at the desired size takes hours to dissolve into 43ºC water. Since this mechanism's design relies particularly heavily on stored strain energy to achieve the desired motion, the corrective bar was manufactured out of aluminum and the resorbable inserts were carved from rock salt for the test displayed in Figure 10.

Testing of Mechanism 3 was performed as follows: A tank was filled with 5 gallons of 43ºC water. The resorbable inserts were placed in their designated locations in the mechanism, which forced the center of the mechanism to a displaced location (see Figure 10a). The mechanism was placed in a rig which fixed its ends and center and allowed use of a force gauge to measure the device's force output over time. The entire rig and mechanism were then placed in the warm water to allow material dissolution to begin. A ruler was placed behind the mechanism to measure the mechanism's displacement over time. Pictures of the mechanism's actuation were taken once every six minutes to track resorption progress.

## Mechanism 4: Catapult

This mechanism shows an instantaneous application for resorbable materials. This catapult is designed from an Euler spiral to maximize energy potential of the compliant arm (34, 35) (see Figure 5). The catapult is loaded with ammunition (in this case, a small foam football) then locked using a resorbable material loaded in shear, as seen in Figure 6. The material resorbs until it catastrophically fails, which releases the strain energy in the catapult arm, launching the football.

The resorbable material utilized in this test was rock salt. Ice would have been preferable, as dissolution in air rather than water would have improved the catapult's functionality, but the bar of ice was too weak to hold the catapult arm in the locked position. The catapult was 3D printed in PLA.

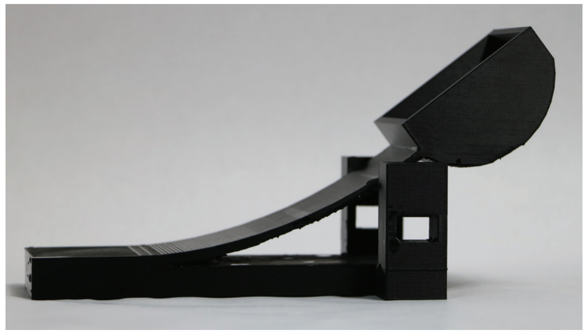
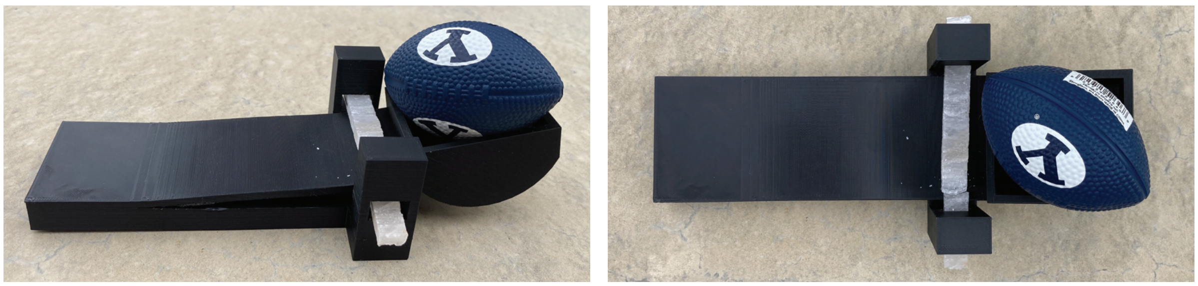


Figure 5: The 3D-printed catapult in its relaxed state.



(a) Angled view

(b) Top view

Figure 6: The catapult with the arm restrained by a bar of rock salt.

