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Experiential Learning: Improving Agility and Coordination with a Piezoelectric Agility Ladder (PLA)

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Experiential Learning: Improving Agility and Coordination with a Piezoelectric Agility Ladder (PAL)

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Abstract

An "agility ladder" is a piece of equipment that aids in performing a variety of high-intensity agility drills. Most often used by professional trainers in sports and the fitness industry, it has regardless found its way into assisted-living homes, schools, and physical rehabilitation centers. Despite its growing popularity and potential applications toward improving physical coordination and agility, standard agility ladders are inherently flawed: they do not provide the user with feedback. Improvement in health and fitness is often tracked via trends. These include, resting heart rate, body mass, body fat, and VO2 max (maximal aerobic capacity). With current agility ladders, there is no easily accessible method of gathering the data necessary to create and track such a trend. This prohibits users from getting important feedback, which provisions for future training adjustments and offers valuable mental encouragement. Such a solution would be attractive to competitive athletes looking to maximize performance as well as more "ordinary" users looking to improve their quality of life. As proven by the YMCA's sudden growth because of "the real demand for [its] kinder, gentler approach and broadly accessible moves" people young and old strive for exercises with tangible and measurable returns (Mull, 2022).

The aim of this project was to eliminate the weakness of traditional agility ladders using piezoelectric (PZT) sensors. When the user performs an exercise with the device, the pressure and vibration from their steps activates the sensors on the mat. Using a programmable microcontroller's (Arduino) in-built clock, the average time between steps is measured and recorded. By integrating a quantitative aspect into this already widely used exercise equipment, the ladder becomes focused on improvement. In this manner, the ladder applies to anyone who has the desire to improve their agility, coordination, or overall fitness regardless of age or current ability.

Integrating the aforementioned technology to create a solution has yielded our Piezoelectric Agility Ladder, or PAL. Compared to a traditional agility ladder it is significantly heavier. This is due to the material used and requirement that each pad be a discrete piece of it. A more final design ought to be made of thinner and lighter material. Using modern manufacturing methods, the relatively large microcontroller and its associated wiring could be downsized and better integrated. Despite these transient limitations, our current prototype functions as designed and measures the interval between steps on consecutive pads. It proves the viability of enhancing an agility ladder with piezoelectric sensors, opening the door for future research in the practical deployment of the device in physical therapy and other settings.

Introduction

Human agility is defined as the ability to change direction while in motion. People have the capacity to improve their agility through "agility drills" which come in countless forms, including jumping and cutting actions. As with most athletic drills, various pieces of equipment can be utilized to assist in training. One such tool, commonly used by soccer players, is the agility ladder (fig. 1). Exercises with an agility ladder can be described as a repetitive series of in-and-out movements between rungs. It is most often used by athletes and trainers, but has found its way into elderly homes, schools, and physical rehabilitation centers.

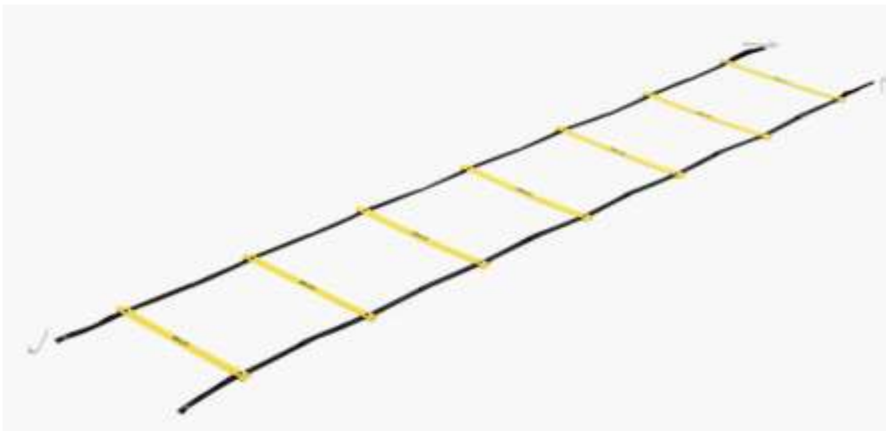

Figure 1: A standard agility ladder

The agility ladder is already well established in the sports realm. Several studies, conducted on athletes ranging from club badminton players from Dindigul city sports clubs to futsal players from Bina Darma University demonstrate that “ladder drills training is a feasible method to enhance the agility performance” (Ali, et. al., 2020; Hidayat, 2019). More recent research has been conducted on the ladder's applicability outside of sports, namely among motor learning in elderly and children. Motor learning encompasses a wide range of phenomena, ranging from relatively low-level mechanisms for maintaining calibration of our movements, to making high-level cognitive decisions about how to act in a novel situation” (Krakauer, et. al., 2019).

