Tendon support for continued training with climbing-related A2 finger pulley injury

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Abstract

We prototype a device relying on an external pulley mechanism capable of rehabilitating an A2 finger pulley injury. Finger pulley injuries are commonly seen in rock climbers and affect their mobility in not only climbing, but other general tasks that load the finger pulleys, i.e. holding grocery bags. An interview was conducted with a mid-20's, experienced rock climber who has twice injured the A2 pulley on his right ring finger without seeking formal medical treatment between occurrences. Our device intends to increase the need-knower's finger mobility by offloading tension from the injured A2 pulley when under stress, thereby reducing pain. The device contains a ratchet-pawl pulley system that supports external loads applied to the injured finger. The system alternates between two states, default and disengaged, depending on the user's perceived motion. Readings from an electromyography (EMG) sensor anticipate the user's grasp motion and concurrently engage the pawl with the ratchet to offload external force as needed. Torsional and linear springs are installed in tandem to the pawl and ratchet, respectively, to maintain appropriate elastic preload for their engagement. Tensile force tests were conducted on the device's pulley system to characterize its load capacity for various flexed finger positions. Completed testing has evaluated the device to be safe and recommended for loads up to 1.9 kg.

I. Introduction

Flexor pulley injuries are amongst the most common finger injuries seen in rock climbing across all ages and experience demographics [1] [2]. They occur when climbers adopt a particular position or motion that overloads the tendons and ligaments in their fingers. The fingers in our hands are composed of five annular ligaments (A1-5) that secure the flexor tendons close to the bone and help provide incredible power and leverage. When climbers support their weight by holding onto small rock edges, a strong tensile load is applied to the pulleys and if that load exceeds the maximum load an annular ligament can bear, the ligament may tear or rupture. Our apparatus seeks to rehabilitate this injury between climbers and non-climbers alike.

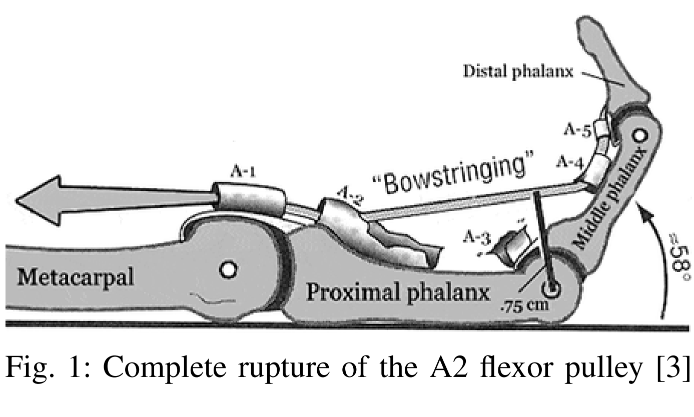

Fig. 1: Complete rupture of the A2 flexor pulley [3]

A. Background

While these injuries are profound in numbers, the methods for protecting and rehabilitating the injured pulleys are rather restrictive and/or ineffective [4]. The top two adopted treatments those with pulley injuries turn to are circular taping about the injured pulley with medical tape, and custom molded thermoplastic rings worn over the injured pulley. Both the tape and the thermoplastic rings aim to relieve enough force on the pulley to prevent further ruptures or propagation of the ligament tears. Taping has been determined to be grossly ineffective by numerous papers despite being used regularly among the climbing community [5] [6] [7]. Though thermoplastic rings are considerably more effective at relieving the loads on the injured pulley, they are highly restrictive and do not allow for the movement of the finger at all [8]. This prevents the gradual rehabilitation of the injury as well as the ability to use your hand in climbing-related activities or general activities such as carrying in a bag of groceries [9]. The alternative to current conservative approaches is the surgical approach, which carries with it long recovery times, high cost value, and adverse physiological risks [10].

In researching existing methods, there appears to be a gap in active rehabilitation while maintaining physical fitness. This sentiment is shared amongst the climbers in this team as well as our need-knower; it would be beneficial to climbers to develop a device that does not limit the individual's training schedule, while providing active rehabilitation and real-time monitoring of the injured pulley's behavior. Additionally, novice climbers are often more susceptible to pulley injuries. Since tendons adapt to mechanical loading at a slower rate than muscle [11], the resulting imbalance in their development often leads to the individual unknowingly straining their tendons with excessive tensile load despite having the sufficient muscular fitness. Moreover, insufficient resting periods combined with an inability to recognize the starting signs of tendon strain only exacerbate the injury and prolong recovery. It is therefore advantageous to develop a rehabilitation device that may be used in tandem with continued activity.

