Automated Bioanalytical Chemistry Sample Tube Uncapping and Capping Device

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Abstract

Capping and uncapping test tubes is not only a time consuming task, but can also pose a risk of injury to the people that do this task in the form of carpal tunnel syndrome. The current practice in labs around the world is to have a clinician manually open and close test tubes in high volumes of up to 700 test tubes a day. Our client experiences this volume in their lab and wants to improve their daily workflow by implementing a new automatic or mechanical device that can do this task. Ideally, time of the lab clinicians will be saved and the risk of developing carpal tunnel syndrome will be heavily reduced. Though several products exist today that accomplish this goal, none are in current use by the client, primarily because of the lab's unique workflow. There are many different mechanical and ergonomical decisions to be made regarding the production of the device, especially in terms of whether it can work on multiple test tubes at once (seen in parallel bars and multiple-grab design ideas) or just one individual (single-grab design idea). The client requests that the team pursues multiple design ideas, as different devices may have certain advantages/disadvantages based on the application in which they desire.

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Introduction

Millions of samples around that globe go through some form of bioanalytical testing for a large variety of reasons. These samples are normally transported and worked with in some form of a laboratory test tube, and subsequently disposed of. Laboratory technicians responsible for processing these samples must undergo the repetitive task of opening and closing these test tubes each time the sample needs to be accessed. With new lab tests constantly being grown and developed, the demand for technicians is, and is expected to continue, remaining strong. The Bureau of Labor Statistics projects a growth of 18 percent from 2014 to 2024 in terms of employment opportunities, adding 29,000 professionals to the 163,400 already in the field (as of 2014).[1] With this given increase in the job market and importance for technicians, it is crucial to make their job as ergonomic as possible.

The repetitive uncapping and capping of twist-top test tubes is taking a physical toll on the lab technicians at a local Madison laboratory. Our team has set out to construct a device capable of reducing some of this physical stress. Whether manual or automatic, the device should be able to remove the top from the test tube, hold it until the work on the contents of the test tube is completed, then securely screw the top back on in a more efficient manner than the current process. This would ideally minimize the risk of injury as well as the maximize time for more important work.

Several products already exist on the market that accomplish the task of automatically capping and uncapping screw-top test tubes similar to those provided by the Madison laboratory. Each approaches the problem with a unique mechanism, yet all share many baseline characteristics. The three products most applicable to the problem statement are the Capit-All Screw Cap Tube Capper/Decapper [2], the PaR Capper [3], and the LabElite DeCapper [4]. In each of the designs, a tray of test tubes is placed/inserted in the area designated for the uncapping to occur. The test tubes used by these machines have specific tops in which a hexagonal/octagonal hole is cut out for the screw/arm of the device to reach down and insert into. This allows the top to either be screwed off or screwed onto the tube. The Capit-All design can handle 24-, 48-, and 96-spot racks and simultaneously caps, or uncaps, them all at once. The machine is capable of recognizing different tray types and sizes, so until the exact same tray is placed back into the device, the machine will not re-place the tops on the test tube. The LabElite DeCapper is very similar to the Capit-All, except the LabElite only works on one row at a time as to minimize time where the contents of the test tube are exposed, thus lessening the risk of contamination. The PaR Capper is the least similar of the three in terms of size, machinery, and functionality. While the Capit-All and LabElite are roughly the size of a desktop printer, the PaR Capper is significantly larger. The user interface, a computer monitor located outside the machine's case, is used to select which test tubes are to be worked on. Subsequently, a robotic arm maneuvers its way around the interior, uncapping and capping specified test tubes one at a time.

