2019

Correcting Human Errors in Rock Climbing

Regina Yan
Regina.L.Yan.19@Dartmouth.edu

CORRECTING HUMAN ERRORS IN ROCK CLIMBING

by

REGINA YAN

Bachelor of Arts Independent Project

Thayer School of Engineering
Dartmouth College
Hanover, New Hampshire

Date MARCH 11, 2019

Approved: ______________________
Advisor's Signature

ABSTRACT

Rock Climbing is a popular sport in the United States, with more than 9 million people each year partaking in the sport (*Funderburke*). One of the main forms of climbing is Sport Climbing, where a climber climbs up with the rope, clipping into bolts along the way. The belayer on the ground is actively managing the rope and ensuring the climber does not "deck" (hit the ground) when he or she falls. When proper procedures are followed, sport climbing results in few injuries; however, improper belay technique resulting from the belayer standing too far from the wall is a main source of accidents and injuries from lead climbing (*Schöffl, Rock*). This problem is exacerbated among beginner and intermediate climbers who have just learned to lead climb and whose confidence in skills is much higher than actual abilities.

This project aims to correct this human error in belaying and ensure the belayer stands within an appropriate "safety threshold" from the wall. Through iterative prototype and experience testing, the resulting product was the Belay Belt, a device that measures the belayer's distance from the wall and alerts the belayer when he or she is standing too far from the wall. Product testing yielded successful results, with participants reducing their average distance from the wall in all trials. In addition to reducing belayer distance from the wall, the device reduced mental strain on the climber by ensuring the belayer would safely catch the him or her. These results show promising evidence that the Belay Belt or similar device to keep the belayer safe and accountable is a big step in promoting safety in rock climbing.

PREFACE

Rock Climbing is an important part of my life, and I dedicated this term (Winter 2019) to developing a product that would make this sport safer for the climbing community. This project would not have been possible without the relentless support of my advisor, Professor Peter Robbie, or the help of my peers Maria Garman ‘19 and Brian Francis ‘18. I would also like to thank Doug Fraser and Professor Eric Hansen for their advice in developing the prototypes, and Sheppard Somers ’19 for his support throughout the process. Finally, I owe gratitude to the Dartmouth Mountaineering Club members for being enthusiastic participants, sources of knowledge, and a loving community.

TABLE OF CONTENTS

INTRODUCTION

With the recently announced addition of sport climbing to the Olympics, the climbing world has skyrocketed in popularity the past few years. Lead climbing is a discipline of climbing that involves a "lead climber" and "lead belayer". The lead climber is climbing up with the rope, clipping into bolts along the way. The lead belayer is on the ground managing the rope by feeding or taking in "slack" (extra rope) to the climber and is responsible for ensuring the climber does not "deck" (hit the ground when falling). Lead climbing is the most popular form of rock climbing and the Dartmouth Mountaineering Club's main focus in indoor and outdoor climbing.

RESEARCH METHODOLOGY

Problem Research

Lead climbing has resulted in six major reported injuries in the Dartmouth Mountaineering Club from 2016-2019 (Appendix A, Page 18). Five of these injuries occurred from the lead climber falling and injuring him- or herself due to improper belaying from the belayer. Further study indicates that a large contributing factor to this improper belaying stemmed from the belayer standing too far away from the wall. This leads to increased slack in the rope, which greatly increases the falling distance for the climber. The schematic in Figure 1 illustrates the physics component to a climber's fall.

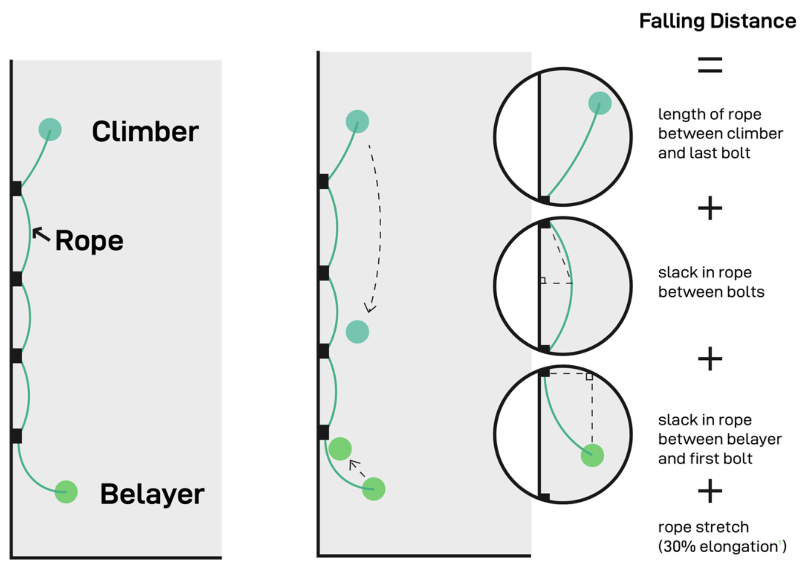


Figure 1: The factors contributing to the falling distance of a climber

Not only is standing too far away from the wall dangerous for the climber, it is also risky for the belayer. The farther a belayer stands away from the wall, the more distance the climber will fall, thus increasing the force pulling the belayer into the wall.