B. Overview:

Throughout this paper, we explore the effectiveness of the external pulley device we developed as it relates to protecting the A2 pulley from tensile loads. In section II, we summarize the interview data we collected from a subject with an A2 finger pulley injury. In section III, we will explore the prototype we developed to address the needs of people with A2 finger pulley injuries, as well as the actuation and sensing capabilities. Section IV is comprised of the device evaluation test we conducted. We will speak on the intellectual merit of our work in section V, as well as the shortcomings and future proposed work. Section VI will dive into the broader impact and benefits a refined version of our device could potentially bring to those afflicted with this injury. Finally, the appendix provides summaries of the literature reviews we conducted prior to the development of the external pulley device, and technical details of our implementation.

II. Preliminary results

Noting that existing pulley rehabilitation such as splints severely limit mobility, our team proposed the following hypotheses about an external pulley device:

a) Such a device can protect a climber's fingers during motion, allowing continued hang-board training and muscle activity to stay in shape.

b) Such a device can *also* relieve enough load on the ruptured pulley to prevent further injury.

To refine these hypotheses towards a functional prototype, we interviewed a mid 20s, male, experienced rock climber who experienced an A2 finger pulley injury in November 2021. We discovered that he did not receive any medical attention following his injury, and had not climbed since. We also learned that he experienced some pain lifting heavy objects like grocery bags following the injury; this later informed the target load, safety factor, and use case we chose when evaluating the device's success — see *Device Evaluation* section. When directly asked what type of assistive device he prefers, he chose a lightweight, low-power, passive device that allows for free movement. We learned that he experiences pain when the injured finger carries a heavy load, and his ideal device would reduce that pain.

On the topic of rehabilitation, our interviewee viewed it as physically and mentally demanding and time-consuming. He would opt for a device that makes rehab simple. Finally, he prefers devices that are affordable and small in size.

From this interview data, we were able to converge on the following 3 needs (collectively weighted 7 out of a possible 10, out of 6 interpreted primary needs):

Interpreted Need	Weight (out of 10)
Device provides rehab	3
Device reduces pain when injured finger is stressed	2
Device is affordable	2

Fig. 2: Summary of User Needs

III. Methods

A. External Pulley Design:

Our device intends to increase mobility of a need-knower by providing rehabilitation and reducing pain when the injured A2 pulley is stressed. To limit load on the A2 pulley, we developed an external pulley device that supports loads applied to the finger. As the injured finger receives load, the pawl in the ratchet gear will engage and prevent the string in the external pulley from extending. On either side of the injured A2 pulley are two rings. A string passes through both rings and wraps around a friction drive which is directly connected to a ratchet and paw mechanism. At the end of the string is a rubber band mounted to an acrylic board which removes the slack in the string. A torsional spring is connected to the pawl and keeps it in contact with the one way ratcheting gear when it is in its default position. The pawl is also connected to a servo motor via a short nylon string. The servo motor has two states: default, where the pawl is engaged with the gear, and disengaged. The PCB board sits behind the servo motor and contains a soldered Raspberry Pi Pico and a 5V voltage regulator. The system is mounted to a standard wrist guard with two fasteners.

When the pawl is disengaged, the finger can freely flex and extend. When the pawl is in its default position, the finger can flex freely, but once the user has any load applied to the finger, the pawl will engage with the teeth of the gear and prevent extension. Thus, when the pawl is in its default position, any load experienced on the finger is applied solely to the external pulley device rather than the injured A2 pulley.

B. Software:

To control our device, we used MicroPython running aboard a Raspberry Pi Pico microcontroller. For full code reference, please see: https://github.com/shaantamchawla/Finger-Pulley. Our software keeps track of the ratchet system's two states, *Engaged* and *Disengaged*, both referring to the pawl's position based on user intent.