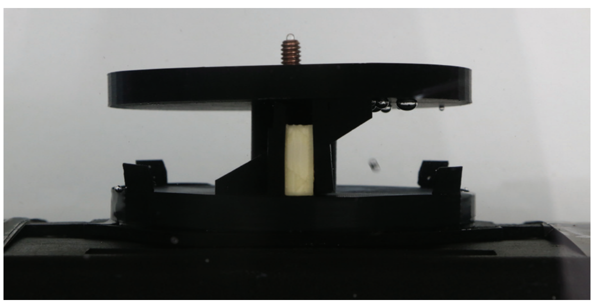
Testing of Mechanism 4 was performed as follows: A bar of rock salt was carved to the correct dimensions to fit in the lock. The catapult was loaded by displacing the arm and inserting the rock salt bar as a lock. The mechanism was then left in a tray of water. Once the rock salt had dissolved sufficiently, the strain energy stored in the catapult arm was enough to snap the bar, directly causing the material's actuation (hence the term "delayed instantaneous actuation"). A video of the actuation was taken so as to not miss the moment of actuation—the rock salt was under significant load due to the strain energy stored in the arm.

# Results

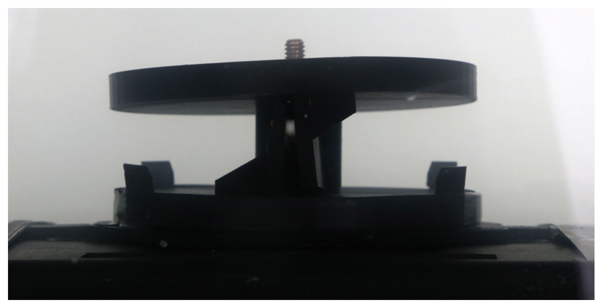
## Mechanism 1: Twist Mechanism

Testing of the twist mechanism was performed first with PVA and then with rock salt as the resorbable insert. The PVA took over twelve hours to dissolve because of its sheltered location within the mechanism; the less water flow across the insert, the slower it dissolves. The rock salt, however, took approximately an hour. These relatively short times were used for the experiment but much longer times would likely be used in most applications.

Comparison between 7a and 7b demonstrates that the mechanism has twisted, closing a gap of approximately 20°. After twelve hours of dissolution when the PVA insert dissolved, the torsional energy stored in the spring forced the mechanism to close that gap, bringing the two vertical black posts adjacent to one another. This test successfully demonstrated that resorbable materials may be used to actuate mechanisms which require torsional motion. The twist mechanism or similar might be used in an application where a valve needs to be gradually opened or closed over a period of time.



(a) Before

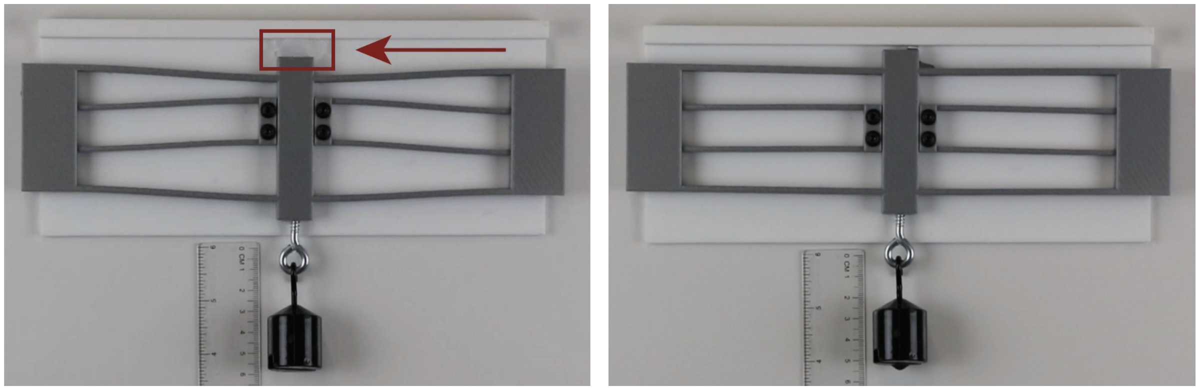


(b) After

Figure 7: Twist test before and after the test which utilized PVA as the resorbable material. The insert is the off-white section visible in the center of the mechanism in (a).