User Research

Surveys and interviews were conducted among members of the Dartmouth Mountaineering Club. A general trend of confidence in relation to time and experience climbing was mapped and shows that beginner-intermediate climbers typically experience a spike in confidence when they learn to lead climb and gain independence (Appendix B, page 19). However, they are overconfident in their skills, suggesting a Dunning-Kruger effect in which climbers with lower abilities mistakenly assess their skills as greater than they actually are. The five previously mentioned injuries all occurred among beginner-intermediate climbers, indicating a potential target user base for innovation.

In a survey among these beginner-intermediate climbers in the Dartmouth Mountaineering Club (Appendix B, Page 19), 47% of individuals stated they "confidently know how to lead belay" however nearly two-thirds (62%) are unsure of the correct distance they need to stand away from the wall in order to give a safe belay. 95% of survey participants indicated that they would feel more comfortable belaying if another person were present or "keeping an eye on them", suggesting that an innovation to ensure proper belay distance would be effective among these beginner-intermediate climbers.

Lead belaying injuries are not unique to the Dartmouth climbing community. A study conducted in Germany analyzing over 500,000 climbing visits shows that human errors in lead belaying is the main cause of sport climbing injuries (*Schöffl*).

SPECIFICATIONS

Specifications

From research findings, the specifications in following table (Figure 2) were chosen for a successful product.

ESSENTIAL	DESIRABLE
Reduce belayer distance from wall	Is aesthetically appealing
Is lightweight	Lasts a long time
Does not disturb other climbers	Is low cost
Is portable	Is easy to equip
Withstands outdoor conditions	

Figure 2: Essential and Desirable specifications for a successful product

The most important of these specifications is reducing belayer distance from the wall, which decreases rope slack and decreases the chance of accidents when the climber falls (*Vodjansky*). Having a lightweight product is also important to ensure it does not negatively impact the belayer's experience or weigh them down. It is also essential that the device not disturb other climbers in order to ensure that other parties at a crag or climbing gym can focus on their own climbing. The last essential specification is durability and the need for the product to withstand outdoor conditions. While climbing generally doesn't happen outdoors when it rains, it is still important for the device to be water resistant enough to withstand rain if it were to occur.

Apart from the essential specifications, additional desirable features would add value and improve the device. Ideally the device would be aesthetically appealing and not discourage belayers from using it. It would also last a long time in regards to battery life if a battery were to be used. The device would also need to be low-cost and therefore affordable and accessible to the climbing community. Finally, the device would ideally be easy and quick to equip to minimize time spent preparing and maximize time spent climbing.

A full specification chart with metrics and values can be found in Appendix C, Page 20.

DESIGN PROCESS

Prototype 1

The initial looks-like prototype was a cardboard prototype shown in Figure 3. The prototype included a foamcore rendition of a distance sensor for measuring distance away from wall, a buzzer that would activate when a belayer stepped out of range, and an LCD screen to display current distance status. The belayer would clip the device to the front of his or her harness.

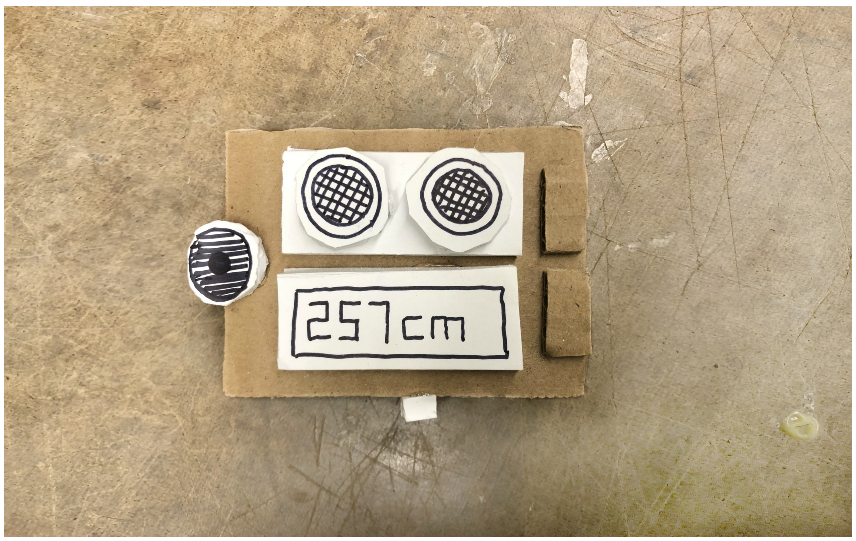


Figure 3: Cardboard prototype with foamcore parts

Prototype 1: Experience Testing

The cardboard prototype allowed for experience testing to see what having a clip-on device would feel like. The purpose of the experience testing was to gain initial feedback and findings to help guide further iterations and works-like prototypes.

The experience test was conducted in Dartmouth's Jonathan Belden Daniels '86 Memorial Climbing Gym with four participants. Each participant performed one round of

lead belaying without knowledge of the device. After this first round, the belayers were informed of the dangers of standing too far away from the wall and equipped with the cardboard prototype. They were instructed to belay the climber again, however this time whenever they stepped outside of the safe distance threshold of 6 feet (*Vodjanksy*), they would be given a verbal "buzz" sound.