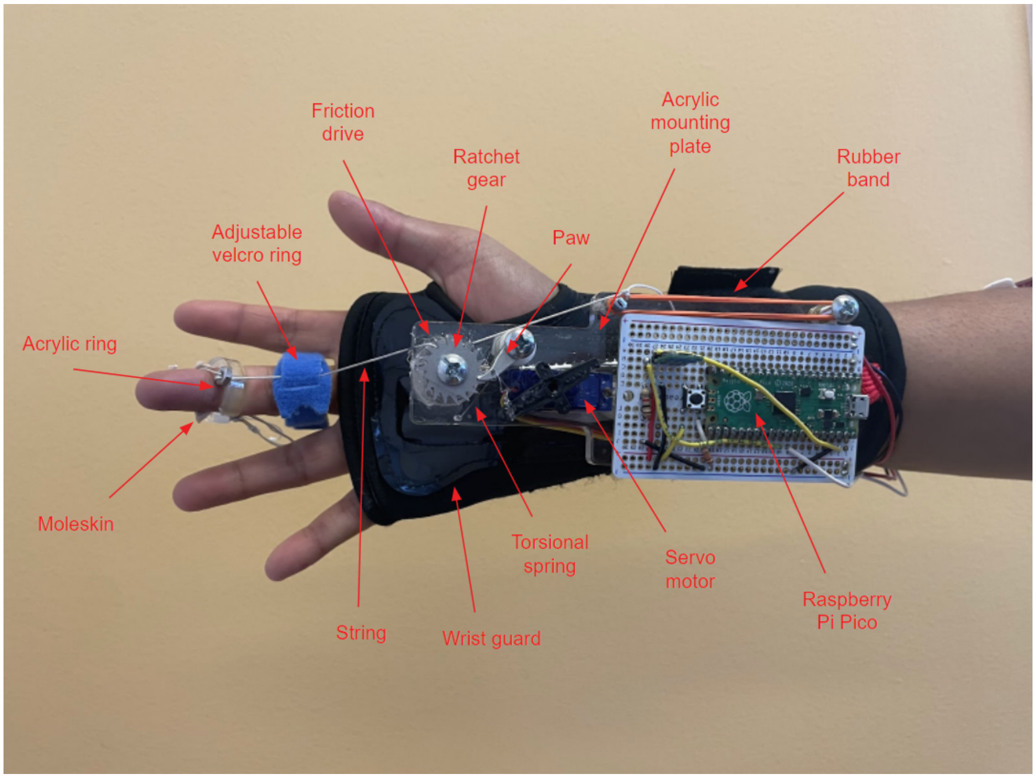

Fig. 3: Diagram of the components of the external pulley device

The electromyography (EMG) sensor we use to decide when to disengage is imperfect, so a push button listening for an interrupt acts as a manual override. This is crucial, since a user's hand may otherwise be stuck in extension if the sensor fails.

We also had to account for when the user already has their hand open, but makes any sort of motion that falsely triggers the EMG. To prevent endless disengaging and erratic motion of the pawl, we ensure there is a waiting period between each *Disengage* action. In addition, we programmed the pawl to automatically re-engage shortly after disengaging so that the user can continue lifting other objects if desired.

Fig. 4 summarizes our software in a state transition diagram.

C. Actuation:

The pawl is disengaged via a TowerPro SG92R digital servo motor. It is lightweight (9 grams) and has high output power while operating at a low voltage (4.8 — 5 volts), sufficient for mounting on the user's sleeve. A servo was appropriate since the device only needs to toggle between two positions — engaged and disengaged with the gear.

D. Sensing:

We incorporate EMG sensing at 100 Hz to detect muscle activity for injured finger extension and pawl disengagement. An EMG sensor placed on the extensor digitorum muscle on the posterior forearm triggers the servo motor, which is connected to the pawl via a short string, to rotate counterclockwise and pull the pawl from the engaged position with the ratchet gear.

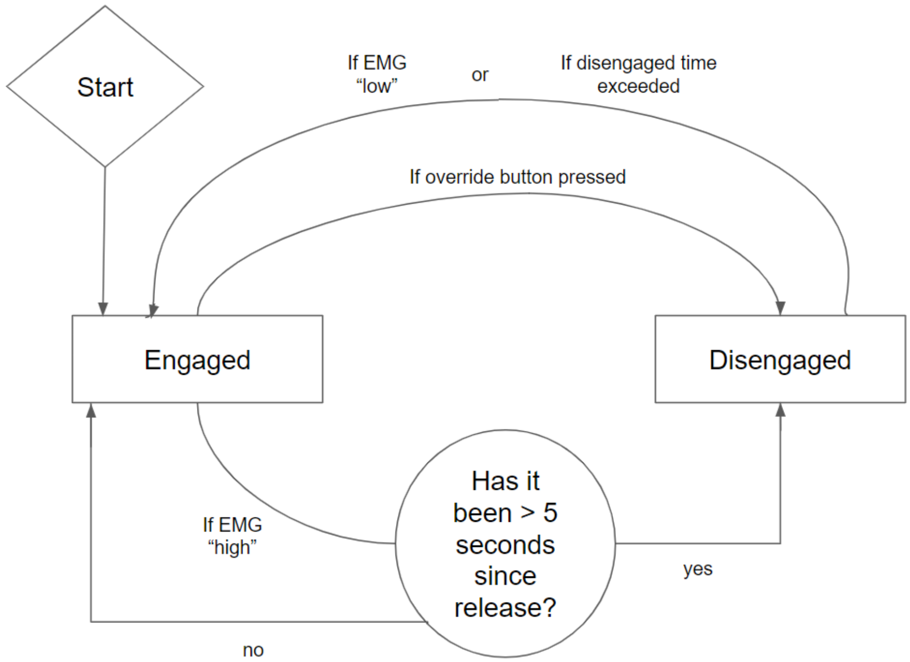

Fig. 4: State Transition Diagram

Raw EMG data is noisy, so we apply a low-pass FIR filter to the filter. We chose a moving average filter of window length 5. While imperfect, moving average filters help counter noise in time-domain signals (like EMG) with low computational cost.

