



**NAZARBAYEV  
UNIVERSITY**

School of Engineering and Digital Sciences

**Bachelor of Engineering in  
Mechanical and Aerospace Engineering**

**Self-powered sensor integrated platform for  
autism rehabilitation**

**(Final Report for Capstone Project)**

**by**

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**April, 2025**

## **Declaration**

We hereby declare that this report entitled “Self-powered sensor integrated platform for autism rehabilitation” is the result of our own project work except for quotations and citations that have been duly acknowledged. We also declare that it has not been previously or concurrently submitted for any other degree at Nazarbayev University.

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Date: April 29, 2025

## **Abstract**

This project transforms a simple balancing board into an interactive rehabilitation tool for children on the autism spectrum by integrating self-powered piezoelectric sensors. A stack consisting of a 1 mm-thick PVDF film, carbon-cloth electrodes bonded with silver paste, and a Kapton protective layer emerged as the optimal design, delivering clean, repeatable voltages up to 150 mV while resisting mechanical wear and triboelectric noise.

Guided by the pressure points of the five-year-old feet, each footpad carries two sensors: one under the heel and one under the forefoot. They capture the load without complicating the wiring or signal conditioning. Coupled to an Arduino-based reader and simple electromagnetic shielding, the sensors provide a linear arduino output-to-force response that reveals weight shifts during the platform balancing. Tiptoe trials elevate the front-sensor output, heel-leaning lights up the rear pair, and controlled board tilts show a clear symmetric pattern: tilting right raises the left-foot load, and vice-versa.

This project shows that the pressure distribution can be effectively captured using the designed device, laying the groundwork for real-time feedback and data-driven balance therapy. The platform now offers a robust, low-maintenance foundation for larger trials and for developing exercises to suit each child's unique motor profile.

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# 1 Introduction and Problem Statement

The contribution of authors is summarized in the table below.

<i>Author's name</i>	<i>Contribution</i>
Ainur Aman	Literature review of the project, animations
Merey Sembay	Sensor fabrication and testing, arduino connection, noise canceling, sensor integration with the balancing platform, device testing, data analysis
Zhassulan Turar	Sensor fabrication and testing, arduino connection, noise canceling, sensor integration with the balancing platform, device testing, data analysis

## 1.1 Background and Context

Autism Spectrum Disorder (ASD) is one of the most common neurodevelopmental disorders associated with difficulty in social communication, which highlights the need for its effective treatment and early intervention. The Centers for Disease Control and Prevention (CDC) reports that around 1 in 59 children suffer from ASD. Parent-reported diagnoses indicate an even higher prevalence, at around 2.5% in 2016. The increase in ASD has doubled since the year 2000 through 2012, indicating a greater demand for interventions [1].

Other frequently co-occurring conditions are intellectual disabilities, anxiety, attention-deficit/hyperactivity disorder (ADHD), seizures and mood disorders. ASD is also often accompanied by various physical health comorbidities, including gastrointestinal disorders, obesity and sleep disorders, which are life-dominating in their own right. ASD is complex and cannot be treated solely through toys that are shown in **Figure 1**. For people with ASD, early and well-targeted intervention is needed in order to teach the individual new skills for daily living, reduce certain symptoms and/or improve quality of life. When treatment includes consideration of both core and co-occurring conditions, outcomes for those with ASD may be significantly ameliorated to allow greater integration within society [1] and improved subjective well-being. If a child on the spectrum does not have an individualized treatment plan that utilizes research-proven treatments (e.g., ABA, sensory integration) and instead has only toys in his/her environment to help them "tip-toe in", progress made may be nonexistent, with

real deficits remain available in communication, social interaction and behavioral regulation.

Self-powered sensors present significant importance for rehabilitation technologies. They can be used for long-term health monitoring, wearable devices, and real-time data collection because these sensors have been proven to work without external power. Self-powered sensors are indispensable in various healthcare applications such as continuous monitoring of vital signs, wireless body area networks are possible by self-powered sensors and to power implantable medical devices leading toward revolution [2]. The integration of such sensors with the balancing platform can lead to more accurate and versatile rehabilitation systems that better respond to patient-specific needs and allow for data-driven adjustments in therapy.



**Figure 1.** (a), (b), (c) Sensory toys and activities used for ASD rehabilitation.

## 1.2 Problem Statement

While rehabilitation technologies have for many years been employed to address physical disability, motor coordination, sensory processing deficits, and speech development, these issues remain prevalent in persons with ASD. These challenges are typically accompanied by sensory processing disorders and manifest as clumsiness, atypical motor coordination, and gross and fine motor skill deficits, typically in conjunction with sensory processing disorders [3]. These cumulative difficulties make the rehabilitation process a complex coordination of motor reorganization under extremely demanding circumstances.

Traditional rehabilitation systems fail to meet the diverse needs of subjects. They over-rely on external power sources, are non-adaptive, and lack the ability to provide real-time feedback, all of which limit their effectiveness and scalability.

### **1.3 Objectives and Scope**

This project looks at how sensing technologies can be integrated into a balancing platform to improve rehabilitation, especially for children with autism. It starts by reviewing current rehabilitation systems and identifying their main limitations, such as heavy reliance on external power sources, limited adaptability to individual needs, and a lack of real-time feedback. It then explores the potential of self-powered sensors and balance boards to offer flexible solutions.

The focus of the project is to replace the slow, trial-and-error methods still common in therapy with real-time, data-driven feedback. In current rehabilitation programs, adjustments to a child's treatment plan are often made based on delayed observations or subjective judgment, which can slow progress and reduce engagement. By visualizing balance and pressure data instantly, our system will allow therapists and caregivers at home to see exactly how the child is responding at each moment. This immediate insight makes it possible to adjust exercise difficulty, session length, or stimulation type right away, ensuring that therapy stays at the right challenge level. For children with ASD, who may have subtle and rapidly changing motor or sensory responses, this kind of moment-to-moment adjustment is crucial for keeping sessions effective, personalized, and motivating.