Prototype 1: Findings

Each participant stood closer to the wall on the second trial which indicated potential for a successful product in this direction. Participants also noted that the device did not impede on their ability to belay or obstruct any movement. However, several problems were noted that provided areas for improvement.

A. Accounting for Belayer Rotation

The first and most important finding was accounting for an individual's rotation movement while belaying. As seen in Figure 4, belayers would often move and rotate around in 3D space, resulting in what would be incorrect readings from a clip-on device.

Figure 4: A belayer standing facing the wall (left) and turning sideways (right)

The device's one sensor would only measure distance in one direction, which would be directly in front of the belayer. This would result in an issue if the belayer were to rotate, and the sensor would record a much higher reading than the belayer's actual distance

from the wall. To account for this problem, three sensors were used in the next iteration, with the smallest distance being used for the actual reading (Figure 5).

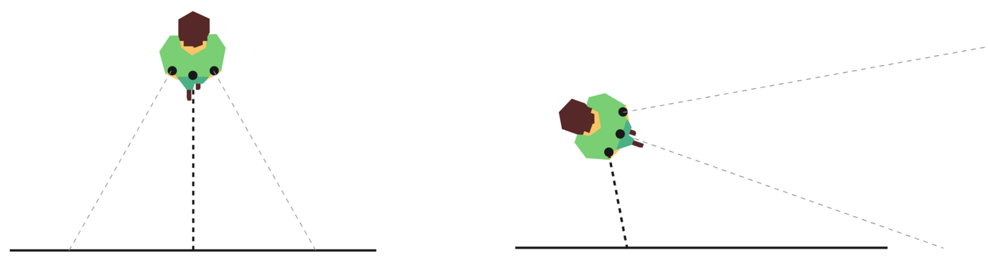


Figure 5: Using three distance sensors to account for belayer rotation. The dark dotted line indicated the reading used in safe distance threshold measurement

Multiple tests were run to ensure that the correct reading was being outputted as the actual distance. An LCD screen was temporarily used to display the measured distance and compare it to the actual distance in a controlled setting. An example test can be found in Appendix E, Page 26 along with the code in Appendix D, Page 25.

B. Different Safe Distance Threshold for Different Belayer-Climber Weight Ratios

Light belayers generally need to stand closer to the wall while belaying than heaver belayers because less falling force from the climber is needed to pull them up or into the wall (*Vodjansky*). Feedback from the experience test showed that belayers, especially in the case when a female belayer was paired with a male climber (leading to a lower belayer-climber weight ratio) would find a device that accounted for weight difference in the safety threshold useful. While the possibility of having an input screen upon turning on the device was explored, that alternative was not used because of the complexity in learning how to use the device as well as the time needed to fully equip the device and

begin climbing. Instead, a mode button was introduced that would toggle between a "standard mode" (roughly equivalent climber-belayer weight ratio) and "light mode" (lighter belayer in relation to climber).

There is no strict guideline for when one would need to use the "standard mode" (6 feet distance threshold) or the "light mode" (5 feet); due to the inherent risk of lead falling and inability to test the distance belayer would need to stand in order to give the climber the same falling distance as a heaver belayer would, the mode relies on user intuition to determine which mode to use. Consulting experienced climbers in the Upper Valley community, a rough approximation of a belayer-climber ratio of under 2:3 is sufficient for switching to "light mode". Code for this button change can be found in Appendix D, Page 23.

C. Incorporation of Audio Sound

In the cardboard prototype, a "buzzing" sound was made to indicate the belayer should move closer to the wall. Feedback showed that individuals did not like the buzzing, noting that it sounded too much like a phone vibration or could be potentially uncomfortable if actually implemented.

A new audio sound was implemented with a piezo buzzer and mode button, with different musical tones playing for different scenarios: switching to "standard mode", switching to "light mode", and "exceeding safe distance threshold". Code for the musical tones and scenarios can be found in Appendix D, Page 21.

Iteration 2: Foamcore Prototype

The next iteration was a foamcore prototype (Figure 6) with electronics components that incorporated the changes from the feedback in Iteration 1.