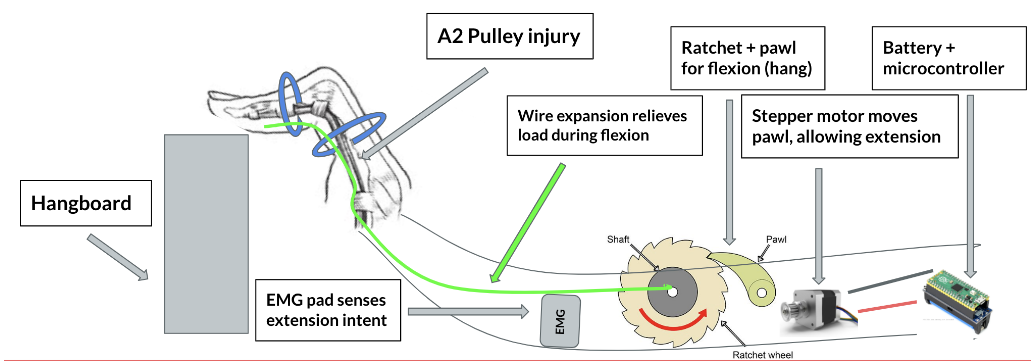

Fig. 5: Diagram of low fidelity prototype.

IV. Device Evaluation

In order to validate the device, we attached the device to a subject's non-injured finger and a tensile force test on the external pulley system was conducted. A force gauge is hooked around the distal phalange. With the finger flexed and the device locked in place, a tensile load is slowly applied with the force gauge in increments of 0.25 kg. At each load, the position of the distal tip of the flexed finger is measured relative to a fixed, flat reference surface. In order to showcase the abilities of this external pulley system, we designed our target load capacity to be that of the weight of a half gallon of milk, which is approximately 1.9 kg. This was to show that the pulley system can support everyday objects that a need-knower with a pulley injury has difficulty lifting. Incorporating a safety factor of 1.42, the test will conclude once a tensile load of 2.7 kg has been applied. If at any point the position of the finger extends open by more than 1 cm from its original flexed position, the device will have failed the force test at the recorded tensile load. If the device fails before the defined threshold of 2.7 kg, a failure analysis will be conducted in order to determine the cause of failure, and modifications will be made before the test is conducted again. The device will have met the determined load-bearing requirements once it is able support the 2.7 kg load without allowing for more than 1 cm extension from the supported finger proxy. The results of the tensile force test indicated that as the force was slowly increased to the threshold of 2.7 kg, at no point did the finger displacement exceed 1 cm. Thus the device passed the tensile force test and this provides evidence that it may be considered safe and recommended for loads up to 1.9 kg.

Fig. 6: Tensile force test set up.

Before testing further in human subjects, however, we would intend to perform this bench top tensile stress test as many times as the Internal Review Board (IRB) for Protection of Human Subjects and the FDA recommends in order to have statistically significant results, and also adjust the safety factor based on recommendations from these institutions. Additionally, we would want to survey subjects to see if they enjoy using the device and find it helpful for rehabilitation. Finally, before performing human subject tests, we plan to submit a protocol for review through the IRB for Protection of Human Subjects, in addition our completion of the CITI training Group 1: Biomedical Research Investigators as of May 6th 2022.

V. Intellectual Merit

One shortcoming of this work is the amount of pressure that a force load applies to the rings of the external pulley device. While moleskin was wrapped around the fingers to prevent slippage and reduce pressure points, as force passed 1.9 kg, the pressure points on the distal ring were uncomfortable. In the future, we would aim to redesign the rings using fundamental equations, particularly Pressure = Force / Area. In order to reduce the pressure on the finger, we would want to increase the contact area between the ring and finger. One method of doing this would be to design a sleeve for the injured finger that would distribute the force load more evenly along the finger.

