Bone Conduction Lock

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1 Introduction

1.1 Objective

The ability to quickly enter a locked door without fumbling for keys is an issue the car industry has recognized and worked to eliminate with features like keyless entry. Home and apartment locks on the other hand, have lagged behind in this field. Even so-called ‘smart locks’ on the market today often require consumers to fumble through their belongings to find a phone and interact with an app [1]—assuming they have remembered to budget enough battery power to keep their phone alive, that is—all the while exposing themselves to cold, rain, or potentially dangerous persons they would rather have on the other side of a locked door. If not dependent on a smartphone, alternate mechanisms are either expensive or vulnerable. Keypads are simple to crack with the aid of fingerprinting dust or an infrared camera [2]. Fingerprint locks can be fooled by pictures of secretly-gathered prints [3]. Iris scanners are impractically expensive for the average household. Facial recognition poses the risk of allowing those who use it to be identified in a crowd without their consent if the data is ever compromised or sold to advertisers [4]. Card-swipe or RFID proximity card locks suffer from the same fumbling problem as keys, and a lost or stolen wallet can render the locks as good as shut.

The Bone Conduction Lock System (BCLS) we propose solves the fumbling issue while laying the groundwork for further investigation of cheap and secure biometric access to be developed atop the platform in the future. The BCLS consists of two parts: a wearable wristband (hereafter, band)—far more resistant to loss than wallet—and a door-mounted lock. When the user wants to unlock a BCLS-secured door, they press a button on the band and touch their finger[1] to the lock. A haptic motor inside the band will then use the bones in the user’s hand as a channel to transmit vibrations to the lock. An amplitude-modulated signal at a carrier frequency signal capable of being conducted through bone will carry a vibration signal to the receiver in the lock. The signal itself will also be perturbed by the channel: the user’s hand. If the signal received at the lock is correct, the lock opens. While not a requirement of the project, this method lays the groundwork to investigate using the specific perturbations imparted by the user’s hand as a form of biometric identification.

[1] The specific finger is arbitrary. It need only be the same finger each time.

1.2 Background

Smartphone dependence of existing smart locks is an issue due to minority populations. The National Federation of the Blind reports there are 1.3 million [5] legally blind Americans. While there are accessibility features for the vision impaired available on smartphones, a system that is entirely haptic such as the BCLS would be more accessible to those populations. It will also be more convenient for the sighted, who will not have to fumble through their pockets for their keys or phone to unlock their doors. Additionally, the elderly or those making too little to afford smartphones could also gain access to the ease and security of smart locks without being required to purchase a phone or take the time to learn to use one. Unlike smartphones, the BCLS band would not have to perform all the battery-draining features of phone, and so would be less prone to running out of battery when it may be needed to enter a locked door.

Previous research also indicates there is enough difference in skeletal structure to potentially warrant unique identification via bone conduction. German researchers undertook a Google Glass based project called Skullconduct, which used vibrations conducted through the skull to identify users correctly with a 97% success rate [6]. The BCLS lays the groundwork for similar applications based on users' hands. Another interesting area to investigate is whether the channel distortion is affected by hand or finger position. If so, users being forced to replicate hand or finger positioning could be another layer of the 'password' when entering a BCLS-secured door.

1.3 High-Level Requirements

- The only communication channel from band to lock must be vibrations conducted through the user's hand.
- When the correct "key" is successfully transmitted from the band to the lock, BCLS must operate with a 90% success rate.
- We must be able to lock/unlock the BCLS in 10 seconds or less.