## Mechanism 2: Folded-Beam Suspension

The folded-beam suspension was tested to demonstrate linear actuation. The PLA mechanism was able to lift a 0.1 kg mass from its initial (as shown in Figure 8a) to final (8b) position as the material dissolved: a vertical distance of approximately 7 mm (see Figure 9).



(a) Before (b) After

Figure 8: Linear test before and after, utilizing ice as the resorbable material. The ice is pointed out in (a).

The plot also displays bars of uncertainty. This uncertainty was accumulated through measuring the displacement data from a ruler, and is therefore ± 0.5 mm for each data point. The downward trend in the data is still evident, even considering uncertainty. This test was therefore successful in displaying that resorbable materials may be used to actuate mechanisms which require translational motion, and may lift loads, the magnitude of which depends on the mechanism design.

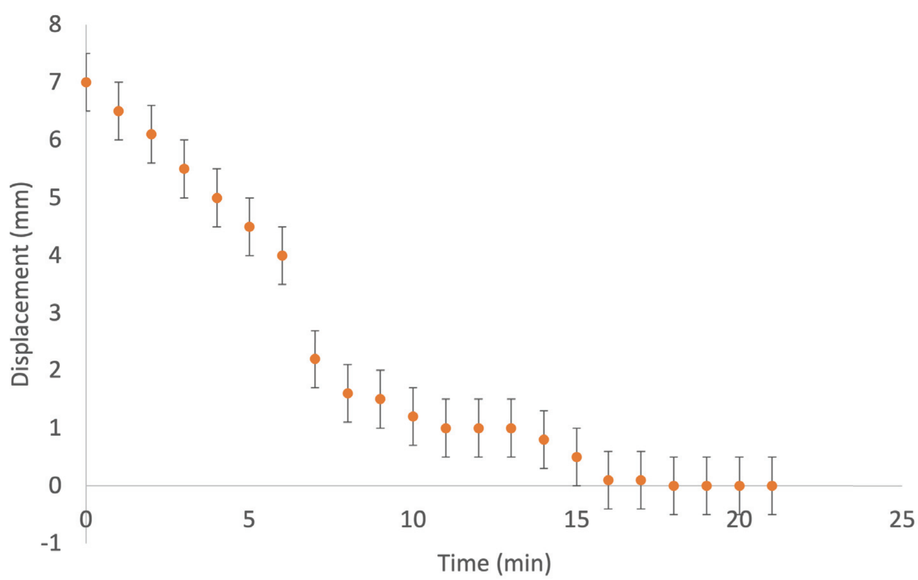
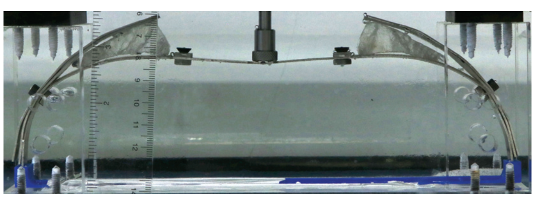



Figure 9: Displacement vs. time data received from the folded-beam suspension test, including bars of uncertainty. This data shows a clear, nonlinear increase in displacement over time as the inserts dissolved.

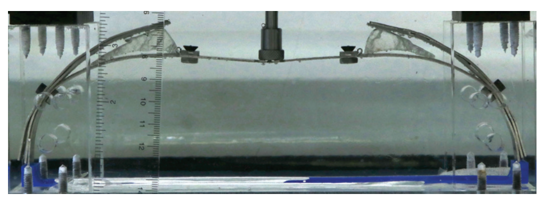
A finite-element analysis of the folded-beam suspension suggests that the design can support a greater force per unit deflection when other materials are used. The PLA exhibited stress relaxation under load, and the use of alternative materials could allow for additional force to be applied while avoiding stress relaxation. This mechanism thus achieved the desired effect of lifting the weight as the ice dissolved. This mechanism or similar might be used in any application where delayed linear motion is required and active actuation is difficult.