Another shortcoming is the lack of reliability in EMG sensing. Measuring user intent accurately requires exact placement of EMG nodes and sensor calibration, a challenge complicated by inherent noise in EMG readings. Future work to improve the sensing capability may include: increasing the window size of the

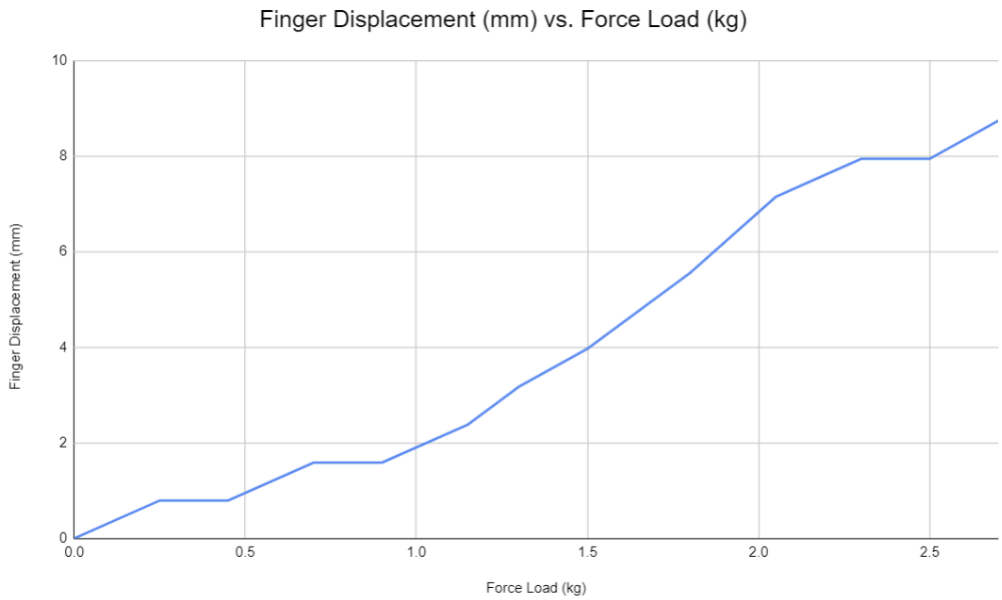

Fig. 7: Displacement of finger with attached external pulley device per kilogram of force load.

moving average filter, changing the sampling rate beyond 100 Hz, and experimenting with frequency-domain filters, such as a Gaussian or Blackman filter.

For the community studying finger pulley injuries, our work provides an easily reproducible setup where new sensing modalities, alternative friction drives, and more compact yet powerful motors can be investigated. For those with makerspace access, most components we made can be waterjet using our open-source files or bought in electronic hobby shops.

VI. Broader Impact

The A2 pulley injury can be devastating to climbers as it normally requires them to take months off from climbing to allow healing time. Existing rehabilitative products like splints limit mobility of the pulley. However, if a product such as this external pulley device could be used to protect the injured fingers of climbers, then climbers could continue to hang-board train and keep their forearms, tendons, and ligaments in shape without compromising the health of their injured fingers. For this type of product to be useful, we predict it would need to be a very slim, scaled down product that has components strong enough to withstand the force loads of the climber's body weight. We hope to make this system open source so others can build off of our prototype and bring this product to those who could benefit from it.

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Appendix A
Discovery Decomposition

Topic of the interview: everyday manual activities with hemiparetic stoke.

1) Pulley Ruptures in Rock Climbers: Outcome of Conservative Treatment With the Pulley-Protection Splint—A Series of 47 Cases: [1].

- Background/Hypothesis: Pulley injuries are among the most common injuries in rock climbing, and conservative treatment involves immobilization followed by a gradual increase in the intensity of finger exercise while always under some form of pulley protection that restricts TPD and further tendon damage. In 2016, Schneeberger and Schweizer evaluated the effectiveness a pulley-protection splint (PPS) and hypothesized it would act as a conservative treatment for a ruptured finger flexor tendon pulley by decreasing the tendon-phalanx distance (TPD).
- Methods: An ultrasound was used to measure before and after treatment with the split of the TPD in active forced flexion.
- Results: TPD was reduced in all patients and 38 out of 43 climbers regained their previous climbing level about 9 months after pulley injury.
- Conclusion: The PPS reduces TPD and is an effective treatment option for finger pulley ruptures
- Test Hypothesis: The splint enabled the majority of climbers to regain their previous climbing level.

2) Use of Thermoplastic Rings Following Venting of Flexor Tendon Pulleys: A Biomechanical Analysis: [8].