2 Design

2.1 Block Diagram

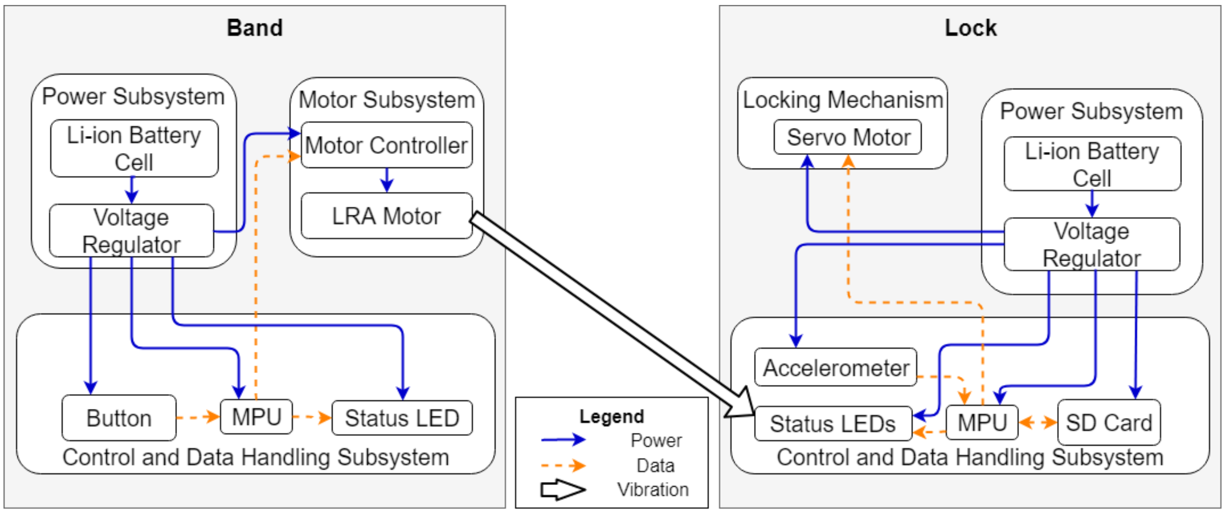

Figure 1: BCLS Block Diagram

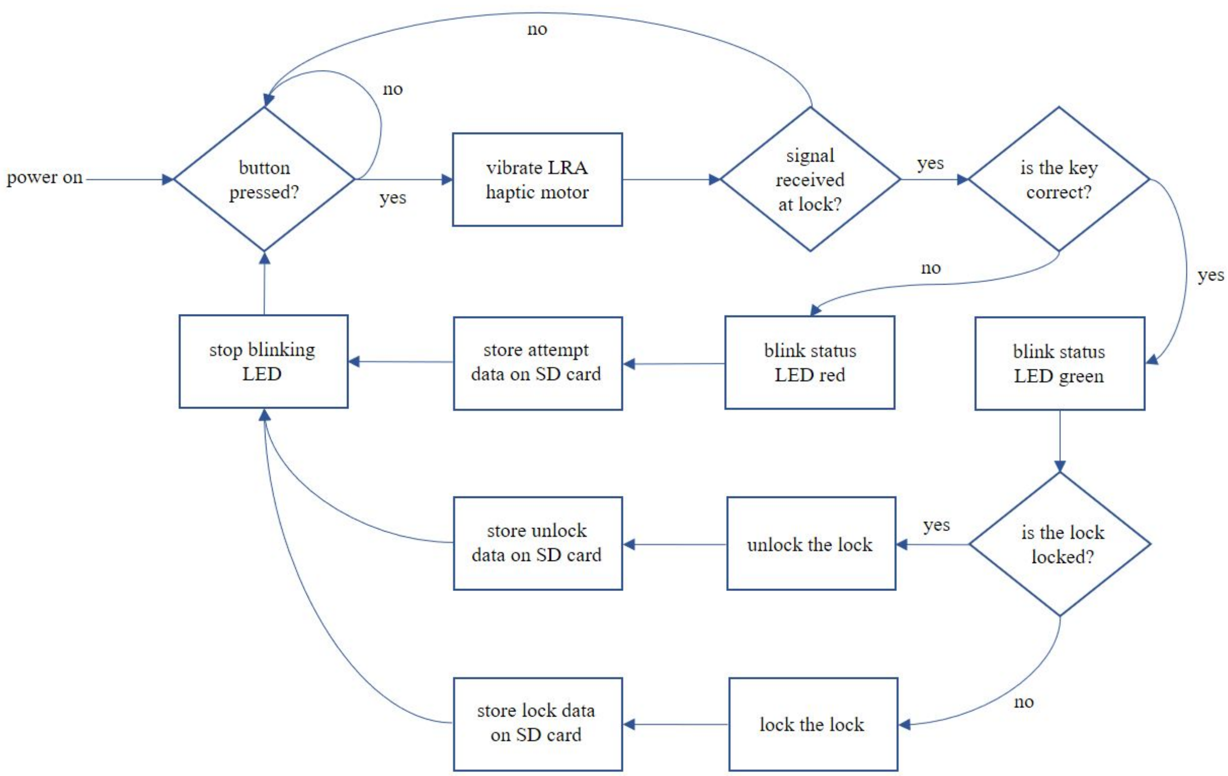

Figure 2: BCLS Operation Flow Chart

As seen in Figure 1, the BCLS has two main components: a band module and a lock module. Both band and lock modules have individual power and control subsystems. This allows the modules to be independent from one another. Each module will have its own PCB: the only interface between the two is the vibration signal.

The band module's control system contains a button and a microprocessor unit (MPU). The button will allow the user to trigger vibrations. The band module's motor subsystem is comprised of a controller and a linear resonant actuator (LRA) motor. The LRA motor generates its vibration by moving a mass back and forth along an axis. When the button is pressed the MPU will send data to the motor controller. This will cause the LRA motor to begin generating a vibration signal. These vibrations will travel from the LRA motor, through the user's hand, and finally reach the accelerometer in the lock module.

In the lock module's control subsystem there are status LEDs and an SD card which are connected to the lock's MPU. The status LEDs will be used to indicate whether a attempt was successful or failed. A red LED signifies a failed attempt and a green LED signifies a successful attempt. The SD card will allow us to store log data and add features to our lock in the future. For example, if the stored data shows five consecutive failed attempts, the lock will freeze for a certain amount of time. Finally, we will be using a servo motor to simulate the physical locking mechanism. Additionally, an overview of the operational flow of the BCLS can be seen in Figure 2.

2.2 Physical Design

2.2.1 Door Lock Module

For the physical design of the lock module, we want to mimic the HID module on the doors in UIUC's Electrical and Computer Engineering Building (ECEB). The HID module is the black rectangle located above the door handle as seen in Figure 3. To operate the door lock, an I-card is placed in close proximity (1- 3 cm) allowing the HID module to read the identification number associated with the I-card. If the identification number is approved, the lock unlocks.

Our lock module will be a close approximation of the HID module in appearance. However, unlike the HID module which uses a wireless communication protocol, we will be using a physical vibration signal protocol. Our lock module is comprised of four main components: the control unit, locking mechanism, status LEDs, and battery.