By using piezoelectric sensors that generate their own power from the child's movements, the platform will reduce energy demands while still providing accurate and continuous feedback. In combining real-time analytics with low power needs, the project aims to create a more engaging, personalized, and evidence-based approach to rehabilitation for children with ASD.

## **2 Literature Review**

### **2.1 The Cerebellum and Balance**

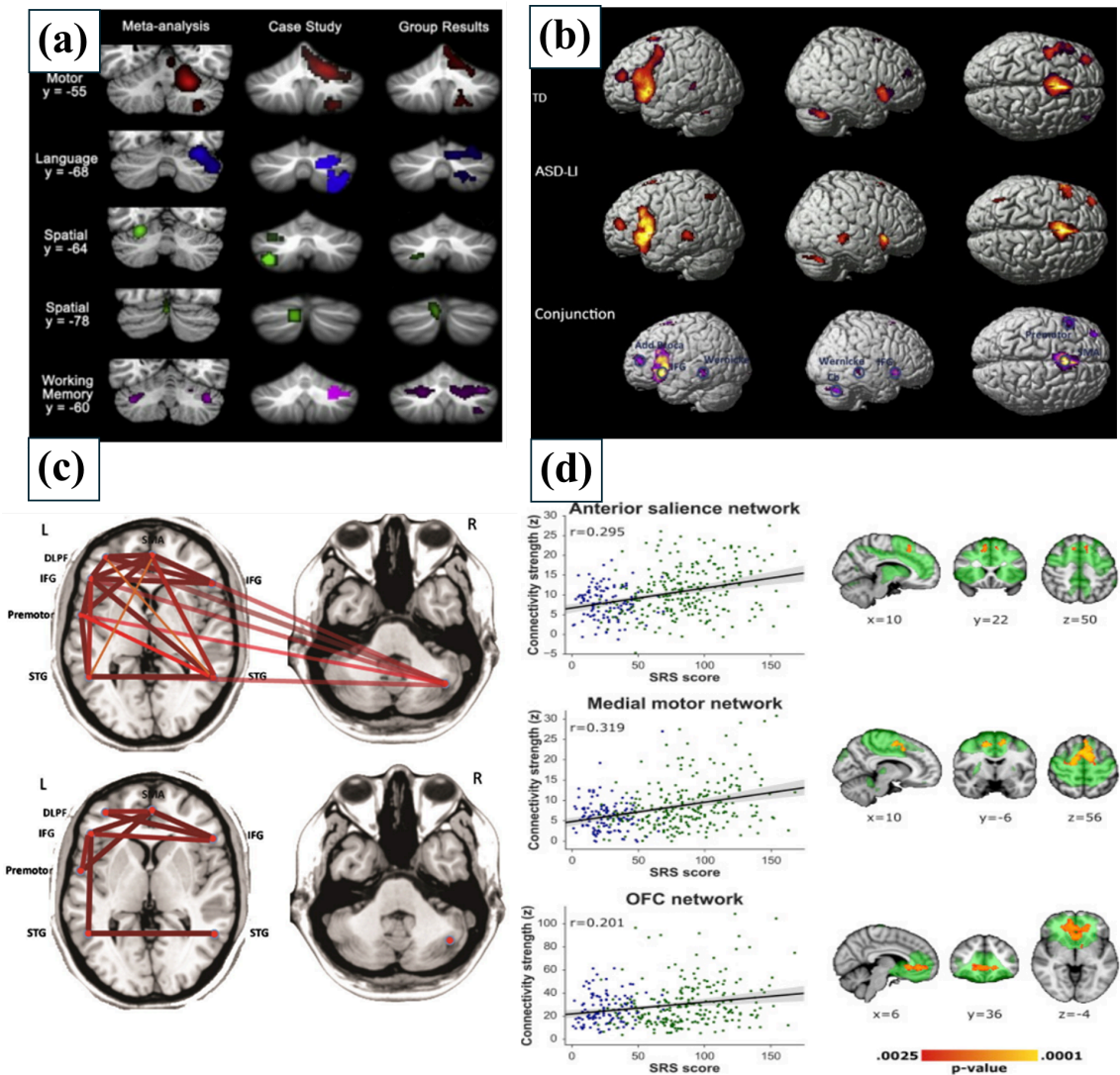
#### **2.1.1 Role of the Cerebellum in Motor Control**

The cerebellum is an essential portion of the motor control system, involved in balance and postural adjustments during movements too complex for just basic coordination. Newer findings highlight cerebellar involvement in the integration of sensory afferents for the refining of movement and postural control, as well as modifying motor output in response to changing environmental conditions [4]. **Figure 2a** shows an analysis in which parts of the cerebellum are highlighted when motor and language functions are used. **Figure 2b, 2c and 2d** also show connections between the cerebellum and communication and there is a comparison of typically developed brains versus ASD brains, highlighting the regions of the brain activated during the information processing.

The introduction of modern neuroimaging techniques like fMRI and DTI has further elucidated cerebellar function. Together, these approaches have revealed the complexities of cerebellar connectivity to other brain areas such as the cerebral cortex and basal ganglia. For example, altered functional connectivity patterns in the cerebellum have been identified by fMRI studies in neurological disorders, which provides a more detailed picture of how cerebellar dysfunction leads to motor and balance deficits. Such findings have also been extended to ASD, with abnormal cerebellar network signatures associated with motor coordination and sensory processing deficits [5].