- Background/Hypothesis: By converting linear muscular force to angular digital motion, flexor tendon pulleys enable nominal finger flexion, however this flexion is greatly reduced if pulley is vented, or laterally released through surgical intervention. In 2021, Kadar et al. hypothesized the use of a thermoplastic ring as an external pulley would increase the finger range of motion (ROM) and improve the biomechanics of the flexor tendon after pulley venting.
- Methods: External thermoplastic pulley rings were placed over the proximal and middle phalanges of cadaver fingers to act in place of the A2 and A4 pulleys, respectively. ROM was measured before and after treatment with the thermoplastic rings over the completely vented A2, A3 and A4 pulleys in the cadaver digits using an *in vivo* active finger motion simulator.
- Results: The thermoplastic ring restore ROM and tendon loads to an insignificant difference when compared with the native, non-vented condition.
- Conclusion: Thermoplastic rings are an effective and noninvasive treatment for restoring range of motion and flexor biomechanics after pulley venting.
- Test Hypothesis: The application of the thermoplastic ring reduces tendon load and restores much range of motion in subjects with vented pulleys.

3) Biomechanical Effectiveness of Taping the A2 Pulley in Rock Climbers: [5].

- Background/Hypothesis: In 2000, A. Schweizer examined the biomechanical effectiveness of taping the A2 pulley of rock climbers. Circular taping of the proximal phalanx is commonly used by rock climbers and is hypothesized to prevent injuries to the A2 pulley and be an effective treatment for tenosynovitis and tendon pain.
- Methods: Schweizer built devices to measure the force of bowstringing and the force applied to the circular taping over the A2 pulley.
- Results: Taping over the A2 pulley absorbed 11 percent of the bowstringing force and decreased bowstringing by only 2.8 percent.
- Conclusion:While commonly used among climbers, the biomechanical effectiveness of taping the A2 pulley is minimal and probably does not relieve enough force on the pulley to prevent pulley ruptures.

- Test Hypothesis: Taping over the A2 pulley does not enable subjects to climb significantly more effectively with a tendon rupture than without the taping.

4) Pulley Injuries in Rock Climbers: [9].

- Background/Hypothesis: In 2003, Schöffl et al. published a journal article on the characteristics the finger flexor tendon pulley rupture commonly seen in rock climbers, and hypothesized the development of a severity grading system on the injury could be used to determine therapeutic guidelines.
- Methods: Six hundred and four injured rock climbers were evaluated over a four year period (1998 - 2001), and each injury was graded based on an introduced pulley-injury score on a scale of one to four, with grades one through three receiving conservative therapy and grade four receiving surgical repair. Rate of recovery was measured for each pulley injury and this was compared across grades as well as different treatment modalities.
- Results: Grades one through three respond well to conservative treatment, and the recommended treatment plans based of the results included the ”loop and a half” technique of Widstrom and colleagues, as well as initial immobilization and early functional treatment with some sort of external pulley protection such as tape or thermoplastic/soft-cast ring.
- Conclusion: Different treatment plans may be best suited based on the grade of the pulley injury.
- Test Hypothesis: Recovery timelines were similar among the members of each particular injury grade, but significantly different across the grades.

5) Injury to the A2 pulley in rock climbers: [4].

- Background/Hypothesis: A 20-year-old climber strained two finger on his non-dominant hand, which led to swelling on the proximal phalanx of his middle finger and eventual bowstringing of the tendon, but no long-term loss of function, even while climbing. This prompted a study of common hand injuries in competitive climbers by S.R. Bollen.
- Methods: Bollen conducted biomechanical analysis of 18 climbers’ dominant hands to measure the forces placed on the proximal phalanx when a falling climber places his weight on one finger, often leading to bowstringing in the A2 pulley.
- Results: A 70kg man falling and catching himself on a pocket with one finger results in a force load of 450 Newtons, leading to sudden tear or gradual stretching, then tearing, of the A2 pulley.
- Conclusion: The ”pulled tendon” injury was previously common in the climbing community, but its precise nature and impact on future climbing abilities was not studied as it was in this paper.
- Test Hypothesis: A climber who falls then catches themselves by a pocket with a single finger is likely to tear their A2 pulley, but residual pain and long-term loss of climbing function is unlikely to happen.

6) The Effect of Circumferential Taping on Flexor Tendon Pulley Failure in Rock Climbers: [6].