Examples are fundamental movements such as walking and grasping to more specific movements like pitching a baseball. Most studies have demonstrated “that performance gains in fine motor tasks are diminished in older adults" and it is crucial to continue exercising these skills to prevent further degradation (Voelcker-Rehage, 2008). A study of healthy adults with a mean age of 66.9 years received 30 minute training intervals with the agility ladder twice a week for 14 weeks and found that “training protocols using an agility ladder are easy and practical and improve physical function performance in older adults" (Castillo de Lima, et. al., 2020). Motor learning is just as important among children to build a strong physical foundation for their growth. A study was conducted on 71 school boys with the average mean age of 9.82 years.

They were instructed to perform agility ladder drills 3 times a week for 6 weeks. Compared tot he control group, the “dynamic balance ability of the school boys [in the experimental group] was significantly enhanced” (Ng, et. al., 2017). Further research could be done to demonstrate the broad application of the agility ladder. The aim of this study is to further improve on this piece of equipment with piezoelectric (PZT) sensors (fig. 2) to broaden its possible applications.

PZT sensors sense mechanical changes in the environment to output an electrical signal which can be used to measure the mechanical change or generate displacement with the electrical output ("What Are Piezoelectric Sensors?"). There are two forms, the relevant one being passive PZT sensors. They are inactive when no signal is present, and only generate electricity after receiving a signal, which can consist of vibrations, acceleration, strain, force, and movement. Only vibrations are applicable to this study.

Figure 2: Piezoelectric sensors

The PZT sensors' ability to operate in confined spaces and high temperatures, and yield high frequency response, transient response, and output make them attractive across a range of industries. Relevant existing applications of PZT sensors include energy harvesting floor tiles which were used to generate electricity from pedestrian walking power (Yingyong, et. al., 2021). In the sports industry, the sensors monitored the moving speed, frequency, joint angle, and sweat lactate concentration of athletes to produce a time-motion analysis (Mao, et. al., 2019). This study combines the well known sports equipment with PZT sensors to create the enhanced Piezoelectric Agility Ladder (PAL). The ladder senses vibrations produced by the user as they complete the drill. This generates an electrical output which is used to measure the speed at which they performed the drill as well as the average time interval in between each rung.

PAL is intended to improve on the existing agility ladder by providing feedback for the user. In the sports realm, researchers are already exploring the importance of feedback. Studies with basketball players, young karatekas, and physical education students have all demonstrated a positive correlation between visual feedback and developing a targeted skill (Mao, et. al., 2019; Vando, et. al., 2021; Modinger, et. al., 2021). A more relevant case study is the VirtualLadder, an agility ladder paired with real time projections of user foot placement (Kosmalla, et. al., 2021). But the findings were more focused on what kind of visual feedback for the agility ladder is the most effective, and the data was limited to a group of twelve participants. Our main goal is to apply the already well understood concept of feedback in skill-based performance with the agility ladder using piezoelectric sensors. A working device could set the foundation for future work in real world applications.

Method and Approach

While the goal remained consistent throughout the production process, our design underwent multiple iterations. The main desires we had for the ladder were safety, durability, and portability. We wanted to maintain the original strengths of the agility ladder, including the ability to fold. Some methods of folding included rolling and accordion folding. Rolling would require one long piece of material and it could possibly damage the sensors. An accordion fold made the most sense to keep the sensors flat. We also wanted to preserve the size of the traditional ladder. The vision was a ten pad ladder with the traditional 20" by 18" inch pads which would make the total length fifteen feet (fig. 3)