Figure 3: Door Lock Unit at ECEB

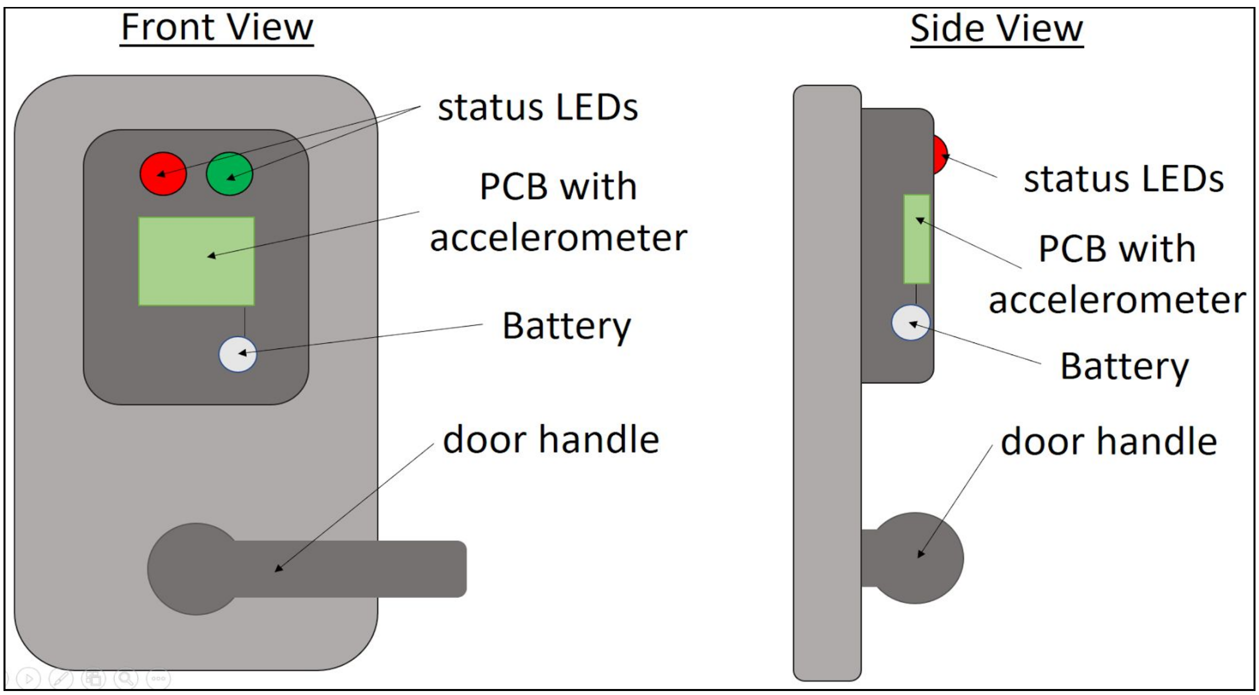

Figure 4: Physical Design of Lock Module

As seen in Figure 4, all the components are housed in a rectangular module located above the handle. Looking at the module, the only exposed components are the status LEDs. The rest of the components will be hidden inside the casing of the module. Since an accelerometer is a microelectromechanical system, to get the best signal to noise ratio, it is crucial to minimize the distance between the accelerometer and the point of contact where the finger touches the module. Because the accelerometer will be surface mounted on the PCB, the PCB will need to be located as close to the point of contact with the finger as possible. A marking on the outside of the casing will indicate the optimal place for the user to touch their finger to ensure the strongest signal possible.

2.2.2 Band Module

The band module is responsible for generating the vibration signal. The band will have a similar form factor to a Fitbit with the exception of coming in two connected parts: the main band and the ring. Preliminary tests showed the signal amplitude from the LRA motor mounted on the ring was far greater than when the motor was mount on the band. This form factor can be seen in Figure 5 and Figure 6. The electrical components of the band are the PCB, the push button, LRA motor, battery, and status LED. The components are housed in the portion of the band located on the top side of the wrist. This connects via a cable to a ring housing the motor. All other components will be contained entirely inside the band’s housing with the exception of the push button and status LED, which will stick out above the surface. The user will be able to push the button to generate the vibration signal. When the battery is low, the status LED will indicate this, prompting the user to change the battery.