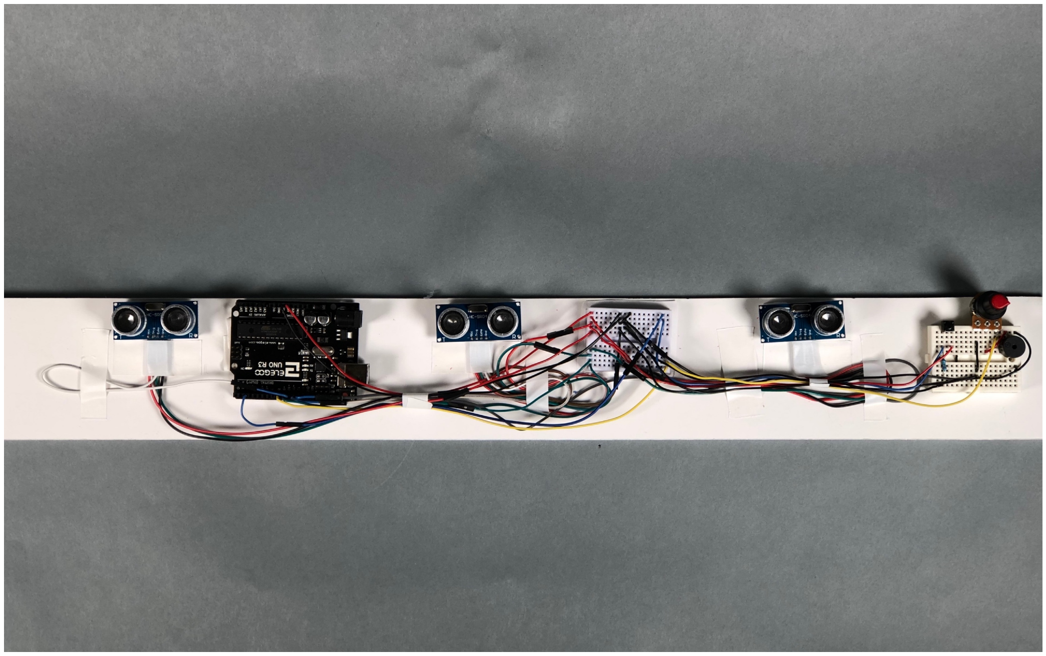


Figure 6: Overhead view of the foamcore prototype

The prototype uses an Arduino Uno along with three HC-SR04 Ultrasonic Distance Sensors. It also incorporates a mode button, piezo buzzer, and volume adjuster (potentiometer). The prototype was built on a foamcore strip to mimic a belt, rather than the clip-on device in Iteration 1. Details of the prototype can be seen in Figure 7.

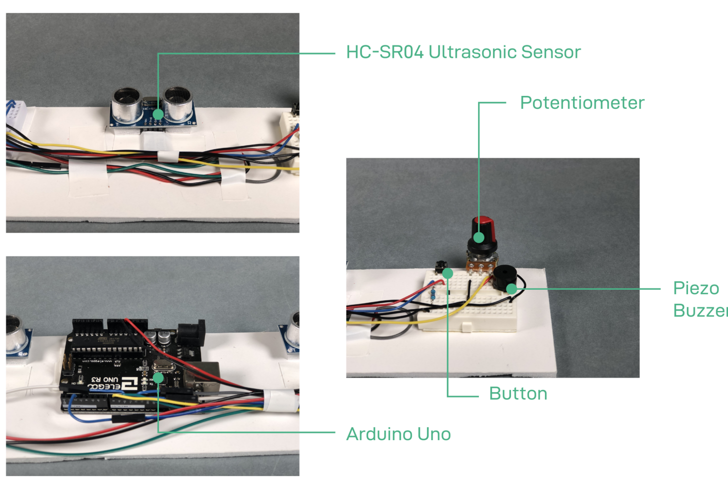


Figure 7: Details of the foamcore prototype and various electronics components

Iteration 2: Testing

Testing for this prototype involved ensuring that the correct distance sensor reading was being used as the measuring distance for the safe threshold. An example test can be found in Appendix E, Page 26 along with the code in Appendix D, Page 25.

Iteration 3: Belay Belt

The third iteration combined works-like aspects of Iteration 2 with a looks-like feel to be used for testing. Figure 8 shows the Belay Belt with additional changes from Iteration 2.

Figure 8: Details of the Belay Belt's exterior

The Velcro seams allow for the inside core of the belt to be removed if needed, which allowed for flexibility in making alterations to the electronics. A removable, rechargeable USB battery was added for convenience, and the belt features a buckle and adjustable straps to fit varying waist sizes. The electronics components, shown in Figure 9, show improvement from the previous iteration. The smaller Arduino Nano replaced the previous Uno, and the sensors were turned in a vertical fashion to allow for more bend in

the belt. The buzzer, potentiometer, button, and Nano were eventually soldered on to breadboards to increase strength after finalizing the prototype (not shown).

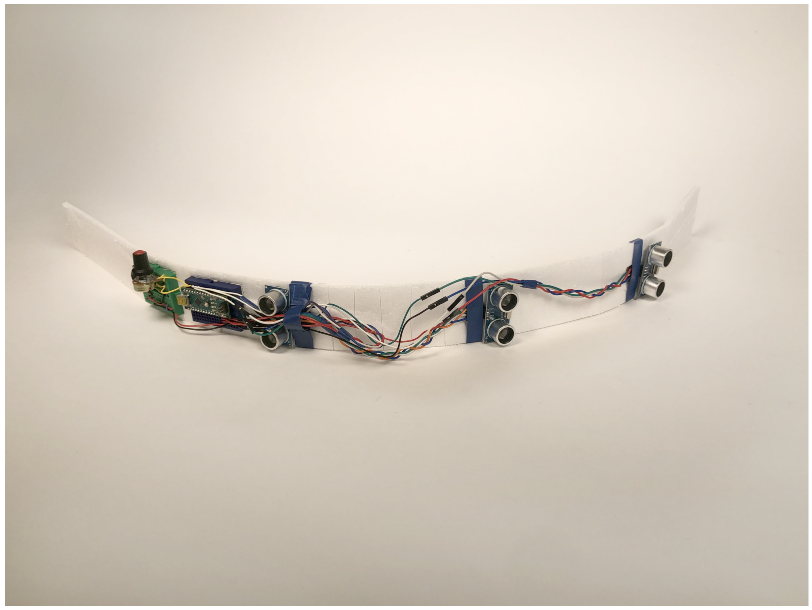


Figure 9: Internal components of the Belay Belt

TESTING AND ANALYSIS

Testing

Testing of the final prototype, the Belay Belt, was conducted at Evo Rock Gym in Concord, New Hampshire.