#### **2.1.2 Balance and Posture Regulation**

Cerebellum-associated balance disorders are particularly prevalent in populations such as the elderly and patients with neurodevelopmental or neurodegenerative disorders. In the elderly, decreases in motor flexibility and postural oscillation caused by age-related cerebellar degeneration can ultimately enhance the likelihood of falls. Likewise, cerebellar dysfunction in neurological conditions such as ASD leads to poor motor coordination, a condition that is associated with altered balance and sensory integration of information at cerebellar circuits [4, 5].



**Figure 2.** (a) Meta-analysis reveals cerebellum areas for movement, language, and memory [6]. (b) Brain scan of patients with TD and ASD-LI [7]. (c) Functional connectivity comparison of patients with TD and ASD-LI [7]. (d) Increased SRS-2 scores link autism to altered brain connectivity [8].

The cerebellum coordinates steady-state movements and postural reflexes through descending pathways to the spinal cord, which plays a vital role in regulating balance and posture. This capability becomes quite apparent in tasks involving vertical postural control and the awareness of space. More specifically, the anterior lobe and lobule VIII of the cerebellum, together known as the sensorimotor cerebellum, are involved in these processes. Despite these seeming disconnects, dysfunction in these areas can manifest as cerebellar motor syndromes [6], a clinical constellation of signs that often includes ataxia, dysmetria (the inability to appropriately scale movement), and impaired oculomotor control – driving home the notion that the cerebellum is

essentially a brainstem structure for balance and coordination. Briefly, the cerebellum plays a vital role in fine motor control, posture, and body balance by integrating sensory inputs, and its impairment is strongly associated with motor and sensory processing impairments in neurological and neurodevelopmental disorders like ASD.

## **2.2 Integration of Self-Powered Sensors to Enhance Rehabilitation**

Self-powered sensors based balancing platform integration in rehabilitation is an important step towards assisting technology, as it provides useful feedback.

Integrating self-powered piezoelectric nanogenerator (PENG) sensors into the balance board translates each weight shift into a real-time electrical impulse that therapists or an onboard algorithm can use to correct posture in the moment. The continuous stream of measurements such as load symmetry, sway and recovery forms an objective record that streamlines personalized treatment and proves visible progress. As the PENG sensors harvest power directly from the child's own motion and the accompanying electronics only take minimal power, the platform is maintained wireless, lightweight and maintenance-free, making data-driven rehabilitation possible in clinics, schools and at home for children with autism.

### **2.2.1 Self-Powered Sensors**

Self-powered sensors are a practical solution for systems like the balancing platform because they don't require external power sources or batteries to operate. Instead, they give voltage outputs to mechanical inputs, and the voltage is utilized as the signal to gather data. For example, piezoelectric sensors generate a voltage when mechanical stress is applied, such that they can function without a power supply [2].

Triboelectric sensors operate in a similar manner by producing electrical signals through contact electrification and thus are suitable for thin and flexible use, e.g., wearable systems. The focus in this project is on using these sensors for their data-providing capacity through their in-house-produced signals and not for energy harvesting. They are thus free from charging or battery replacement and hence offer themselves as low-maintenance and reliable for rehabilitation platforms [9].

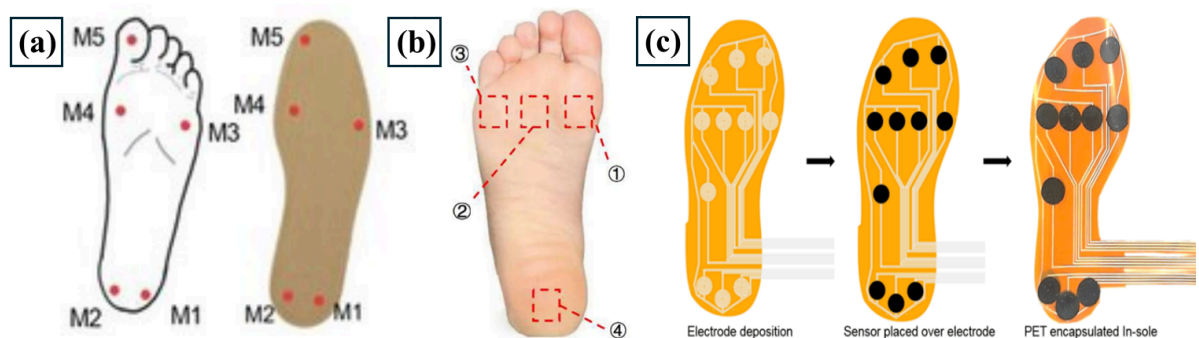
They are therefore sensor-independent no battery replacement or charging is needed on the sensor end and require only an infinitesimal coin-cell or thin Li-ion pouch to drive the Bluetooth Low Energy transmitter that sends data; at the module's sub-milliwatt duty cycle this cell will last for several months before needing

replacement, so the system as a whole is maintained low-maintenance and highly reliable for application in rehabilitation [9].

### 2.2.2 Sensor Placement and Design Considerations

The optimal placement for self-powered sensors is non-trivially positioned on the balancing platform. The placement of the sensor should be dictated by the main purpose of this platform; such as to observe patient movements, assess forces or motion of the platform. Therefore, areas where the most pressure is applied need to be considered.

The configuration of these sensors also affects their energy efficiency and lifespan. To improve data collection about a patient's mechanics of foot activity, a smart insole system consisting of four or five piezoelectric textile sensors strategically placed at relevant pressure points, as shown in **Figure 3a**, while **Figure 3b and 3c** demonstrate detailed schematics for sensor attachments. A better understanding of the above aspects would require sensitivity mapping during the integration process and help optimize the sensor and ensure that the correct data is acquired in rehabilitation applications to achieve rehabilitation efficiency. Materials that are flexible and strong, like graphene or polymer composites, offer constant sensor sensitivity over time while being capable of withstanding cyclic mechanical loads [10]. This really helps you in rehabilitation because it cannot be affected by the moisture, but these sensors are protected through this mode of encapsulation as well. Moreover, the elaboration of complex structural features to maximize energetic transduction and efficiency in real-time information processing through 3D printing has been evident [9].