## Mechanism 3: Corrective Bar

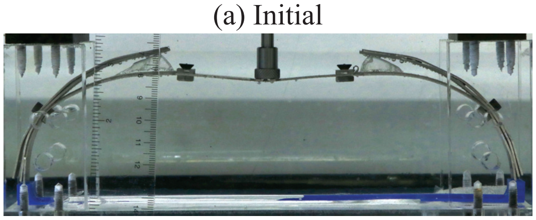
Figure 10 shows the aluminum corrective bar throughout material dissolution. This design would require modification before in vivo use, but gives proof of concept. Because aluminum did not suffer from significant stress relaxation in the time of experimentation (unlike many polymers) and because of the aluminum's greater elastic properties, it is more ideal for displaying the functionality of resorbable materials. There is, however, still a slight plastic deformation of the bar visible in 10d; the left side of the bar has not managed to return entirely to its initial position. This is likely because the bar had been used for several tests prior to this one.



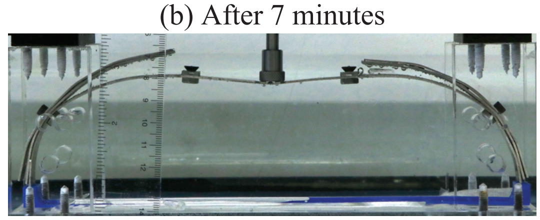
(a) Initial



(b) After 7 minutes



(c) After 13 minutes



(d) Final: after 20 minutes

Figure 10: Pectus bar throughout resorption process from test 3: Aluminum mechanism with rock salt inserts.The rock salt is visible in (a) on each upper side of the insert.

The corrective bar produced a maximum force output of approximately 4.5 N. Again, using different materials and mechanism designs would allow the mechanism to lift even greater weights. The plot shown in Figure 11 displays a correlation over time with the force produced by the pectus bar. As the resorbable material dissolved, it is clear that the force the bar exerted on the force gauge also increased. Such data could be used to create models to predict dissolution rate based on material properties, the insert's dimensions and volume, force placed on the inserts, and characteristics of the surrounding environment (2,36). While the uncertainty in the measurements is not displayed on the graph, the force gauge used has an uncertainty of ± 0.1 N, which is not significant enough to call into doubt the conclusion drawn from the data.

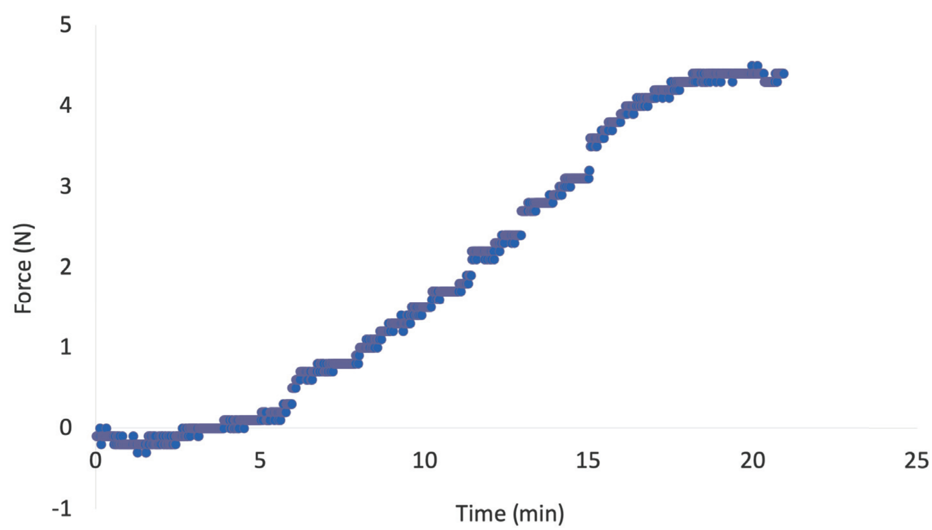



Figure 11: Force vs. time data received from test 3. This data shows a clear increase in force over time as the inserts dissolve.