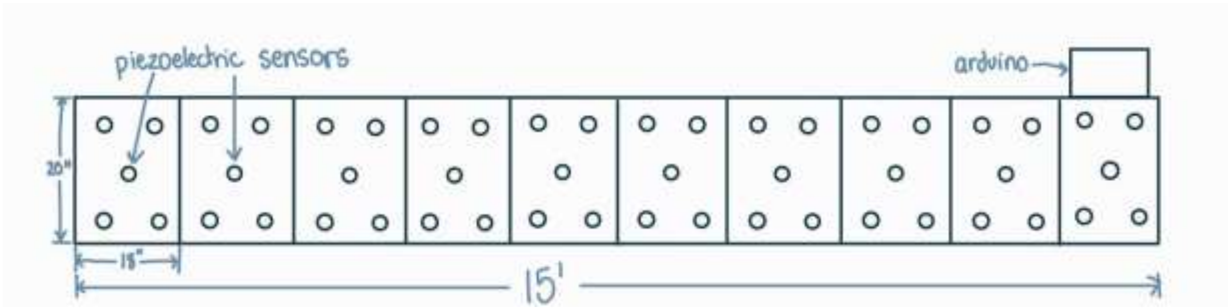

Fig. 3: Original design of full ladder

Our original idea was to place the piezoelectric sensors between two pads so the wire and the sensors would not be exposed. The idea was also that if a stiff enough material was used, if one part of the pad was stepped on, at least one of the sensors would detect the vibration. But this presented multiple issues when considering materials. Foam is light, but it is not durable and would not be able to withstand use in rough terrain. If it is placed on a wet turf field, it would likely slip and endanger the user. There is also no way to guarantee that it is stiff enough to distribute the user's pressure across the sensors as intended. Wood was discarded as too stiff.

The next iteration of our design put aside the idea of placing the sensors and wires between pads. The sensors would be placed directly on top and the wires would be run along the bottom. We wanted a strong material, and we determined out of commercially available options, gym mat tiles would be sufficient. They are made of rubber, which makes them water resistant, non-slip on different surfaces, and comfortable for the user. Our desire for portability took less priority. With this design, we needed to decide how to secure the wiring and sensors since they would be exposed.

We considered wrapping the mat in a thin fabric, but this would defeat the purpose of non-slip. To maintain the accordion fold, attach the pads together, and hide the wires, we concluded that the best material would be a thick elastic band running along the sides of the ladder. The next issue was the placement of piezoelectric sensors to ensure that the user would activate at least one sensor on each pad. We wanted to optimize the placement while keeping the number of sensors to a minimum. A square pattern was considered, but while testing, there was a chance the user stepped in the center. The same issue became apparent with a triangle pattern. We came to the final conclusion that a triangle with an additional sensor in the center covers the most area of the pad (fig. 4).

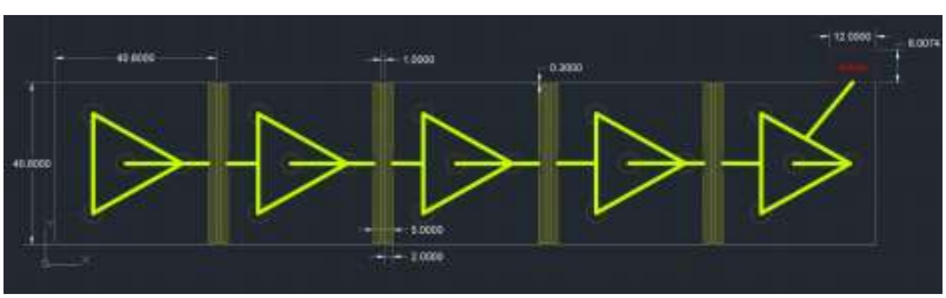

Fig. 4: Next design iteration including placement of sensors

With the majority of the design of the pads complete, it was necessary to determine the placement of, and container for, the Arduino microcontroller. The first decision made was to place it near the side of the terminal pad. This would prevent the Arduino and its case from presenting an obstacle to the user. Attaching it in such a way that it hung off the edge of the pad also facilitated the folding design of the PAL, increasing portability.

Durability, especially with its intended use being a piece of sporting equipment, was always a dominant concern in designing the PAL's. As such, mitigating accidental damage or misuse was a necessary requirement of the integration of a microcontroller. This precondition made it necessary to brainstorm several container designs and materials. Many of the materials available to us: acrylic, plywood, cardboard, and 3D-printed ABS plastic, were inadequate. Furthermore, the "simplest" design: a box, would have inherent weak points at its corners. It would potentially fail to withstand an impact of the magnitude from an average-sized human landing on their feet. With all of the above in mind, and after browsing the materials readily-available to the team, we determined that an elongated arch made of PVC plastic would be an ideal receptacle for the Arduino microcontroller. PVC is not only impact resistant and inexpensive, but an arch is self-supporting and able to support a large (relatively) amount of weight. This is due to how it transfers force from its top to its walls and foundation (Chudley, et. al., 2008). Since the PAL would also need to display information to the user, acrylic could be used in a partial role: as a window for an LCD contained within the case.