**Figure 3.** (a) Smart insole diagram with five piezoelectric textile sensors [11]. (b) Schematics of sensor attachments [12]. (c) Pressure sensor placement within the insole [13].

### **2.2.3 Feedback Mechanisms and Adaptive Rehabilitation**

The use of self-powered sensors in the balancing platforms provides a promising system to offer feedback in real-time and adapt therapy, leading to better rehabilitation outcomes. The sensors can be integrated into the platform and include information such as joint angles, muscle activity, and distribution of force. This data provides insights that therapists can act on and create a plan of exercises for each patient. Another example is the use of piezoelectric sensors, which respond to minute changes in force or pressure, which could provide accurate feedback on patient performance during balance training or gait rehabilitation exercises [2].

Adaptive rehabilitation is further improved by fusing sensor data with sophisticated control algorithms. These algorithms can modulate the movements of the platform in real-time depending on sensory feedback to maintain the exercises within a challenging region for the patient (i.e. where he/she is able but that challenges progressively his/her affected motor functions) For example, the TENGs can monitor active limb movement to help guide the platform in adjusting its trajectory toward natural gaps between joints for optimal recovery [9]. In the same manner, TENGs are also leveraged on the rehabilitation platforms end-effector to record touch-based interactions and store motion details [10].

### **2.2.4 Challenges and Future Directions**

However, the combination of balancing platforms with self-powered sensors has not yet been fully investigated. These systems offer energy harvesting solutions; however, the energy harvested may not satisfy the requirements for complex rehabilitation platforms and thus enhancements in terms of energy efficiency and management are needed. This also complicates the ease with which sensors can be integrated into existing systems and makes it difficult to ensure scalability and compatibility with more advanced engineering [2].

The integration of balancing platforms with artificial intelligence (AI)-enhanced self-sustaining sensors, such as piezoelectric technology-based sensors, is an area that has not yet been explored. They employ their capability of power harvesting to provide stable and predictable information without depending on external energy sources. Machine learning (ML) and AI may be used to enhance the capability of these sensors to utilize the data they collect to establish differences and patterns within patient behavior. The system may be trained with the sensors through the use of ML algorithms

so that the system can see patterns and modify rehabilitation methods to fit the specific needs of each patient, increasing the overall effectiveness and responsiveness of the platform.

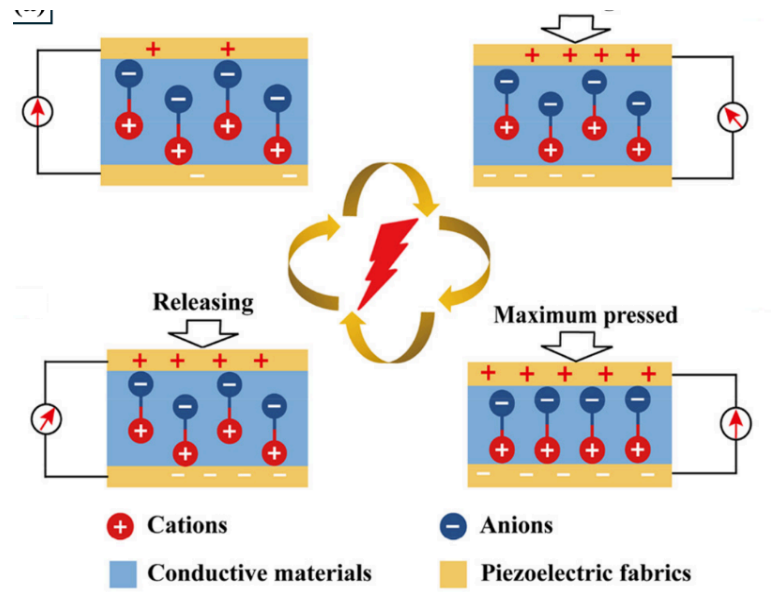
There should be additional research to improve the sensor design for energy harvesting efforts without compromising long-term integrity. New materials and fabrication techniques, including micro-patterned surfaces or exploiting porous structures to increase the overall amount of sensing material, may provide significant improvements in sensor performance. It will also be important to create unified data processing systems to integrate sensor signals into the platform's control system so that everything runs smoothly and in real-time.

Combined with the self-powered sensor, it leads to a revolutionary robotic rehabilitation method using balancing platforms. The energy harvesting potential of PENGs and TENGs would further enhance the sustainability and autonomy of these platforms. The intelligent spatial arrangement of sensors, along with suturing feedback, is used to monitor and adjust patient-specific therapy. Despite the challenges, the continuous development of sensor technology and system integration may allow for a breakthrough in rehabilitation practices and outcomes.

## **2.3 Role of Self-Powered Sensors in Rehabilitation**

### **2.3.1 Piezoelectric Nanogenerators based self-powered sensors**

PENGs, which are used in similar technologies, work on the piezoelectric effect, that is, when a mechanical stress is applied to a few materials, they charge. Simplified working principles of PENG sensors are illustrated in **Figure 4**. With this effect, mechanical energy (symptoms: vibrations, pressure or motion) can be harvested as electrical energy by PENGs. The features of high power output, instantaneity and reliability make them ideal when dynamic and accurate data capturing is needed [11] for rehabilitation technologies. It is commonly used for healthcare monitoring due to its scalability and fast response time [12]. High responsibility to pressure changes (4.4 k $\Omega$ /kPa) and pressure range up to 330 kPa make it ideal for foot rehabilitation uses [13].