Background

About one-third of all occupational injuries and illnesses stem from over exertion and/or repetitive motion, one of the most common being carpal tunnel syndrome. The median nerve is a nerve in humans that runs down the forearm, through the palm, and into several of the fingers. It controls sensations to the thumb and fingers and sends impulses to small muscles in the hand that allow for movement. The carpal tunnel is the narrow passageway made of ligaments and bones which holds the nerve and related tendons. When muscles and tendons surrounding the passageway get inflamed, the median nerve gets pinched, causing tingling, numbness, weakness, and pain in the hand and the wrist that radiates up the arm. This problem is called carpal tunnel syndrome, and can be caused by a variety of things including obesity, pregnancy, rheumatoid arthritis, and repetitive wrist work. Since the prevention of obesity, pregnancy, and arthritis are out of the scope of this project, the repetitive wrist work is focused on instead. Some of the movements that cause this inflammation include repeated wrist flexion/extension, radial/ulnar deviation, and forearm supination/pronation, all of which combine to produce the motion of screwing small caps on and off test tubes. [5]

CTS is becoming increasingly prevalent among laboratory workers due to the high volume of work without ergonomically-favorable tools. One of such processes causing significant stress on the wrists and hands of technicians across the world is pipetting. Another is the repetitive uncapping and capping of test tubes. Even more manual effort is required to remove the top of screw-on/threaded test tube as compared to a non-threaded, stoppered test tube, making the technicians at this specific Madison laboratory all the more susceptible to hand injury.

According to the U.S. Department of Labor Occupational Safety & Health Administration, of all work-related repetitive injuries, CTS results in more days away from work than any other workplace injury. Ergonomic injuries including these cost the industry roughly $15-20 billion in workers’ compensation costs annually, which is clearly unfavorable for the employers. The employees, as well, are harmed by such injuries, as they have to follow through with physical therapy and/or surgical repair and risk permanent disability in the wrist in severe cases. [6]

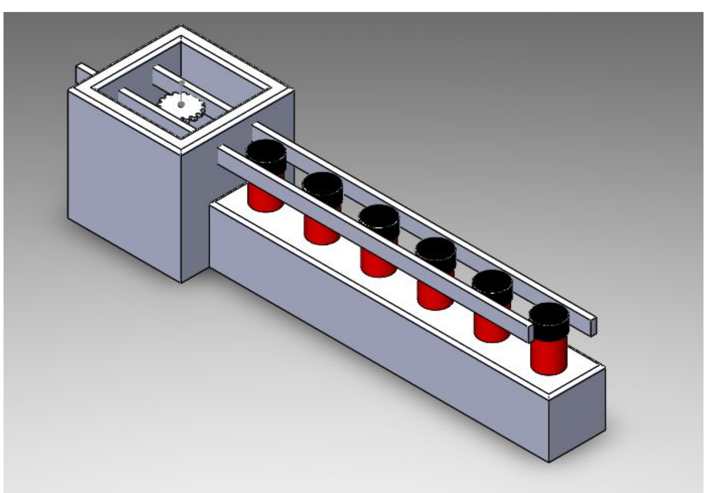
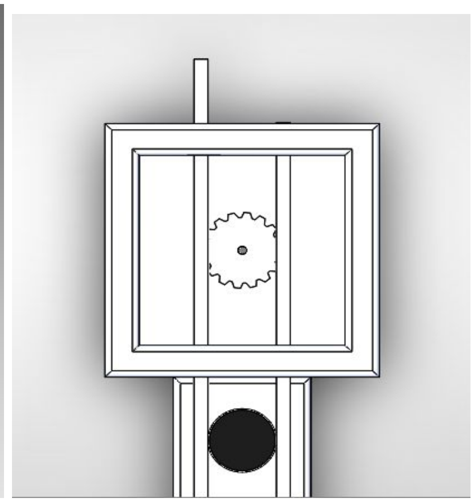
Professor Robert Radwin of the University of Wisconsin-Madison is serving as a liaison for the local company. The lab wants to lessen the manual labor required to open and close a high volume of test tubes by having our team design a device to automatically do this task, or at least lessen the labor of this task with a mechanical device. This improvement to their lab would allow their trained clinicians to spend more time on tasks that require their training and less time opening and closing test tubes by hand.

The design of this device is intended to reduce the cost, labor, and time in comparison to the current manual individual capping and uncapping method. In order to achieve these goals, the device must be able to cap and uncap at least 10,000 test tubes per month, and be available at cost cheaper than what it would take to pay a lab technician to perform the same job. Furthermore, the product must be easy to use in an attempt to minimize training time. The design should be small enough to fit onto the workbench so as to not interfere with the current workflow. Finally, the product must be sterilizable as it comes into contact with a variety of unknown substances, therefore we need to either avoid small parts or make the product autoclavable. The full list of product design specifications can be found in Appendix A.