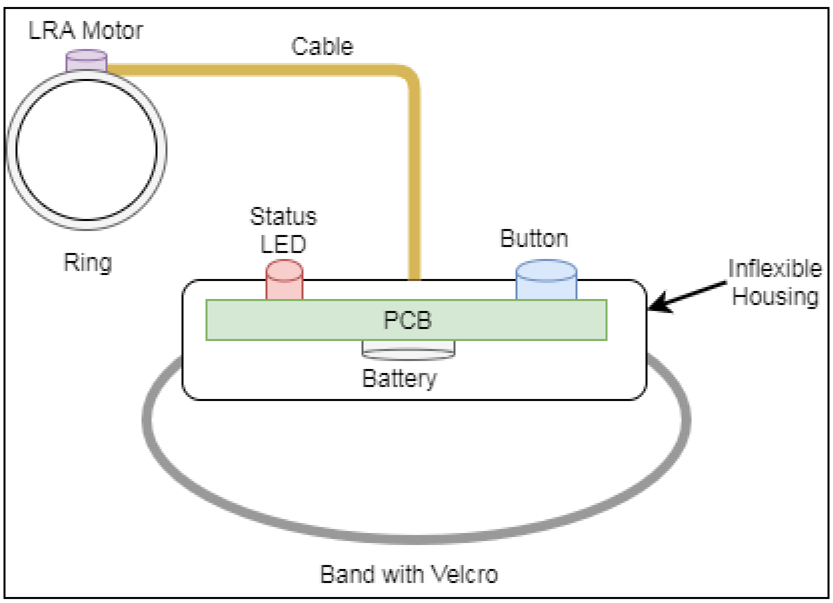

Figure 5: Physical Design of Band Module, Side View

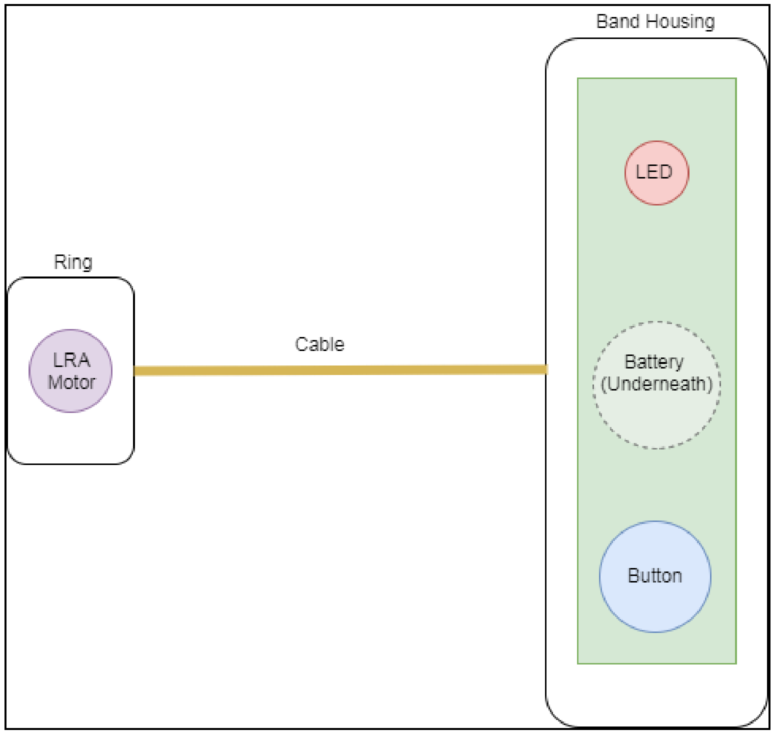

Figure 6: Physical Design of Band Module: Top View

2.3 Functional Overview/Requirements

2.3.1 Lock Module

2.3.1.1 Power Subsystem

This power subsystem is responsible for supplying power to the lock module's control subsystem. Specifically, it powers the SD card, LED, MPU, and accelerometer. It is composed of a Li-ion battery cell and voltage regulator. We chose to have our lock module to be powered by a battery because we wanted the lock to be independent from the house it would be connected to. This makes installation easier and would provide a working lock even in the event of a power failure.

(a) Li-ion Battery Cell

The Li-ion battery cell must be able to provide enough power to the rest of the band module. The MPU, LEDs, and SD card all require 3.3 V to operate.

(b) Voltage Regulator

The voltage regulator will provide a smooth input voltage to the components the power subsystem needs to power. Our Li-ion battery has a 3.7 voltage rating. A low-drop regulator IC could be used to lower that voltage to a constant 3.3 V.

Requirements:

- *The power subsystem is required to output a 3.3+/- 0.2 V to all components of the band module that require power.*

2.3.1.2 Control Unit

The control unit is responsible for receiving the vibration signal and determining what action to take: unlock, lock, or do nothing. The control unit contains the microcontroller, an accelerometer to detect the vibration signal, a status LED, and a SD card.

(a) Microcontroller

The microcontroller is connected to the sensor, status LED, and SD card. The microcontroller constantly reads the output from the sensor and processes data to determine if a vibration signal has been received and then takes the appropriate subsequent actions.

(b) Accelerometer

Observes the environment and outputs data that correlates to the vibration the accelerometer experiences. The sensor is connected to the microcontroller, which is constantly reading the the sensor output.