Design Details

Soon after beginning construction, we realized the initial size was unrealistic for our prototype. It would require more wires than the Arduino could handle and it would weigh quite too much. The device was downsized to five pads to better demonstrate the PAL's viability. Regarding physical construction, we started by using a jigsaw to cut off the excess pieces of each gym tile. With the excess cut off, each tile was roughly 14 inches by 14 inches. This made the full ladder 14 inches by 70 inches. The piezoelectric sensors were being placed on top and we did not want the users to step on exposed wire, so we drilled holes through each pad to run the wire along the bottom.

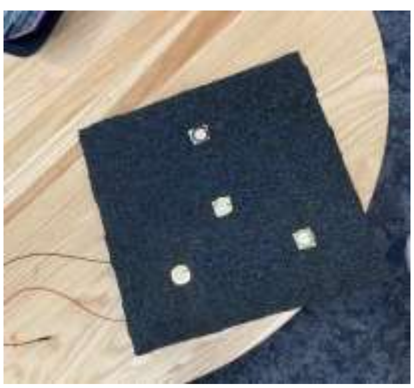

Fig. 5: One completed pad

Fig. 6: Completed PAL

After all of the wires connecting the sensors were soldered, the pads were connected using a 3 inch elastic band. The band was hot glued vertically along the sides of the bottom of the ladder, threading the wire through to secure them. An extra strip of elastic was attached between the pads to secure them further. These elastic bands could stretch enough to allow the pads to fold. On the front side of the ladder, we covered the spaces between each pad with a strip of elastic horizontally. Then more of the band was glued on the sides vertically and folded over to the bottom to create a cleaner aesthetic. The sensors were hot glued down and then we cut pieces of electrical tape to cover them. We considered other materials, but we needed something thin so the sensors could still register pressure. Since PZT sensors are polarized, the red wire was connected to the analog pins and the black wire was connected to the ground (fig. 7). The four The four sensors on each pad were wired in parallel (fig. 8).

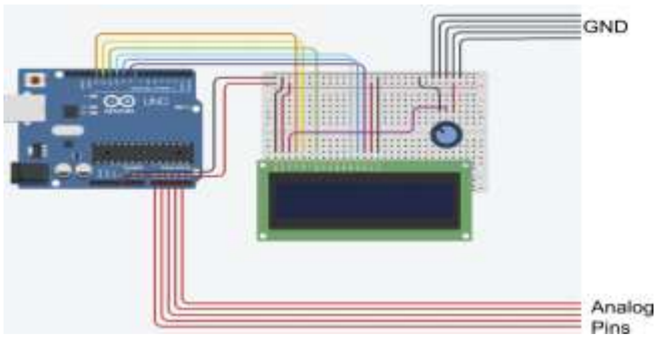

Fig. 7: Circuit diagram

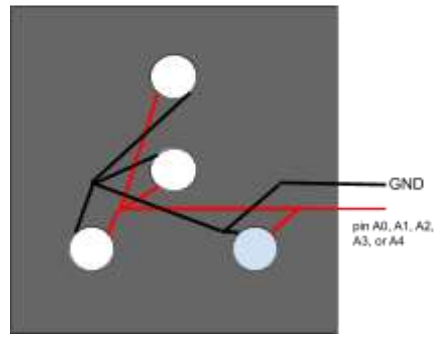

Fig. 8: Wiring of individual pad

The sensor wiring ultimately terminates inside our custom-designed Arduino microcontroller case. Fabricated according to specifications set out in the design process, the case houses the Arduino, LCD, a “breadboard” to connect the various components (including the sensor wires), and an external battery pack. The baseplate is a ~0.150-inch thick plywood plate. The semicircular portion of the case consists of a portion of 0.250-inch thick PVC piping cut down its longitudinal axis. The end of the case that houses the microcontroller is closed off using a 3D-printed ABS plastic plate that mirrors the silhouette of the case itself. The plate has two holes for access to the 5V DC “barrel” jack, and the Arduino’s Micro-USB port. The opposite end is made of a 0.125-inch clear acrylic plate attached by flexible plastic to the bottom plate of the case. The acrylic is secured in such a way that it closes off the case using a strip of velcro. This allows the Arduino, breadboard, and LCD, all of which are mounted to a free-moving cardboard plate with 3M Dual Lock™ strips, to be “slid” out and removed. The LCD is positioned under a clear acrylic window which has been heat-molded to match the semicircle’s arc in figures 9 and 10.