Preliminary Designs

Design Idea 1: Parallel Bars

This design involves the anti-parallel motion of two bars in order to remove the caps of twist-top test tubes. The bars are powered by a single gear-driven motor, and they can act on an entire row of test tubes at one time. The job of the clinician is to line up the test tubes in the correct orientation relative to the parallel bars, and then power on the device, which results in the uncapping of the test tubes.

Figures 1 & 2: An overview of the parallel bars design with test tube rack inserted (Figure 1, left). A top view of the mechanism that would move the parallel bars (Figure 2, right).

Design Idea 2: Single-Grab

This design is a small, hand-held, mechanical device that can remove and replace the cap of a single test tube. In order to operate, it involves a motion similar to that as operating scissors. A spring loaded head is rotated when the two handles are squeezed together, and when released, it springs back into its original orientation. The head is placed on the cap of a single test tube, the handles are squeezed, and the rotation of the head twists off the cap and is held inside the head of the device. The clinician can then perform their work with the opened test tube, and then return the cap to the test tube by aligning the cap with the tube and releasing the handles, which rotates the head in the opposite of the original direction.

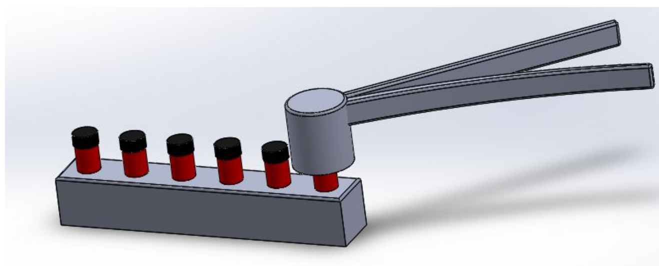
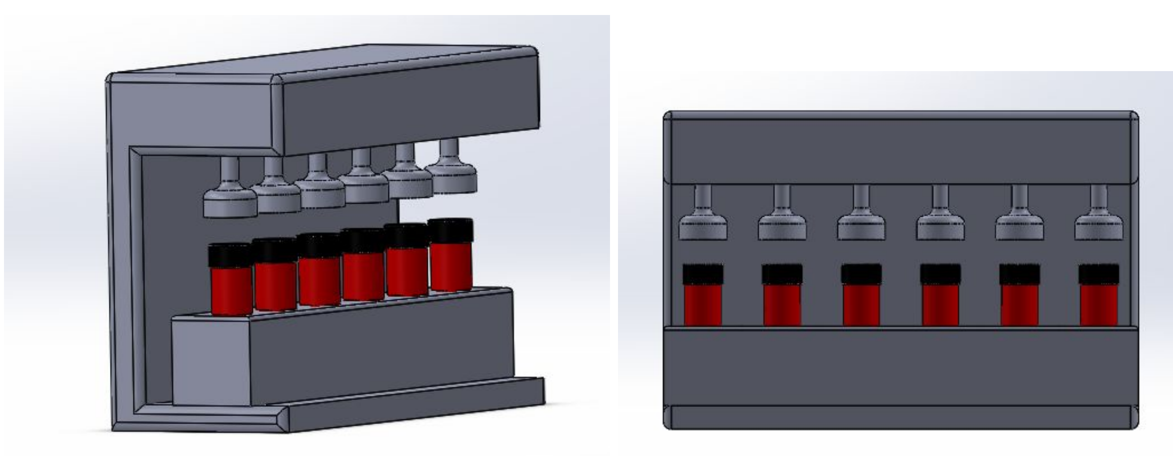


Figure 3: Model of the single-grab design uncapping a test tube.

Design Idea 3: Multi-Grab Design

This design involves six rotating heads that twist off, and then back on again the caps of six test tubes. The clinician lifts the row of test tubes up to the rotating heads, uncaps the test tubes, does the work with the uncapped test tubes, and then return the row of test tubes to the caps, which have been held in the rotating heads, to be recapped. This design can be redesigned with any amount of rotating heads that are desired by the client.