The most important specification was reducing belayer distance from the wall. To test this specification, eight individuals ranging from Dartmouth climbers to climbing community members performed one round of lead belaying without the Belt and one round with the Belt (in "standard mode"). Their average distance away from the wall was calculated from measuring their distance every five seconds with distance markers. Each individual reduced his or her average distance from the wall with the Belt, with all of them being within the safety threshold when equipped with the Belt, but only half being within the safety threshold without the belt. The full table of results can be found in Appendix F, Page 27.

The Belay Belt passed the weight specification by weighing just under the ideal value of 200g at 192g. Put in perspective, a climbing harness generally weighs about 450g.

To test the audio component, the potentiometer ensured that the audio would not disturb other climbers and could easily achieve the value of less than 60dB. However, testing showed that the sound was actually not loud enough – half the participants mentioned they could barely hear the notification tone at maximum volume, partly due to the noise in the climbing gym (there was a climbing competition that day). A solution would require using a more powerful audio buzzer.

The Belay Belt also passed the portability specification in that it packed into the same mesh bag as a climbing harness.

The Belt however did not pass the outdoor conditions test. To withstand the outdoors, the Belt would need to be waterproof or water resistant. More durable materials such as nylon or polyester webbing could be used to increase strength and prevent failure in rain conditions.

To test aesthetics, a survey was conducted and results showed that 87% of participants would be “willing to wear the belt” as is, and 100% would wear the belt “if it mimicked the look and feel of a climbing harness”. Survey responders were also asked to rate the Belt on a scale from 1-10 (10 being the most appealing) to measure the aesthetic appeal. On average, responders rated the product 7.1/10 which matches the ideal value of 7/10. The full survey responses can be found in Appendix G, page 28.

To test longevity, it was assumed that the limiting factor in the product would be the battery life. Because a rechargeable USB battery is used, battery life is no longer an issue because the device can easily be recharged by removing the battery (this is also a more sustainable option because no disposable batteries are used). The specification called for a minimum of 10 hours battery life, and continuously running the device showed that a fully charged 2200mAh battery will keep the device operating for at least 90 hours.

For the low-cost specification, each individual part’s cost was calculated to produce a total parts cost, which totaled $27.22 (Appendix H, page 29). This is less than the ideal $30, which passes the specification of making the belt affordable. If the product were bulk manufactured, the cost per belt would decrease further.

Finally, for the ease of equipping specification, each participant was timed when putting on the belt. The average time of equipping the device was just over 7 seconds, which passes the ideal value of less than 15 seconds.

Analysis

Testing yielded positive and promising results. The success of the device in reducing belayer distance from the wall shows that this prototype could positively influence the climbing community and make lead climbing safer especially for those just starting out. Participants noted that "it's nice to have a constant reminder, especially when you're not sure, or you are so focused on the climber up there that you aren't paying attention to what's going on down here". Another participant noted that "safe lead belaying is so important. I've seen my fair share of accidents, and this could really save lives".

While this device was targeted towards the belayer, climbers themselves also noted positive impacts. One said he "felt better when climbing because I don't have to worry if my belayer isn't belaying well or standing too far away, and I can focus on my climbing and pushing myself instead". Qualitative user feedback can be found in Appendix F, page 27.

While these preliminary results point to the potential for this device being an integral part of learning to lead belay safely, further testing would be needed to show if this belt would have lasting effects that change a belayer's behavior even when the belt is not present.

NEXT STEPS

Prototype to Product

The immediate next step would involve developing the prototype to production-level Belay Belt that would meet all expectations and be marketable. In other words, the current "works-like" prototype would be fully functional and "looks-like" as well.

On the electronics side, this would involve reducing the size of components such as replacing the Arduino Nano with a chip or smaller microcontroller. In terms of construction, the Belt would need materials such as nylon or polyester webbing to withstand outdoors conditions. Closed-foam cell would increase comfort, and mesh would enhance breathability.

Future Innovations

As suggested from feedback from participants, further exploration could be made regarding helping individuals change their behavior over time. One possibility could include taking advantage of Bluetooth or WiFi capabilities (potentially using Raspberry Pi rather than Arduino) and sending distance data to a console where individuals could track belay progress. Data could potentially be incorporated into the popular climbing app, Mountain Project by REI.

This product makes belaying safer by reducing the belayer's distance from the wall. Another factor that contributes to safe lead belaying is proper rope management. This device does not assess the actual amount of slack in the rope, however further studies could look into the feasibility of measuring the total amount of slack in rope relative to the climber's height.

CONCLUSION

Millions of individuals across the world partake in rock climbing each year. Assessing the human factors that contribute to accidents is necessary to ensure people pursue their passion while managing risks. This product successfully addresses the human error in lead belaying by encouraging belayers to stand closer to the wall and acting as a reminder that safety comes first.