- Background/Hypothesis: Climbers often tape their fingers around the circumference of the proximal phalanx level to prevent A2 pulley ruptures — the most common injury in rock climbing. Warme et al proposed that this would increase the A2 pulley’s load to failure and decrease risk of injury.
- Methods: Loads were taken on nine pairs of hands from cadavers, each hands being mounted to a specialized rig mimicking the load placed during climbing. In total, load data for taped vs. untaped fingers was taken across 22 pairs of fingers.
- Results: The A2, A3, and A4 pulleys collectively failed in 55% of test cases. The sequence of pulley failure was unaffected by the presence of wrapped tape.
- Conclusion: Contrary to the original hypothesis and common practice by climbers, placing tape around the circumference of the proximal phalanx does not increase the load tolerance of the A2 pulley while climbing.

- Test Hypothesis: Failure of the A2 pulley when climbing is often accompanied by, but not guaranteed by, simultaneous failure of the A3 and A4 pulleys. The A2 pulley is most tolerant to high-load tears, followed by the A3 and A4 pulleys.

7) Injury Trends in Rock Climbers: Evaluation of a Case Series of 911 Injuries Between 2009 and 2012: [2].

- Background/Hypothesis: This study recognizes the frequency of rock climbing hand injuries and their variety, and surveys the demographics, distribution, and severity of injury patterns.
- Methods: Over 4 years, Schöffl et al conducted question and answer surveys of 836 patients with a total of 911 independent climbing injuries.
- Results: 833 of the 911 injuries were upper body injuries, and 52% of all injuries were in the fingers. Of these, pulley injuries were the most frequent.
- Conclusion: The plurality of all climbing-related injuries in the survey period were finger pulley injuries. The rate of A4 pulley injuries has surpassed A2 pulley injuries.
- Test Hypothesis: Finger injuries are the most common across different age and experience demographics among climbers

8) Injuries to the Finger Flexor Pulley System in Rock Climbers: Current Concepts: [10].

- Background/Hypothesis: Closed traumatic ruptures of finger flexor tendon pulleys present a new complex injury in rock climbers.
- Methods: Two investigators reported on a climber with closed traumatic pulley rupture. Both investigators achieved good functional results with two types of methods: conservative treatment and surgical procedure.
- Results: Nonsurgical treatment is becoming standard for the single rupture. Grade IV injuries require surgical repair to prevent functional deficits. The basis for surgical repair are the biomechanical studies and comparison of surgical repairs performed by Widstrom.
- Conclusion: For single rupture injuries, 1.5 cm-wide tape above the A2 pulley allows good protection of the pulley. In Grade IV injuries, a simple suturing of the remaining incomplete rims of the pulley tears have proven insufficient so a reconstructive-type repair is essential.
- Test Hypothesis: The traumatic mechanism in closed pulley ruptures for climbers is nearly the same as lifting heavy items with crimped fingers.

9) Impact of Taping After Finger Flexor Tendon Pulley Ruptures in Rock Climbers: [7].

- Background/Hypothesis: Finger flexor tendon pulleys maintain flexor tendons closed to the phalanges of the finger and prevent bowstringing. When high forces are applied to the pulley system, a rupture of one or more pulleys can occur. Certain taping methods can provide the necessary therapeutic approach to minimizing pulley ruptures.
- Methods: In order to compare the effects of taping methods described in literature with a newly developed taping method, Klauser performed standardized ultrasound examinations of eight subjects with singular A2 pulley rupture and multiple pulley rupture of A2 and A3 pulleys.
- Results: The H-tape method reduced the tendon-bone distance by 16 percent compared to without tape. The other two tape methods did not significantly affect the tendon-bone distance.
- Conclusion: The force being applied on the finger flexor tendon pulley system is a function of the tension being developed in the flexor tendons and the angle between the tendon and the pulley. In order to decrease the force on the pulley and prevent ruptures, the goal must be to diminish this angle since tendon tension cannot be influenced.
- Test Hypothesis: The new taping method influenced the path taken by the tendon in an injured finger more effectively than the previously described taping methods.