A finite-element analysis performed on the pectus bar model verified that the maximum force produced by the bar at this continuous deflection was approximately 5N. This verification makes it clear that the resorbable inserts are redirecting a portion of the force, and that once they have dissolved, the mechanism functions as it would without the inserts. This also serves as a proof-of-concept for the device, showing that it could perform a gradual correction of the deformity by applying greater and greater forces onto the sternum over time. The pectus bar test was therefore successful in proving that resorbable materials may be used to actuate mechanisms which require more complex linear motion, and may also generate force. Different material choice and mechanism design would be able to produce various linear deflections and forces.

## Mechanism 4: Catapult

The catapult, the before-and-after for which may be seen in Figure 12, provided proof-ofconcept for instantaneous actuation via resorbable materials. The rock salt pin restraining the charged catapult arm shattered instantaneously: the moment of failure is shown in Figure 12b, where a large portion of the bar was propelled away and may be seen below the football. This design allowed the catapult to launch its ammunition with the strain energy stored in the arm at once, rather than releasing the strain energy gradually as was done in the previous three tests.

(a) Before

(b) After

Figure 12: Catapult test before and after the test which utilized rock salt as the resorbable material. Refer to Figure 6 for a better visualization of the insert in (a); in (b), the shattered pieces of insert are visible behind the explosion of water.

The catapult was actuated more quickly than the three previous mechanisms: it actuated within thirty seconds, while the others took between twenty minutes and twelve hours. Interestingly, the rock salt used to lock the catapult had a grain that may have contributed to the speed at which the catapult was actuated.

The ammunition travelled approximately three meters. It is likely that if the test had been performed in air instead of partially submerged in water, the catapult would have been able to produce a greater force and propel the ammunition farther. Additionally, decreasing the thickness of the compliant arm would have contributed to increasing the force produced by the mechanism. However, the catapult was still able to prove the concept of instantaneous actuation. When utilizing resorbable materials for actuation and in cases where instantaneous actuation is required, a design similar to the one used here may therefore be a viable option.

## Conclusion

Resorbable materials may be used as actuators in a variety of loading conditions, and to cause either gradual and continuous or delayed instantaneous actuation. They are primarily beneficial in situations where the mechanism is required to actuate only once, and have unique benefits in locations which are difficult to reach, as shown in Figure 13.

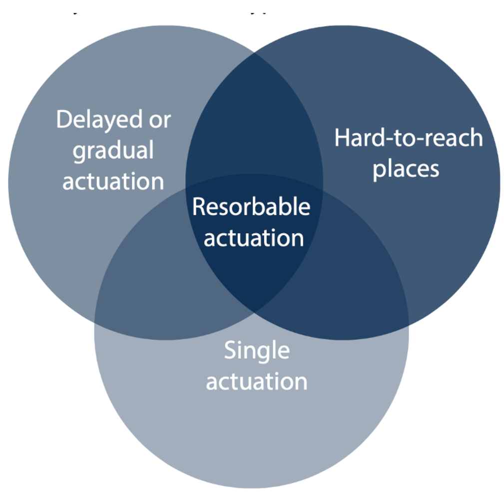



Figure 13: A diagram displaying the intersection of situations in which resorbable actuation presents the greatest benefit.

The time of actuation may be predicted based on size of material, temperature, volume, agitation of water, and the choice of material (3, 37). This tailorability of the materials makes them a viable and unique choice for mechanism actuation. In many cases of mechanisms which benefit from auto-activation and may be designed to store internal energy, the novelty of resorbable materials may also allow for the creation of mechanisms whose motions were previously difficult or impossible.

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