APPENDIX

Appendix A - Summary of Dartmouth Mountaineering Club Case Reports

Fall 2016: Torn ACL

Location: Rumney, New Hampshire

Individuals Involved: Student ’19, Student ’18, Student ‘18

Summary of Incident: Lead climber falling and subsequently tearing ACL when decking

Spring 2017: Concussion

Location: Red Rock Canyon, Nevada

Individuals Involved: Student ‘18

Summary of Incident: Lead climber falling and hitting head on rock

Fall 2018: Severe Rope Burn

Location: Rumney, New Hampshire

Individuals Involved: Student ’19, Student ‘19

Summary of Incident: Large lead fall and severe rope burn from slow rope management

Winter 2019: Broken Neck

Location: Dartmouth Climbing Gym

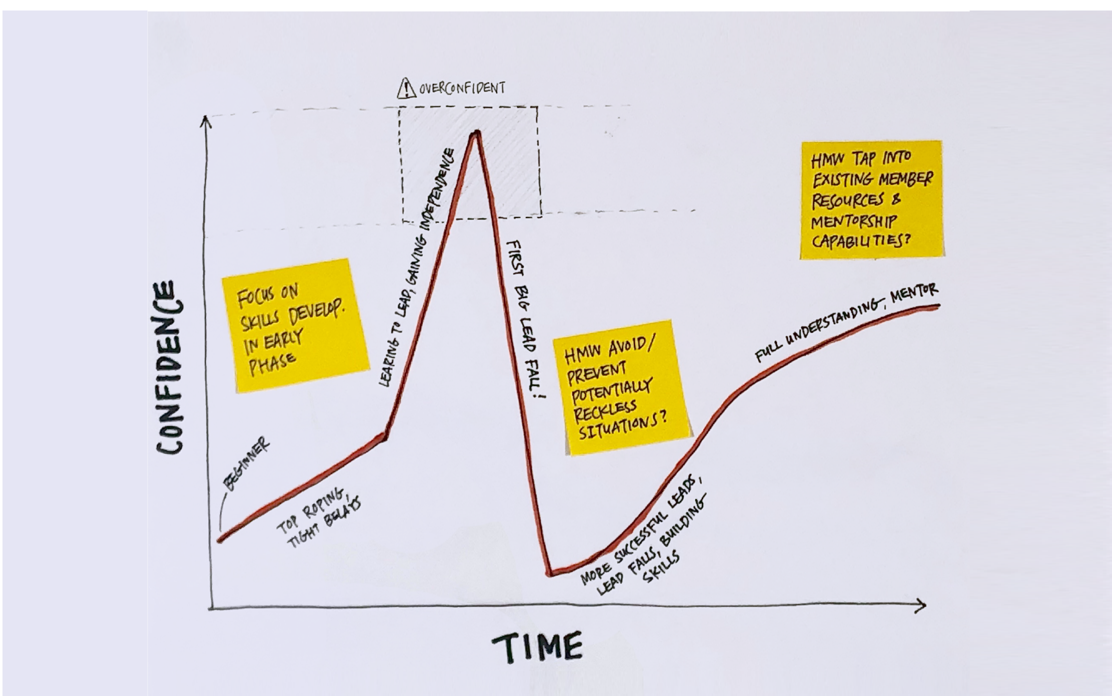
Individuals Involved: Student ‘22

Summary of Incident: Student breaking neck when another climber fell on the individual

Appendix B - Survey of Dartmouth Mountaineering Club Climbers
Responders: 60 self-reported beginner and intermediate climbers

"Do you confidently know how to lead belay"	47% Yes 53% No
"Are you aware of the proper distance one must stand away from the wall as a lead belayer?"	38% Yes 62% No
"Have you passed a lead belay test at a climbing gym?"	20% Yes 80% No
"Would you feel more comfortable lead belaying if another skilled individual is with you / keeping an eye on you?"	95% Yes 5% No
"Have you ever experienced catching a lead fall in a real scenario?"	60% Yes 40% No

Time vs. Confidence Graph of climbers



Appendix C - Specification Chart

SPECIFICATION	METRIC	IDEAL VALUE
Ensure correct belayer distance from wall	Average distance from wall (m)	< 6 m
Is lightweight	Total weight (g)	< 250 g
Is not disruptive	Loudness (dB)	< 60 dB
Is portable	Yes/no	Yes
Withstands outdoors conditions	Yes/no	Yes
Is aesthetically appealing	Scale out of 10	> 7/10
Lasts a long time	Battery life (hrs)	> 10 hrs
Is easy to equip	Time to equip (s)	< 15 s
Is low cost	Cost of manufacture (dollars)	< $30