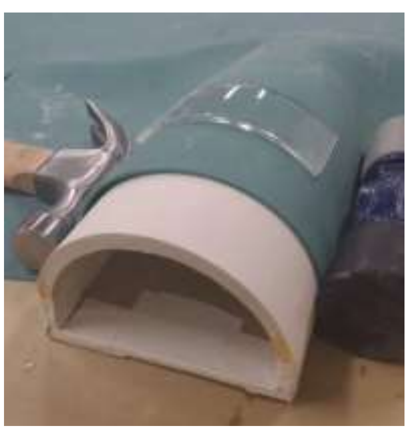

Fig. 9: Arduino case in production

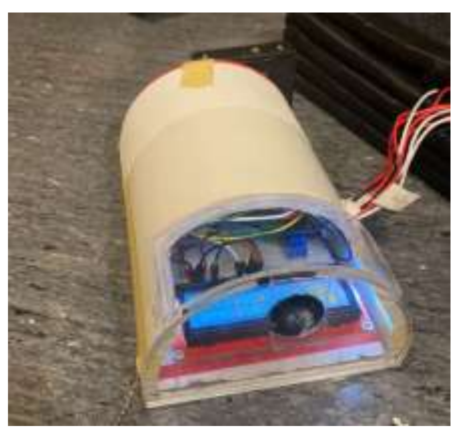

Fig. 10: Finished Arduino case

Our goal while writing the code for the microcontroller was to accurately assess the time variables between each sensor pad and relay that data back to the user. The original version contained only the code necessary to read each pad and display their readings into the serial monitor. Due to how each pad is wired, any of the four sensors registered as input for said pad. Our second iteration consisted of many different variables, such as the time-holding variable called "TrackedT", which stores the time from the pad being triggered to the subsequent pad. Each pad received its own variable (i.e "TrackedT1, TrackedT2, etc). A later iteration eliminated the time variable and instead used the millis variable in the individual methods for each pad. The average is calculated at the end of each run, when the user finishes touching all five pads. An average is found by finding the sum of the differences of time variables, which is then divided by the number of pads. The time differences were calculated by simply subtracting a time variable by the one that preceded it (i.e "T2-T1, T3-T2, etc"). This calculation yields the average time it takes for the user to step from one pad to another.

$$\text{Average Time} = ((T_2 - T_1) + (T_3 - T_2) + (T_4 - T_3) + (T_5 - T_4)) / 5 \quad \text{Eq. 1}$$

Methods

With our objective of testing the viability of a piezoelectric agility ladder, we collected two sets of data. We wished to demonstrate how a future consumer would interact with the PAL. Our first involved running different drills several times with 1 test subject. This could resemble when an individual is training with the ladder and exercising different muscle movements. These drills, sometimes called by different names, were the "bunny hop" (fig. 11), "alternating feet" (fig. 12), and the "single leg in-and-out" (fig. 13). These drills were chosen because they are all relatively common among current agility ladder users and imitate real-world usage.

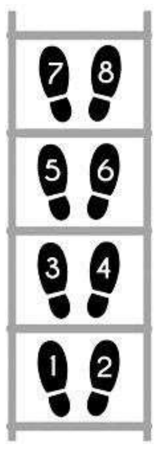

Fig. 11: "Bunny hop"

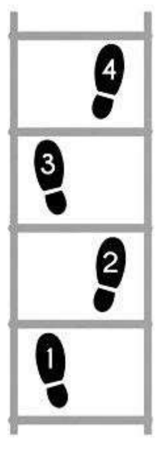

Fig. 12: "Alternating feet"


Fig. 13: "Single leg in-and-out"

For the second dataset, five different subjects performed the same drill, thus simulating when groups of people take turns running an exercise. The chosen activity was the "bunny hop." The subjects rotated for each trial to ensure adequate recovery and prevent fatigue-related performance variation. Users performed six rounds each. This number was chosen as a median between too few and too many exercises. We set out to collect data resembling possible real-world scenarios.