(c) Status LEDs

The status LEDs act as a visual representation of the state the microcontroller is in. When the lock is unlocked, the green LED is on. When the lock is locked, the red LED is on. When a correct key is received, the green LED blinks. When an incorrect key is received, the red LED blinks.

(d) SD Card

The SD card is connected to the microcontroller and is used to store the activity of the lock. It logs when a signal was sent to the lock, if the signal was correct or not, and when the lock was locked and unlocked.

Requirements:

- *Accelerometer needs to have a full-scale range of at least ± 2 g.*
- *Accelerometer also must have sample rate ≥ 800 Hz.*
- *Microcontroller must have a data rate of at least the accelerometer bit resolution per 1.25 milliseconds.*

2.3.2.2 Locking Mechanism

(a) Servo

The servo is connected to the microcontroller. The servo is responsible for locking and unlocking the physical lock mechanism.

Requirements:

- *Must have two clear states: locked and unlocked.*

2.3.2 Band Module

2.3.2.1 Power Subsystem

The power subsystem is responsible for providing power to the control and motor subsystems inside the band module. Specifically it provides direct power to the motor controller, button, status LED and MPU. It also indirectly powers the LRA motor since the LRA motor is powered by the motor controller. The power subsystem is composed of a Li-ion battery and a voltage regulator.

(a) Li-ion Battery Cell

The Li-ion battery cell must be able to provide enough power to the rest of the band module. The MPU and LRA motor require 3.3 V to operate.

(b) Voltage Regulator

The voltage regulator will provide a smooth input voltage to the components the power subsystem needs to power. Our Li-ion battery will have a 3.7 voltage rating. A low-drop regulator IC could be used to lower that voltage to a constant 3.3 V.

Requirements:

- *The power subsystem is required to output a 3.3+/- 0.2 V to all components of the band module that require power.*

2.3.2.2 Control Unit

The control unit takes user input and determines when to generate the vibration signal. The control unit contains the microcontroller and a push button.

(a) Microcontroller

The microcontroller is the specific component tasked with handling the user input and initiating subsequent tasks. It gets its power from the battery and is connected to the push button and the motor driver.

(b) Push Button

The push button is the method the user will use to communicate with the band. The push button is connected to the microcontroller. When pressed, the push button will send a signal to the microcontroller to initiate the vibration signal. Even with just one button, many unique commands can be sent to the microcontroller such as single and double presses.

(c) Status LED

The status LED acts as a visual representation of the battery level of the wristband. When the battery is about to die, the status LED is red.

2.3.2.3 Motor Subsystem

The motor subsystem is responsible for generating the vibration signal. It contains the motor driver and the LRA motor.

(a) Motor Driver

The purpose of the motor driver is to drive the motor. The motor driver is connected to the microcontroller and the LRA motor. When a vibration signal needs to be generated, the motor driver receives a signal from the microcontroller that tells the motor driver what frequency the motor needs to run at. With this information, the motor driver drives the LRA motor appropriately.

(b) LRA Motor

The LRA motor is the actual mechanism that produces the vibration signal. The LRA motor is connected to the motor driver, which gives it AC power at a frequency that runs the motor at the desired frequency.

Requirements:
- *LRA motor must have resonance frequency between 150 - 13500 Hz [7].*
- *The signal's vibrational amplitude conducted through the hand to the fingertip must exceed a magnitude of 1.02 g (g is for g-force).*

2.4 Risk Analysis

The band-lock interface posses the most significant risk to the completion of this project. By band-lock interface we're referring to how the vibration signal is transmitted and then received from the LRA motor to the accelerometer in the lock. If the amount of vibrations required to get a signal at the receiver is uncomfortable to the wearer, dangerous to their health, or requires an unfeasibly large battery it could compromise the project. This is why the ring design was chosen over the standalone wristband: to minimize the amount of hand-material damping the vibrations. Even then, the design will require a strong motor.

Some other questions that will need to be answered when implementing this interface include: how tight will the wristband and ring need to be? How hard will the user need to press their finger against the casing containing them accelerometer to get reliable signal reception?