Appendix D – Final Code

```
#define  c     3830    // 261 Hz
#define  d     3400    // 294 Hz
#define  e     3038    // 329 Hz
#define  f     2864    // 349 Hz
#define  g     2550    // 392 Hz
#define  a     2272    // 440 Hz
#define  b     2028    // 493 Hz
#define  C     1912    // 523 Hz

// DEFINE PINS
int speakerOut = 11;
int DEBUG = 1;
int trigPin1=7;
int echoPin1=8;
int trigPin2=7;
int echoPin2=9;
int trigPin3=7;
int echoPin3=10;
int buttonPin = 12;
int buttonState = 0;
boolean mode;

long safedistance;
long highdiff = 220;
long lowdiff = 275;

int trial=1; // console trial testing


void setup() {
  Serial.begin (9600);
  pinMode(trigPin1, OUTPUT);
  pinMode(echoPin1, INPUT);
   pinMode(trigPin2, OUTPUT);
  pinMode(echoPin2, INPUT);
   pinMode(trigPin3, OUTPUT);
  pinMode(echoPin3, INPUT);
  pinMode(speakerOut, OUTPUT);
  pinMode(buttonPin, INPUT_PULLUP);
}

// MELODY and TIMING
int melody[] = {  c,  d,  g,  c,  d,  a,  g,  d,  c };
int beats[]  = { 16, 16, 16,  16,  16,  16, 16, 16, 64 };
```

```
int MAX_COUNT = sizeof(melody) / 2;

int melody1[] = {  c, d, c, d, c };
int beats1[]  = { 8, 8, 8, 8, 16 };
int MAX_COUNT1 = sizeof(melody1) / 2;

int melody2[] = { C, g, C, g, C, g, C, b, C };
int beats2[] = { 16, 16, 16, 16, 16, 16, 16, 16, 64 };
int MAX_COUNT2 = sizeof(melody2) / 2;

int melody3[] = { c, d, c, d, c, d, c, g, c };
int beats3[] = {16, 16, 16, 16, 16, 16, 16, 16, 64 };
int MAX_COUNT3 = sizeof(melody3) / 2;

long tempo = 10000;
int pause = 1000;
int rest_count = 100;

int tone_ = 0;
int beat = 0;
long duration  = 0;

// PLAY TONE
void playTone() {
  long elapsed_time = 0;
  if (tone_ > 0) {
    while (elapsed_time < duration) {
      digitalWrite(speakerOut,HIGH);
      delayMicroseconds(tone_ / 2);
      digitalWrite(speakerOut, LOW);
      delayMicroseconds(tone_ / 2);
      elapsed_time += (tone_);
    }
  }
  else {
    for (int j = 0; j < rest_count; j++) {
      delayMicroseconds(duration);
    }
  }
}


void loop() {
  delay(500);
  Serial.print ("Trial  ");
  Serial.println ( trial);
```

```
  trial +=1;

// Mode Button
  buttonState = digitalRead(buttonPin);
  if (buttonState == HIGH) {
    mode = !mode;
    if (mode == false){
      for (int i=0; i<MAX_COUNT; i++) {
        tone_ = melody2[i];
        beat = beats2[i];
        duration = beat * tempo;
        playTone();
        delayMicroseconds(pause);
      }
    }
    else{
      for (int i=0; i<MAX_COUNT; i++) {
        tone_ = melody3[i];
        beat = beats3[i];
        duration = beat * tempo;
        playTone();
        delayMicroseconds(pause);
      }
    }
  }
  if (mode == false){
    safedistance = highdiff;
  }
  else {
    safedistance = lowdiff;
  }
  Serial.print("Safe distance:  ");
  Serial.println(safedistance);

// Sensor 1
  long duration1, distance1;
  digitalWrite(trigPin1, LOW);
  delayMicroseconds(2);
  digitalWrite(trigPin1, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPin1, LOW);
  duration1 = pulseIn(echoPin1, HIGH);
  distance1 = (duration1/2) / 29.1;
  if (distance1 >= 500 || distance1 <= 0){
    Serial.println("Out of range");
  }
```

```
  else {
    Serial.print ( "Sensor1  ");
    Serial.print ( distance1);
    Serial.println("cm");
  }
  delay(20);

// Sensor 2
  long duration2, distance2;
  digitalWrite(trigPin2, LOW);
  delayMicroseconds(2);
  digitalWrite(trigPin2, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPin2, LOW);
  duration2 = pulseIn(echoPin2, HIGH);
  distance2= (duration2/2) / 29.1;
  if (distance2 >= 500 || distance2 <= 0){
    Serial.println("Out of range");
  }
  else {
    Serial.print("Sensor2  ");
    Serial.print(distance2);
    Serial.println("cm");
  }
  delay(20);

// Sensor 3
  long duration3, distance3;
  digitalWrite(trigPin3, LOW);
  delayMicroseconds(2);
  digitalWrite(trigPin3, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPin3, LOW);
  duration3 = pulseIn(echoPin3, HIGH);
  distance3= (duration3/2) / 29.1;
   if (distance3 >= 500 || distance3 <= 0){
    Serial.println("Out of range");
  }
  else {
    Serial.print("Sensor3  ");
    Serial.print(distance3);
    Serial.println("cm");
  }
```