Results and Analysis

Upon examination of the collected data, we found it to be relatively consistent. For the one-subject "bunny hop" exercise, the user aimed to repeat the test within similar times to prove the accuracy of the PAL. The results yielded were roughly a one-second average, demonstrating the accuracy and reproducibility of the device (fig. 14). The results of the first set of data were graphed to compare the various trial times of each exercise relative to one another (fig. 15). For the "alternating feet" exercise, trial 2 had a higher than average time of 3.99 seconds. This extraneous set of data resulted from the user tripping and needing to get back on the previous pad to continue the exercise. This further demonstrates the relation of time output to the actions of the user. Of the data collected, the "bunny hop" exercise took consistently less time to complete because of its relative simplicity. This is an example of how a user might determine which exercises require a greater time commitment to mastering.

	Bunny Hop (s)	Alternating Feet (s)	Single Leg In-and-Out (s)
Trial 1	1.01	2.27	1.83
Trial 2	0.98	3.99	1.54
Trial 3	0.75	2.03	1.69
Trial 4	0.88	2.11	1.78
Trial 5	1.13	1.98	1.91
Trial 6	0.79	1.91	1.60

Fig. 14: Data from one user, different exercises

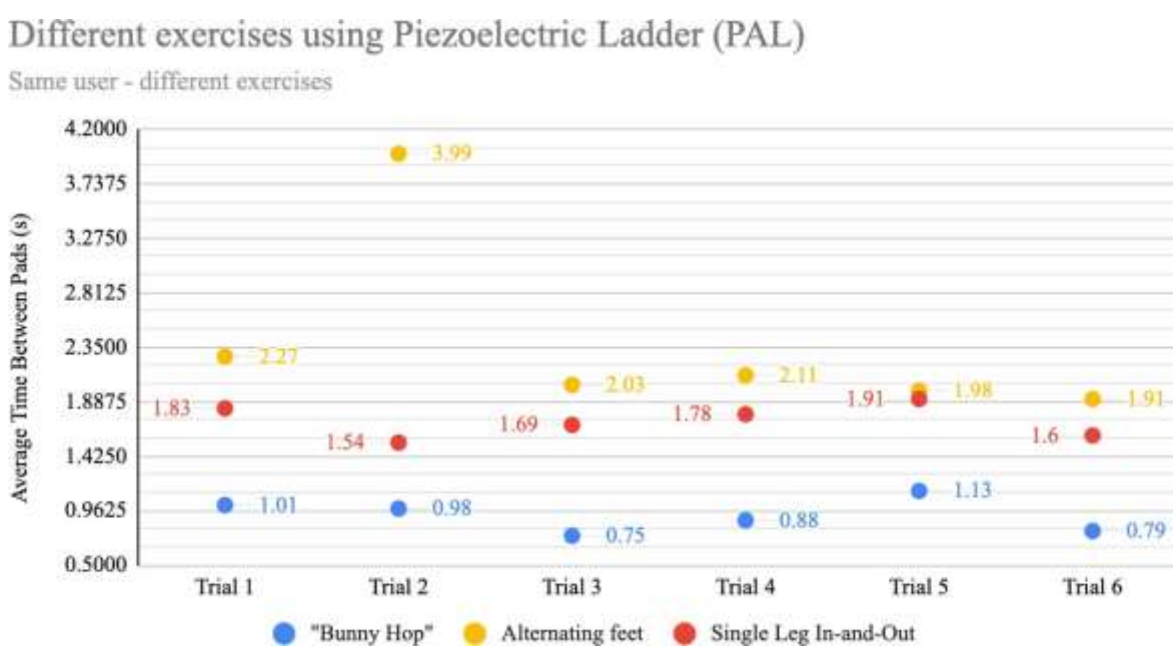

Fig. 15: Graph of one user, different exercises

The second set of data supported the findings of the first (fig. 16). Different users had different speeds, with subject 1 performing consistently faster (except trial 4). All times for each subject were within one second of their lowest and highest times. Plotting and comparing user data in this way demonstrates one use of the PAL as an athletic training tool.