**Figure 4.** Working principles of PENG [14].

PENGs have drawn significant attention with their capability of converting mechanical energy into electrical energy at the nanoscale, which makes them suitable for self-powered sensors and energy harvesting devices. Their implementation in wearable electronics, implantable medical devices, and IoT encourages continued research and development.

Recent advances in materials aim to enhance PENG performance. Graphene and derivatives of graphene, for example, reduced graphene oxide (rGO), are researched due to high electron mobility and flexibility that will boost the piezoelectric response [15]. Porous structures such as aerogels and sponges have high surface area which is crucial in increased charge collection and efficiency of energy conversion and therefore suitable for wearable and IoT devices [16]. Lead-free piezoelectric materials such as NaNbO<sub>3</sub> and BaTiO<sub>3</sub> are becoming popular as environmentally friendly substitutes for lead-based materials [17]. Piezoelectric polymers such as PVDF and their copolymers are always sought after due to their flexibility and biocompatibility and are generally blended with inorganic materials in composites to take advantage of their respective strengths.

New design and manufacturing techniques are also critical to enhance PENG technology. Microstructuration and surface engineering optimize the piezoelectric effect. New structural geometries like sandwich and layered structures are used to provide mechanical strength and energy conversion [17]. Porous structures improve

sensitivity and flexibility. New processing methods like 3D printing, electrospinning, and soft lithography enable the formation of designed and high-performance sensor structures [18]. Flexible substrate integration like PET and PDMS is needed for wearable devices [18].

PENG sensors are finding widespread applications. For medical purposes, implantable and wearable PENGs monitor human movements and body vital signs. Pressure sensors and tactile sensors are inducing robotics and human interfaces. Environmental monitoring utilizes stand-alone PENGs to analyze air quality. They also serve as clean sources of power for IoT and wireless sensor networks [19].

Performance of the PENG sensors is continually improving, with enhanced sensitivity, detection range, response time, and stability. Output voltage and power density vary according to design and material type-specific, and research further enhances these characteristics [18].

Challenges persist in the attainment of greater energy conversion efficiency, durability, and cost-effective manufacturing. Future research will most likely persist in seeking new materials, innovative designs, stress-free integration of complex systems, and artificial intelligence integration to further improve the properties and applications of PENG sensors.

### **2.3.2 Polyvinylidene Fluoride Films (PVDF)**

Polyvinylidene Fluoride Films, PVDF films, and their copolymers are thus the benchmarks in this field where flexible piezoelectric materials can be developed owing to the polymer's unique combination of properties. PVDF is one of the strongest and most rugged thermoplastic fluoropolymers available as well as being inexpensive, flexible and processable which makes it ideal for self-powered sensor and energy harvester applications. Although it possesses the lower piezoelectric coefficient value [16], its mechanical flexibility and biocompatibility gives many advantages over rigid and fragile inorganic piezoelectric materials such as piezoelectric ceramics. PVDF films can be tailored in methods of spin-coating, electrospinning and hot-pressing to produce high-density PVDF thin film which provide higher performance piezoelectric response. In addition, the thermal stability of PVDF as well as its long lifetime (over 36,000) [20] cycles and free lead-based biocompatibility, ensure safe energy-harvesting applications especially in biological surroundings which are hazardous for commercial lead-bearing materials. Preparation method is the main factor that influences the piezoelectric

properties of PVDF film [21], and so, methods that yield a PVDF film with required physical features should have to be selected which in turn offer adequate performance for conducting experiments or applications. In recent studies, the fabrication of the porous PVDF/PMMA matrix from a water phase infusion and the potential use as a piezoelectric sensor with a significantly higher  $\beta$ -phase content (85.7%) obtained from the ice bath and liquid nitrogen quenching compared to the pure PVDF polymer [20]. Similar techniques might be used to enhance sensors' capabilities making it more suitable for rehabilitation applications.

Rehabilitation-driven research in recent years vouches for the clinical promise of PVDF. A gait-monitoring system that inserts a thin film of PVDF in shoe soles beneath the heel converts each heel-strike into diagnostic pulses and sends them to a receiver for evaluating fall risk in the elderly [22]. Three-dimensional PVDF "nano yarn" fabrics woven into breathable compression sleeves preserve skin comfort while monitoring joint flexion, holding out a prospect for long wear during physio sessions [23]. Hybrid PVDF–ZnO nanofiber mats integrated into knee braces enable self-powered pedometry and range-of-motion read-outs suitable for post-surgery rehabilitation [24], while recent reviews highlight PVDF's biocompatibility, potential for miniaturization, and low-power Bluetooth compatibility as facilitators of future smart-therapy platforms [25].

Together, PVDF-based PENG sensors offer the rare combination of softness, biocompatibility and battery-free operation qualities that allow them to be integrated into shoes, straps or balance boards without adding bulk or wiring. This invisible, always-on sensing is exactly what pediatric neurorehabilitation is missing: children with autism spectrum disorder tend to struggle with balance, proprioception and rapid sensory feedback. Embedding PVDF elements in therapy equipment enables each oscillation or foot-strike to be translated into numerical data and real-time visual or tactile feedback, enabling therapists to tailor each session in real time. The next section therefore discusses these specific rehabilitation needs in ASD and illustrates how self-powered sensing platforms can fill the long-standing feedback gap.

## **2.4 Specific Rehabilitation Needs for Individuals with ASD**

Individuals with ASD often face motor difficulties and sensorimotor issues that can make their life more challenging. These obstacles can limit their ability to participate in social interactions. This part looks at the main challenges in motor and

sensory development and how rehabilitation tools, like those used in this project, can be adapted to better support their needs.