A. *Engineering Drawing of External Pulley Device*

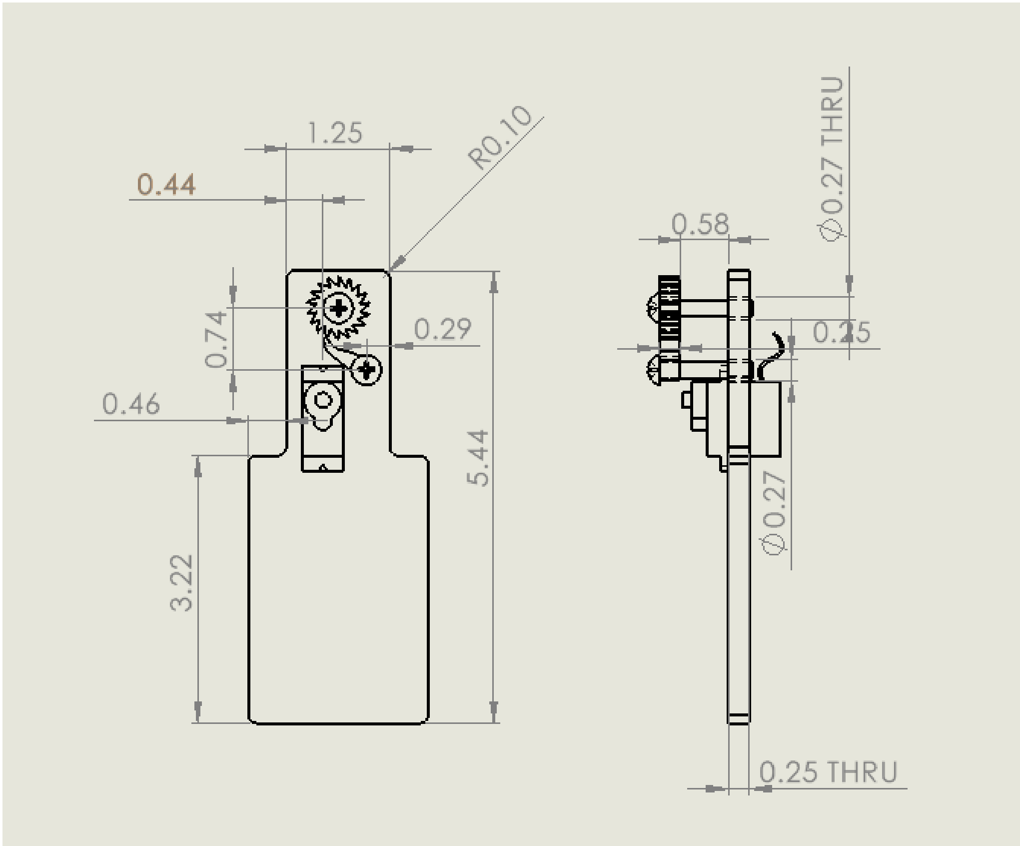

Fig. 8: Engineering drawing with dimensions of external pulley device.

B. *Bill of Materials — Mechanical*

Item No.	Item Desc	Qty
1	1/4” acrylic mounting plate	1
2	Ratcheting gear	1
3	Pawl	1
4	1/4” x 20 thead size 1” screw	6
5	1/2” nylon standoff	2
6	1 mm cotton string	1
7	Acrylic ring	1
8	Adjustable velcro ring	1
9	Wrist guard	1
10	Threaded heat set inserts	6
11	Rubber band	1

C. *Bill of Materials — Electrical*

Item No.	Item Desc	Qty
12	Raspberry Pi Pico	1
13	1/2-Sized Breadboard PCB	1
14	Push Button	1
15	220 Ohm Resistor	1
16	TowerPro SG92R Servo	1
17	5V Regulator	1
18	MyoWare Muscle Sensor	1

D. *Electronics*

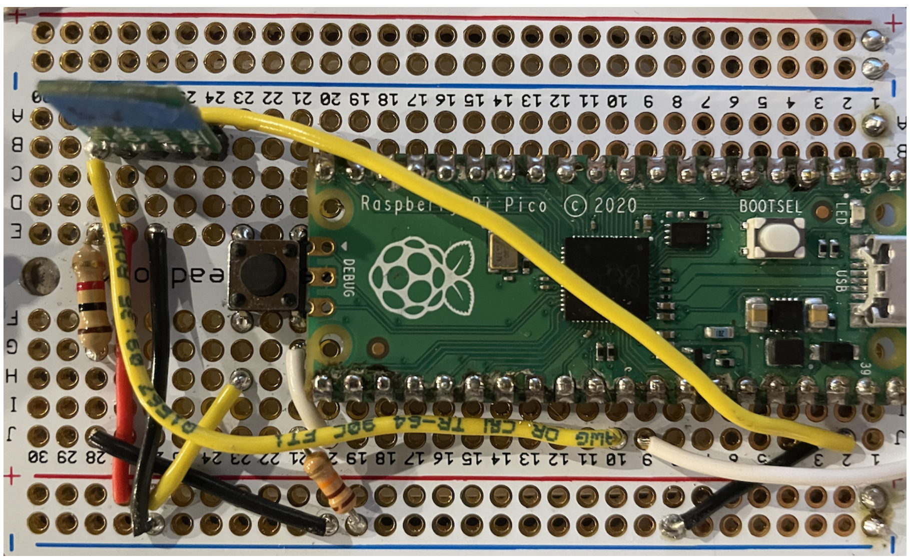

Fig. 9: Electronics Close-up.