	Subject 1 (s)	Subject 2 (s)	Subject 3 (s)	Subject 4 (s)	Subject 5 (s)
Trial 1	0.9	1.30	1.43	1.79	1.61
Trial 2	0.93	1.21	1.54	1.53	1.54
Trial 3	1.03	1.42	2.31	1.68	2.43
Trial 4	1.5	1.07	1.36	1.43	1.42
Trial 5	0.91	1.01	1.26	1.39	1.38
Trial 6	0.78	0.96	1.32	1.49	1.56

Fig. 16: Data from different users, one exercise

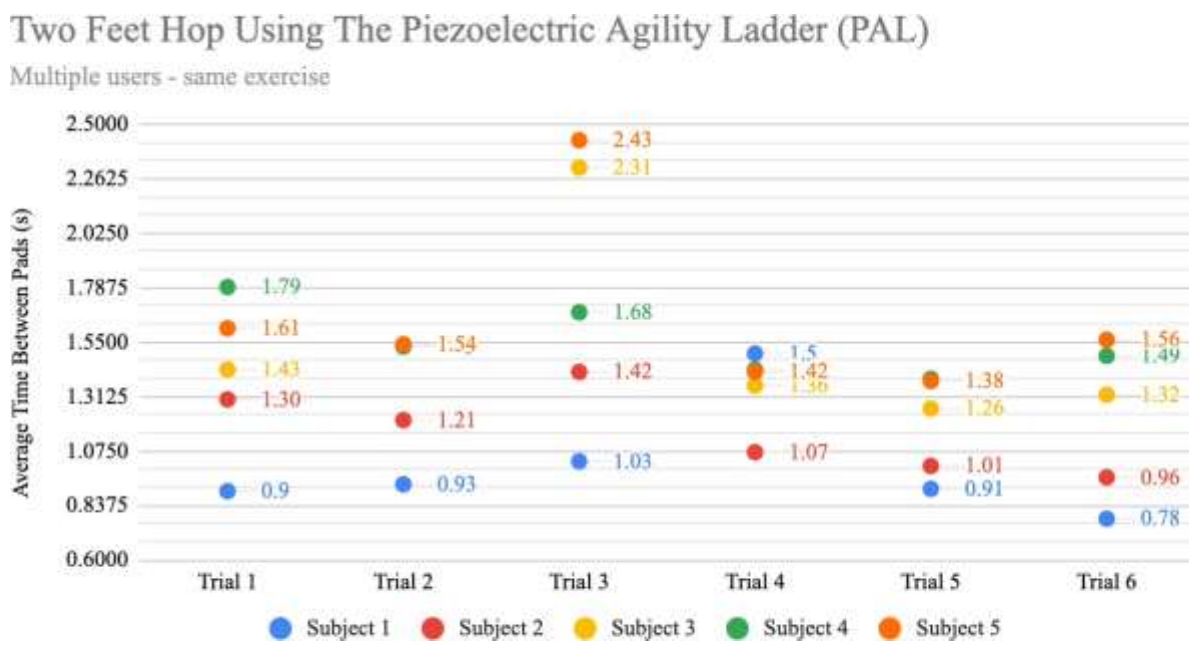

Fig. 17: Graph of different users, one exercise

A collection of real-world user data produced by the PAL demonstrates its ability to fulfill its primary function. Such data is valuable information for someone seeking to track their progress. All our users received instant feedback on their performance over several trials.

Discussion

Although we were limited by the resources available and our design was modified several times to meet these limitations, the overall goal of enhancing an agility ladder with piezoelectric sensors was reached. We pursued this project with the desire for it to be user-friendly for people of all ages and athletic abilities. In our current design, however, the height of the squares and the nature of the sensors require more user coordination than intended. Not only does the thickness of the pad material create a potential tripping hazard, but there is also no guarantee users with smaller-than-average feet will consistently hit the sensors. In this manner, the device becomes targeted to a smaller audience than desired. In an ideal future, with more resources available, we would find and implement an alternative material: one that is lightweight, slightly stiff, comfortable to step on, and thin. We might also conceal the wires and sensors, making the ladder truly water-resistant and more durable.

Additionally, improvements to the programming and technology used could be made. Periodically, the device malfunctions as a result of the voltage of the sensors (from the microcontroller's perspective) not updating as soon as the user steps on a pad. This malfunction is detrimental to the reliability of the PAL. Going forward, to mitigate or eliminate this issue, we might implement a check to determine if one sensor triggers out of order and display an error message to the LCD. Currently, we are only able to perform one operation at a time instead of multiple operations in parallel. Either software, such as a more advanced integrated development environment (IDE), or more capable hardware, would have to be utilized in order to implement this solution.