#### **2.4.1 Motor Impairments**

In addition to postural instability, motor coordination is another main problem described with ASD. When this occurs, they are unable to participate in tasks or activities that demand fine motor control, speech or the execution of gross movement which prevents them from performing complex or learning new motor skills. Motor planning difficulties are established features of ASDs and frequently coexist with core features, complicating rehabilitation success [26]. Balancing platform due to its customization properties, enables the simulation of movements that are propitious to its user.

#### **2.4.2 Sensory Processing Challenges**

Sensory processing in ASD may manifest as hypersensitivity or hyposensitivity. First, enhances responses to sensory input, which can cause discomfort or anxiety in places with loud noises, bright lights and certain textures while hyposensitivity leads to a lower awareness of sensory input — this means that it would take greater stimulation for one to respond. Indeed, sensory-seeking behaviors such as rocking and spinning can be part of a continuum of self-regulatory mechanisms centered on repetitive movements [26].

Therapy sessions become difficult as patients are unable to handle certain therapeutic environments or activities; sensory overload could encumber their capacity to concentrate. Some children may not engage which may further limit momentum during rehab. Because of these factors, proper planning and customizing the therapy to suit specific sensory needs is required. Gradual introduction to the platform may adabate sensory overload caused by environmental factors.

#### **2.4.3 Adaptations of Rehabilitation Technologies for Autism**

One of the popular modalities for treating sensory processing issues in ASD is called Sensory Integration Therapy. SIT's goal is to help people interact with sensory stimuli to guide rehabilitation environments and technologies to match the sensory needs of individuals with ASD [27]. In these environments by controlling the sensory input, therapists can help individuals with hypersensitivity to stay calm and process information calmly. Good practices that are favorable adaptations include visual

support, consistency and sensory adjustments. The use of pictures or videos demonstrating the exercises can prove useful as it helps an individual with ASD to break down complex movements into smaller, manageable steps and performing the same set of exercises in a predictable order can help decrease anxiety and improve concentration. For example, incorporation of VR systems to existing technologies can reduce sensory overload by presenting controllable light, sound and image elements. Moreover, virtual reality of realistic tasks can facilitate social skill acquisition in a safe environment. Lastly, changing the sensory setting (eg, reduction in noise or light) or using sensory-friendly equipment can facilitate exercises [27].

#### **2.4.4 Addressing Specific Rehabilitation Needs**

The motor and sensory profile of individuals with ASD is essential for developing effective rehabilitation strategies. Each subject should be assessed separately for postural control, motor coordination and sensory processing abilities. Based on such assessments, therapists can create unique intervention plans which are suited to the needs of the individual [26]. In addition, multidisciplinary treatment is necessary when managing patients with ASD. Interdisciplinary therapy provided by occupational therapists, physiotherapists, speech language pathologists and psychologists can provide a comprehensive treatment protocol with focus on physical, sensorimotor and cognitive elements [27]. New stimuli and exercises can be introduced step-by-step by therapists to provide individuals with time to establish tolerance and become accustomed to new sensations [26].

### **2.5 Challenges and opportunities**

Combining self-powered sensors with the balancing platform provides a promising solution to a current problem in ASD rehabilitation. Challenges and opportunities for future development exist and will be discussed below.

The system offers a unique opportunity to track the progress of autistic children during therapy by monitoring their balance and movement patterns in real-time. This is helpful for therapists. Besides, by providing dynamic feedback without the need for external batteries, this system supports greater portability and reduces the need for maintenance, which simplifies usage.

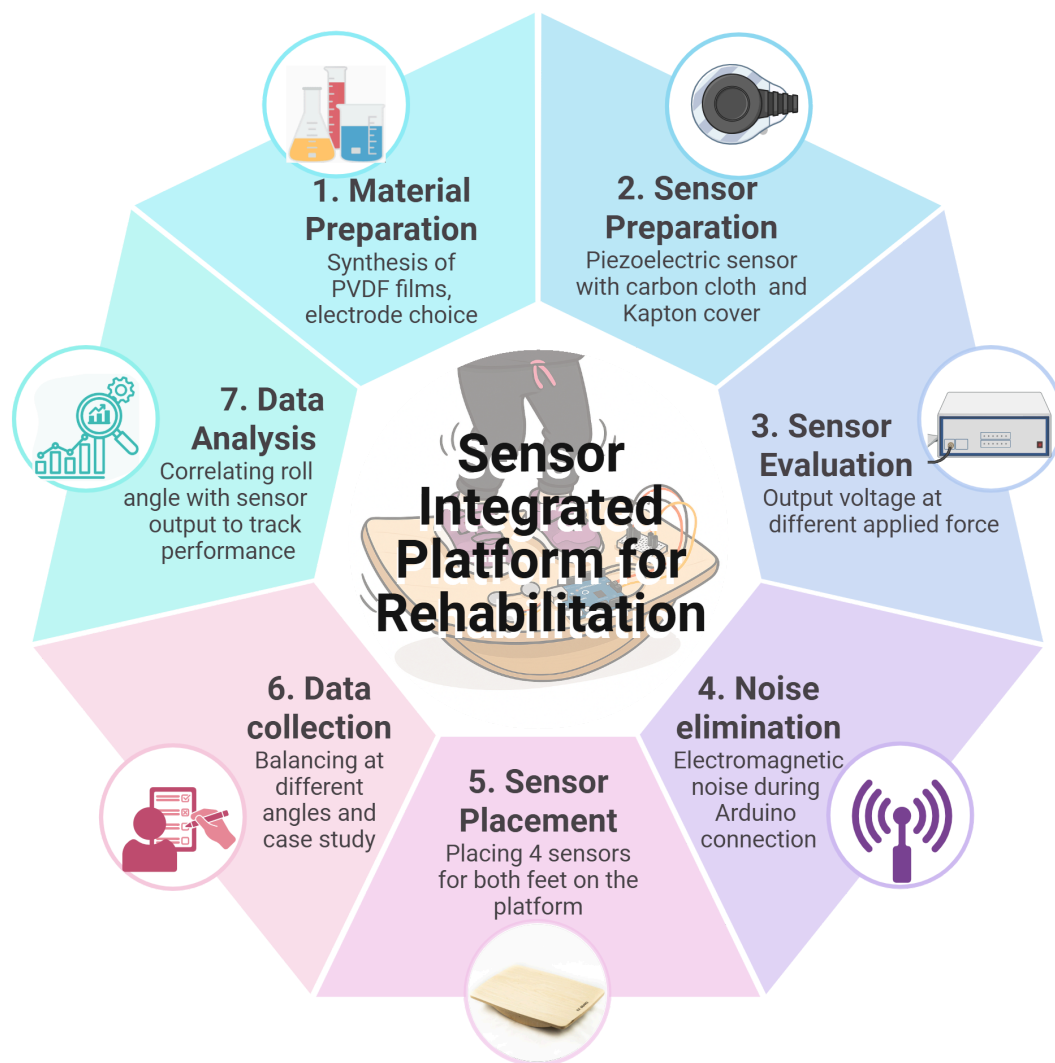
However, the integration of energy harvesting technology into rehabilitation systems also has its own challenges. This presents the major challenge that self-powered sensors have a significant noise which may limit usage in complicated systems such as