Figures 4 & 5: An overview of the multi-grab design with a test tube rack inserted (Figure 1, left). A front view of the device showing the heads lining up with the tube caps (Figure 2, right).

Preliminary Design Evaluation

A plethora of criteria are included in the preliminary design evaluation because of the extensive design specifications from the client. These design criteria and evaluations can be seen in design matrix below (Table 1). A total of nine design criteria were chosen and each criterium was given a value of importance in the final project. The reduction of manual effort is one of the most heavily weighted because it is very important to the client as employees are at risk of long term ailments from the repetitive task of uncapping tubes. The speed and success rate of the uncapping device is also very important for the client to efficiently process a large amount of samples each day. Many variations of test tubes are used by the client so the versatility of a design to uncap and cap different test tubes will also be important in the final design. Ease of fabrication is important given the timeframe of the project. The client noted the device needed to be very durable to last in the laboratory environment and not fail after uncapping thousands of tubes. Cost and safety have importance in any laboratory device. Finally, the lab technicians have limited bench space so size of the device was also part of the design matrix.

Design Criteria (Weight)	Parallel Bars		Single-Grab		Multi-Grab	
Reduction of Manual effort (20)	4/5	16	2/5	8	4/5	16
Speed (20)	4/5	16	1/5	4	4/5	16
Success rate (15)	4/5	12	3/5	9	3/5	9
Versatility (15)	1/5	2	5/5	10	2/5	4
Ease of fabrication (10)	2/5	4	4/5	8	2/5	4
Durability/longevity (5)	3/5	4	5/5	4	4/5	4
Cost (5)	3/5	3	5/5	4	3/5	3
Safety (5)	5/5	5	5/5	5	5/5	5
Size (5)	3/5	3	5/5	5	3/5	3
Total (100)	69		62		68	

Table 1: The design matrix used to evaluate the three preliminary designs.

Proposed Final Designs

The final design matrix shows the three designs being rated relatively similar scores from the proposed criteria. The main difference in scoring between the designs is whether the device can uncap many tubes at a time versus if that design is versatile in uncapping many varieties of tubes. Due to these two different problems, two general designs will continue to be developed and tested; one design that can uncap many identical tubes at once for speed and another design that uncaps a single tube but with much more versatility. The technicians at the lab suggested this idea of continuing with multiple designs, as the the single-grab idea may be very useful for one application while the parallel bars idea may be useful for another, for example.

Development Process

Proposed Testing

Due to the fact that the device is simply capping and uncapping test tubes, the testing criteria will be borrowed from the criteria of the design matrix. The areas of greatest importance to us are the reduction of manual effort, speed, and success rate. Reducing manual effort is the main goal of this project but speed and success rate are both necessary for our product to fit in within the lab technicians work flow and not be a hinderance on the amount of testing they are able to do in a day. Testing will be conducted as soon as the first model is produced, allowing us to refine aspects of the design prior to presenting it to the lab team. The team's goal is to meet with the technicians multiple times to get continuous, quality feedback and receive advice on what components of the design need improving. Ideally, the models can be run through the criteria of the design matrix, producing a quantitative value based on the weights of their categories and the score they received in each. This should give a very good idea of how well the project's goals are being accomplished.

Conclusions

Lab technicians in the bioanalysis field have to uncap and recap thousands of tubes a week to perform their jobs effectively. Repetitive tasks such as unscrewing a test tube cap have been found to cause long term ailments such as carpal tunnel syndrome, which hurts both the employee and the company. A novel device needs to be created to help these technicians reduce the strain on their hands while efficiently uncapping and recapping these test tubes for them.