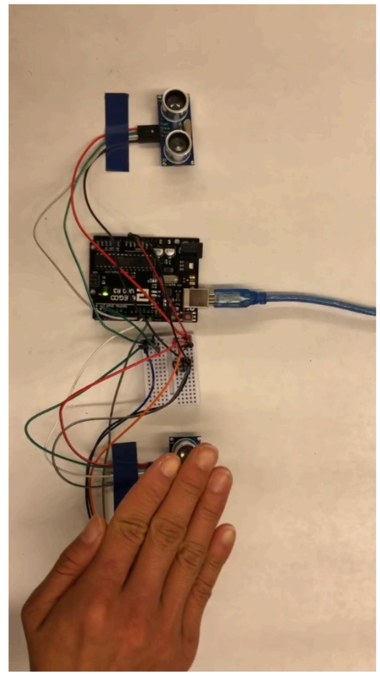
```
// Choosing Sensor
  long shortestdistance;
  shortestdistance = distance1;
  if (distance2 <= distance1){
    shortestdistance = distance2;
  }
  if (distance3 <= distance2 && distance3 <=distance1){
    shortestdistance = distance3;
  }


// Trigger alert tone
  if (shortestdistance >= safedistance && shortestdistance <= 500){
    Serial.println("Move closer!");
    for (int i=0; i<MAX_COUNT; i++) {
      tone_ = melody[i];
      beat = beats[i];
      duration = beat * tempo;
      playTone();
      delayMicroseconds(pause);
    }
  }
  if (shortestdistance >= 500){
    Serial.println("Signal too far");
      for (int i=0; i<MAX_COUNT1; i++) {
        tone_ = melody1[i];
        beat = beats1[i];
        duration = beat * tempo;
        playTone();
        delay(pause);
      }
  }
  Serial.println("done");

  delay(1000);
}
```

Appendix E - Testing Distance Sensors

```
Trial  1
Sensor1  40cm
Sensor2  40cm
Sensor3  39cm
Trial  2
Sensor1  3cm
Sensor2  44cm
Sensor3  39cm
Trial  3
Sensor1  40cm
Sensor2  5cm
Sensor3  6cm
```



Console Output (left) and Testing (right)

Appendix F - Belay Belt Testing results

TRIAL	AVG. DISTANCE FROM WALL (w/o Belay Belt)	AVG. DISTANCE FROM WALL (w/Belay Belt)
1	5.7 ft	4.4 ft
2	7.6 ft	3.6 ft
3	6.0 ft	5.2 ft
4	7.5 ft	4.5 ft
5	5.8 ft	5.0 ft
6	4.5 ft	4.0 ft
7	4.5 ft	3.5 ft
8	6.2 ft	4.0 ft

User Feedback

"It's nice to have a constant reminder and especially when you're not sure, or you're so focused on the climber up there that you aren't paying attention to what's going on down here" – Participant 1, Student '20

"This is great. It's small, it's compact, I'd probably give it to my kids when they're starting out, the musical tones are pleasant" – Participant 3, Community Member

"My one thing is that the sound is hard to hear sometimes. I don't know if it's phantom sound, but I could see it be distracting if I'd have to divert attention to try to hear the sound if I'm at a busy crag. As a belayer, I liked it because it made me really think about what was going to happen if the climber actually fell. Sometimes I see people belaying and when the climber falls, they get surprised almost to the point of letting go of the rope, so I think having a reminder that they need to do their job is important" – Participant 4, Student '21

"I felt better when climbing because I don't have to worry if my belayer isn't belaying well or standing too far away, and I can focus on my climbing and pushing myself instead. I do wish this had some sort of tangible feedback. I like how the sound helps change things in the moment, but what if this could tell me if I'm improving?" – Participant 5, Student '21

"Safe lead belaying is so important. It's the number one reason why people fail their lead belaying tests in climbing gyms. I've seen my fair share of accidents… and this could really save lives" – Participant 6, Community Member

Appendix G - Aesthetics Test

Responders: 42 Individuals

"Would you be willing to wear this belt?"	87% Yes 13% No
"Would you be willing to wear this belt if it mimicked the look and feel of a climbing harness?"	100% Yes 0% No
"Rate the aesthetic appeal of this belt on a scale 1-10"	Average: 7.1 Max: 10 Min: 3 Median: 6

Appendix H - Cost of Parts

ITEM	COST
Arduino Nano (1)	$2.89
Jumper Wires Pack (1)	$1.95
HC-SR04 Ultrasonic Distance Sensor (3)	$2.07
Potentiometer (1)	$0.95
10k Resistor (2)	$0.48
Button (1)	$0.20
Piezo Buzzer (1)	$1.79
Portable USB Battery (1)	$14.95
Velcro Strip (1)	$0.45
Fabric (1/2 yd)	$1.49

TOTAL COST: $27.22

BIBLIOGRAPHY

"Climbing Fundamentals." *American Mountain Guides Association*. N.p., 14 Apr. 2015. Web. 12 Mar. 2019.

Funderburke, Ron. "Know the Ropes: Belaying." *Know the Ropes: Belaying*. AAC Publications, n.d. Web. 12 Mar. 2019.

"Rock Climbing Rescues in Boulder County, Colorado and Eldorado Canyon State Park, Colorado, 1998 - 2011." *Wilderness and Environmental Medicine* (2012): n. pag. Print.

Schöffl, and Klinikum Bamberg. *Acute Injury Risk and Severity in Indoor Climbing-a Prospective Analysis of 515,337 Indoor Climbing Wall Visits in 5 Years.* Diss. NCBI, 2013. N.p.: US National Library of Medicine National Institutes of Health, 2013. Print.

Vodjansky, Matt. "How to Belay a Lead Climber | REI Expert Advice." *REI*. N.p., n.d. Web. 12 Mar. 2019.