the balancing platform. To overcome these limitations, it is necessary to optimize their output to effectively cancel the noise [2]. Also, to guarantee that the sensors last and read accurately despite being mechanically stressed repeatedly over a long period of time requires innovation in material science as well as sensor technology.

Moving forward, rehabilitation technologies need to take advantage of the data-driven nature of self-powered sensors to increase personalization. Live data about how well a patient is moving, which muscles are working and with what kind of response to stimuli will allow platforms to tailor therapy according to the progress of each person. Wearable sensors connected to the balancing platform could be used to provide continuous feedback on joint angles and balances over the exercises, allowing for immediate comparison between therapists and patients [28]. This flexibility is important for individuals suffering with ASD who experience sensory overload and motor deficits [26] hence the need for highly individualized approaches. Future trends include the development of mixed sensor systems improving its sensing capability through functional materials, and the application of machine learning algorithms to interpret sensor data with higher accuracy [29].

### 3 Methodology

This section provides information about the experimental part of the project, including material and sensor preparation. All the processes, starting from material preparation, of this project are shown and described briefly in **Figure 5**.



**Figure 5.** Schematic representation of project processes.

#### 3.1 Materials

Polyvinylidene fluoride pellets (PVDF,  $M_w \sim 400\,000\text{ g mol}^{-1}$ ), atactic poly(methyl methacrylate) (PMMA,  $M_w \sim 350\,000$ ),  $N,N'$ -dimethylformamide (DMF, ACS reagent,  $>95.8\%$ ), and glycerol ( $\geq 99.0\%$ ) were provided by Sigma-Aldrich and used without further modification.

### 3.2 Synthesis of PVDF Film

To synthesize the Polyvinylidene fluoride (PVDF) film, the method published by Mubarak et al. was used, **Figure 6**. A polymer solution was prepared using 20 wt.% PVDF, 3 wt.% poly(methyl methacrylate) (PMMA), and dimethylformamide (DMF) as a solvent. The mixture was stirred at 40°C for two hours to dissolve the granules completely. Once dissolved, 5 wt.% glycerol was added for the purpose of achieving the porous matrix, and the solution was subjected to ultrasonication for 10 minutes using a 5-second pulse interval to ensure uniform dispersion.

To fabricate thin films from the prepared solution, a doctor blade was used. PVDF layers with different thicknesses were cast onto an Aluminum foil and then transferred into a distilled water bath. Ice bath quenching with nitrogen was done, after which the system was left undisturbed until the nitrogen evaporated completely and the ice melted, allowing the films to stabilize.

Following stabilization, the films were transferred to a fresh distilled water bath maintained at 40°C for 12 hours to remove residual glycerol to form a porous matrix. Finally, the films were annealed at 60°C for two to three hours to dry and improve their structural integrity.



**Figure 6.** Preparation of PVDF film.

### 3.3 Preparation of Piezoelectric Sensors

To prepare the piezoelectric sensors, the synthesized PVDF film with wet film thicknesses of 0.5 mm, 1 mm and 1.5 mm was taken and cut into  $4.0 \times 3.0 \text{ cm}^2$  pieces. Three types of electrodes were selected for experimentation: aluminum, copper, and carbon cloth. Electrodes measuring  $3.5 \times 2.5 \text{ cm}^2$  were applied to each side of the PVDF film, forming a sandwich structure as shown in **Figure 7a**. For the aluminum and copper electrodes, adhesive tapes made of the respective materials were used to ensure proper attachment. In the case of carbon cloth, silver paste was applied to secure the electrodes. To provide protection and enhance durability, Ecoflex and Kapton tape were chosen for testing.