The other modules of the bone conduction lock system are typical electronic elements which have been well documented. The transfer of vibrations using the body is relatively cutting-edge. This means plenty of testing and learning as we go to ensure the vibration is transferred from motor to accelerometer in a reliable and efficient way.

3 Ethics and Safety

Exposure to vibrations is known by the Occupational Hazards and Safety Administration [8] and the Canadian Centre of Occupational Health and Safety (CCOHS) to be a workplace hazard. According to the CCOHS, exposure of the hands and arms to vibrations can result in Hand-Arm Vibration Syndrome, a disorder affecting blood flow to the fingers and resulting in a loss of touch sensation [9] . A 2002 article in The Journal of Low Frequency Noise, Vibration, and Active Control titled *EU Directive on Physical Agents - Vibration* provides guidelines on the amount of safe hand-arm vibration exposure [10]. It is measured by the RMS magnitude of acceleration normalized by exposure time: a stronger vibration means a shorter exposure time before there is a risk of damage. The shortest time listed in the article was a half hour. Over this time period, the maximum acceleration deemed to be safe was 20 m/s^2 . Preliminary tests of haptic motors of similar size to those we plan to use showed a peak strength below that: 18.04 m/s^2. Additionally, since one goal of ours is to unlock the door in a timely manner, the time of vibration exposure will be on the order of seconds, not minutes or hours.

The operating frequency of the motors to be used in this project also make it unlikely that the vibrating band will cause damage to the user. In Shrawan Kumar's *Biomechanics in Ergonomics: Second Edition* [11], the author proposes damage may be more likely to occur at the resonant frequencies of certain internal organs and structures within the body. Their frequencies are listed in Table 1. Note that some organs and structures have ranges of resonant frequencies. Others have multiple discrete resonant frequencies. The former is notated by a hyphen, the latter with the word "and".

Internal Organ / Structure	Resonant Frequency (Hz)
Spine	5
Pelvis	5 and 9
Abdomen-thorax	3 and 5-8
Lower Intestine (while seated)	8
Heart	7
Head-Neck-Shoulder[2]	20-30
Eyeballs	60-90
Lower Jaw-Skull	100-200

Table 1: Resonant frequencies of various biological structures

These resonant frequencies are outside the range of ~200-250 Hz which our motors will be operating at. The lower jaw and skull, the biological structure whose resonant frequency is closest to our motor's operating frequency, is located at great distance from the source of the vibrations, making damage to those body parts an unlikely scenario.

Testing and wearable technology comes with the risk of having dangerously hot or burning electrical components strapped to human testers in the event of a catastrophic failure. If a CO_2 fire extinguisher—the kind typically used on electrical fires—is used to put out a piece of technology being worn by a tester, they are liable to receive cold burns from the extinguisher as well as heat burns from the fire. To counteract this, as many tests as possible will be done without wearing the band while testing. Additionally, we will design the band and ring such that they can be easily removed in the event of an emergency. Using velcro as the band fastener was one proposed way to ensure this.

Ethically, the major issue which concerns this project is user data safety. If our project progresses rapidly enough to get to the biometric identification step, keeping users' biometric data secure becomes a concern. This issue can be handled by not storing the raw data[3]. The logs which will be written to an SD card inside of the lock do not store information about the signal received, only the time of attempt, bit sequence received, and indication of success or failure. The calibration data used to judge whether a particular user is authorized for entry will be stored

[2] The odd wording is courtesy of the original author. Whether this refers to all three body parts as separate or the system as a whole is unclear. Regardless, the implication that our motors operate well outside this frequency range is clear.

[3] At least not in the final product. In testing, gathering large amounts of raw signals to process later will be helpful when investigating biometrics, and the SD card provides an easy way to do that.

in the memory of the microcontroller. Considering its position inside the physical lock itself, and the relative difficulty of offloading this data in comparison to say, taking an SD card, it is unlikely that this data will be compromised. Other ethical issues—namely those listed in the IEEE Code of Ethics[12]—are not made especially relevant by the nature of the work to be done. There are no exceptional safety risks, conflicts of interest, potential for environmental damage, etc. outside of the risks bound to occur on any electrical engineering project

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