Future Work

The preliminary designs still have changes that need to be made before fabrication can begin, especially after the very recent visit to the laboratory. A substantial amount of useful information was gathered from the laboratory visit that will be put into good use as the current designs are being refined. The general workflow was a major change in the problem that will need to be assessed. All tubes are uncapped then placed into standard racks, then later the racks are taken out and fresh caps are used to recap the tubes. It was also noted that there are even more sizes of tubes than earlier expected, including multiple different test tube diameters. Due to this the team will only be tackling the uncapping and recapping of the three most frequently used tubes. As stated above, design and fabrication will still be done of two design ideas: a device that can uncap one or two tubes, as well as a device that could upcap the entire rack of tubes. After designs have been finalized, fabrication will occur and the team will need to properly test the designs for their efficiency, effectiveness and reduction of hand strain. Finally, the two designs will be presented to the client and lab technicians for use in their current protocols.

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Appendix

Appendix A: Product Design Specifications

Function: A device that can, with or without automation, efficiently cap and uncap test tubes with twist tops and save our client from finger joint damage and from wasting valuable time manually capping 500-700 test tubes each day.

Client Requirements: The device must be stand alone, easy to use, and more efficient than manually capping and uncapping test tubes. It must also be compatible with multiple sizes of test tubes. It should be a simple design that is easy to use, reliable, and fits into a lab setting where bench space is limited. The device must average the capping and uncapping of 10,000 test tubes per month, making this a fairly robust design. It must work every time, and the design needs to be low cost and low maintenance.

Design Requirements:

1. **Physical and Operational Characteristics**
    a. *Performance Requirements:*
    Device has to be able to withstand high use without failure; must work every time with an average of 10,000 samples uncapped per month. Efficiency is also of great interest, as minimizing down-time while the device is in use is important.
    b. *Safety:*
    Must fit into a regulated work environment and pass all of its sterility checks. It should not pose a risk of injury for anyone using or near the device.
    c. *Accuracy and Reliability:*
    Must work every time with an average of 10,000 samples uncapped per month.
    d. *Life in Service:*
    Design should be able to be used for many years of heavy use. If the product has an element that is prone to breaking down, there should be a simple procedure for replacement/correction of that part.
    e. *Shelf Life:*

This design is being made for a specific client, so as of right now, no shelf life is expected for the first product. However, the device should be able to sit on a shelf indefinitely and still be functional should it be used by laboratories across the world.

f. *Operating Environment:*
A laboratory where bench space is limited. For that reason, the device should take up as little workspace as possible. Sterility is of great importance in a setting like this, so ideally the product will be able to be cleaned after previous usage.

g. *Ergonomics:*
Must be capable of withstanding heavy use from multiple technicians. The device should be easy to use and have a very small learning curve, as technicians should be able to teach other technicians how to use it.

h. *Size:*
Should fit into a lab setting with limited bench space; no larger than a desktop printer.

i. *Weight:*
No restriction on weight for the design.

j. *Materials:*
Must be able to be cleaned and sterilized without the risk of damaging the device.

k. *Aesthetics, Appearance, and Finish:*
Device should not stick out from the other devices and machines of the lab, so a look similar to those devices is desired. As this product is centered around efficiency, aesthetics are a lower priority as compared to functionality.

2. Production Characteristics

a. *Quantity:*
One device for our client for now, however its construction would ideally be easy enough to mass produce the product.

b. *Target Product Cost:*
Cost will be decided based on materials/parts used in construction as well as the client's thoughts on the usefulness of the design.

3. Miscellaneous

a. *Standards and Specifications:*
Being able to cap and uncap multiple test tubes simultaneously is preferred. The device also should not break any of the sterility standards of the laboratory. We must be sure that there is no cross contamination between the samples during the process, as that would greatly interfere with the technicians' results.

b. *Customer:*

Professor Robert G. Radwin and a research lab in the Madison area.

c. *Patient-related Concerns:*
Lab technician did not seem nearly as concerned about risks of repetitive wrist motion as their supervisors did.

d. *Competition:*
There are several products already on the market that serve the role of capping and uncapping test tubes. These include the Capit-All™ Screw Cap Tube Capper/Decapper, the PaR Capper, and the LabElite DeCapper. All three are capable of accomplishing the same task, yet involve different mechanisms/processes. The biggest difference between the three is the number of test tubes capped/decapped at once. The Capit-All can simultaneously work with up to 96 test tubes at once, the PaR capper individually uncaps/caps, and the LabElite uncaps/caps one row at a time.