Another cause of incorrect data is the result of the constraints of the coding of the Arduino microcontroller. The pads must be triggered one at a time in order. This is because our current algorithm computes the sums of the times from one pad to the next, which are then divided by the number of pads. Ex: pad2 - 1, pad3 - 2, pad4 - 3 etc. As a result, if pad 2 is triggered (either intentionally or by mistake) before pad 1, that value would be a negative time, obfuscating the output. If a pad is triggered twice, the microcontroller arbitrarily determines which time value to use in its calculations. The resulting output is unreliable.

Conclusion & Implications

Despite its drawbacks and relative immaturity as a design, the PAL is a success as a prototype and demonstration that enhancing an agility ladder with piezoelectric sensors is a viable solution to the problem laid out in this paper. Tracking the user's footsteps with PZT sensors yields accurate data (if unreliably), which constitutes feedback current agility ladders fail to provide.

This feedback, in the form of a time measurement of the user's pace, allows agility ladders to be used as part of a training regime that acts as a closed feedback loop: adapting itself based on the user's progress.

As a prototype, the PAL could be improved upon with further time and funding. Although the current design is functional, more sophisticated materials and manufacturing processes would increase its portability, performance, and overall aesthetic. One particular area where the current iteration of the PAL especially needs improvement is the processing speed and ability of the microcontroller. Part of the aforementioned reliability issue is the delayed processing of analog signal inputs by the Arduino. This presents an especially pressing issue due to the nature of our device: mainly those users will operate it at a high intensity. A more capable microcontroller might allow for the PAL to possess more advanced logic, which could filter out extraneous sensor input, store user information in multiple profiles, or track and display more advanced statistics.

The centerpiece of our project: piezoelectric sensors have proven their capability. By being both extremely thin and having no moving parts subject to friction wear, PZT sensors are well suited to the role of detecting a user's steps. To that end, however, testing the PAL has revealed a caveat of using PZT sensors as opposed to other technologies. While our design specifically includes a pattern of sensors intended to maximize the chance a user steps directly on one, we underestimated the necessity for the user to directly impact them. This increases the number of sensors required in future designs, and subsequently the cost. Further testing could determine if a more rigid pad material would better transmit vibrations to the sensors, or if a different form-factor of PZT sensor is required. Regardless of the drawbacks of, or potential improvements that might be made to the PAL, it demonstrates the utility of using piezoelectric sensors to create an agility ladder that interacts with its users.

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Appendix 1: Code

```

int count1 = 0;
int count2 = 0;
int count3 = 0;
int count4 = 0;

int sensorReading11;
int sensorReading22;
int sensorReading33;
int sensorReading44;

int count = 0;

double one;
double two;
double three;
double four;

double average = 0;
```

```

bool onepressed;
bool twopressed;
bool threepressed;

#include <LiquidCrystal.h>

LiquidCrystal lcd(13, 12, 11, 10, 9, 8);

void setup() {
  Serial.begin(9600);

  lcd.begin(16, 2);
  lcd.clear();
}

void loop() {
  lcd.setCursor(0, 0);
  lcd.print("Step on pad 1");

```

```
  sensorReading11 = analogRead(A0);
  Serial.print("1:");
  Serial.println(sensorReading11);

  if (sensorReading11 >= 1000)
  {
    onepressed = true;
    count1++;

    if (count1 == 1)
    {
      one = millis();
    }
  }
  if (onepressed == true)
  {
    sensorReading22 = analogRead(A1);
    Serial.print("2:");
    Serial.println(sensorReading22);

```

```
    if (sensorReading22 >= 1000)
    {
      twopressed = true;
      count2++;

      if(count2 == 0)
      {
        two = millis();
      }
    }
    if (twopressed == true)
    {
      sensorReading33 = analogRead(A2);
      Serial.print("3:");
      Serial.println(sensorReading33);

      if (sensorReading33 >= 1000)
      {
        threepressed = true;

        if(count3 == 0)
        {
          three = millis();
        }
      }
      if (threepressed == true)
      {
        sensorReading44 = analogRead(A3);
        Serial.print("4:");
        Serial.println(sensorReading44);

        if (sensorReading44 >= 1000)
        {
          count4++;

          if(count4 == 0)
          {
            four = millis();
          }

          count++;

          if(count == 1)
          {
            average = -((((two - one) + (three - two) + (four - three))/4)/1000);
          }
        }
      }
    }
  }

  Serial.println(average);
  lcd.setCursor(0, 1);
  lcd.print("avg: ");
  lcd.print(average);
  lcd.print(" s");

  delay(500);
}
```