### 3.4 Material and Sensor Characterization

The piezoelectric characteristic of the prepared PVDF film was calculated after FTIR testing on the Nicolet iS10 FT-IR Spectrometer. To test the output of sensors, a self-made testing platform including a horizontal linear motor (LinMot: PS01-37×120F-HP-C), and a dual-range force sensor (Vernier LabQuest Mini, max 50 N) was used, **Figure 7b**. The linear motor can simulate a required pressure change by series of controlled contact and separation. The force sensor identifies how much force is applied on the sensor. These components were installed inside a cage constructed from metal rods, simulating a Faraday's cage by reducing unwanted electromagnetic noise from the surroundings. To measure the output voltage from sensors the oscilloscope (Tektronix TBS 1000C Series) was used. Sensors were securely attached to the force sensor using double-sided tape, and their electrodes were connected through wires to the oscilloscope.

### 3.5 Sensor Integration with Arduino and Force Testing

An Arduino Uno microcontroller board was used to test the output of the piezoelectric sensors. The sensors were connected directly to the Arduino and tested under three conditions to ensure good analog signal readings: without isolation, with isolation from electromagnetic disturbances, and with the addition of a resistor. To reduce the noise in the readings caused by surrounding electromagnetic waves, the sensor connections were wrapped in aluminum foil and then insulated with a layer of resin. For the same purpose, the Arduino board was also isolated using tape. A resistor of  $7.5 \text{ M}\Omega$  was integrated into the circuit to refine the output signal. The setup allowed

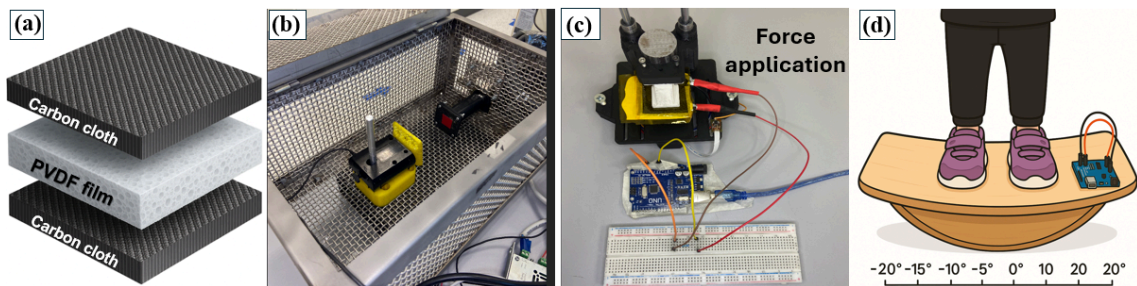
for the measurement of the sensor's response under controlled conditions. For Arduino and data collection, the codes in **Appendix B** were used.

The force testing was conducted using a dedicated force testing system, as shown in **Figure 7c**. To evaluate the sensor's response to varying forces, masses from 100 g to 1 kg were successively attached in 100 g increments and dropped onto the sensor using the setup. These masses correspond to forces ranging from 1 N to 10 N in 1 N intervals. The sensor was positioned beneath the system to measure its output voltage in response to the applied forces at each interval.

### 3.6 Sensor Placement and Device Testing

Sensor positioning was tackled theoretically. The research was conducted in order to find out which areas of the foot experience maximum pressure when standing or balancing activities are performed. This was derived from biomechanics research and past research on pressure distribution of the foot, which provided information on where to position the sensors.

Device testing was conducted to find the correlation between different bending (roll) angles and sensor output. The subject was asked to balance for 10 seconds at each of the angles from  $-20^\circ$  to  $20^\circ$  with a step of  $5^\circ$  (**Figure 7d**). Results collected from the Arduino setup were analyzed to find the average sensor output at each angle. This correlation was further used during the analysis of the case study, where subjects had to freely balance on the platform without a fixed angular constraint. The collected data enabled us to visualize and interpret the subject's balancing behaviour.



**Figure 7.** (a) Linear motor system in Faraday's cage, (b) Force testing system. (c) Device testing setup, (d) balancing platform with integrated sensors and electronics.

## 4 Results and Discussions

This section details the outcomes of the fabrication process, highlighting the choices made throughout and their impact on the outcomes. The results part was divided into three sections.

### 4.1 Sensor Fabrication Outcomes

#### 4.1.1 PVDF Film Thickness

To study the relationship between thickness, output voltage, and durability, sensors with PVDF films of 0.5 mm, 1 mm, and 1.5 mm thickness with copper electrodes were prepared, as shown in **Figure 9a-c**. The output voltage of each sensor was measured at a frequency of 0.25 Hz with 3 N force applied. As shown in **Figure 9g**, the 0.5 mm film generated the highest output among 3 sensors reaching the peak-to-peak output voltage of 140 mV, while the 1 mm film produced approximately 100 mV, and the 1.5 mm film gave the lowest output voltage of 80 mV. These results demonstrate that thinner films produce higher output voltages with their increased flexure and piezoelectricity. Yet, although demonstrating superior output, the 0.5 mm film was extremely fragile and sensitive to tearing by handling and testing, making it unsuitable in applications where ruggedness is required. On the other hand, the 1.5 mm film fabrication came with additional challenges due to greater difficulty in having a smooth surface with increased thickness. Thin films in blade-coating allowed for uniform spreading of the solution, leading to smooth surfaces and homogeneous piezoelectric characteristics. In contrast, the 1.5 mm film exhibited surface irregularities, **Figure 9c**, which caused the output to be highly inconsistent and random. Moreover, these surface irregularities resulted in small cracks on the film during pressing, which led to a short circuit of the system since the two electrodes came into contact at the cracks. The 1 mm film had a balance between performance and mechanical properties. Based on these findings, the 1 mm film was selected as the optimal thickness for further experiments and sensor fabrication.

#### 4.1.2 FTIR Analysis

The  $\beta$ -phase is particularly crucial to the piezoelectric behavior of PVDF since only this phase possesses the correct polar crystal structure. It is not easy to develop a high content of  $\beta$ -phase since PVDF tends to crystallize in the non-polar  $\alpha$ -phase under standard

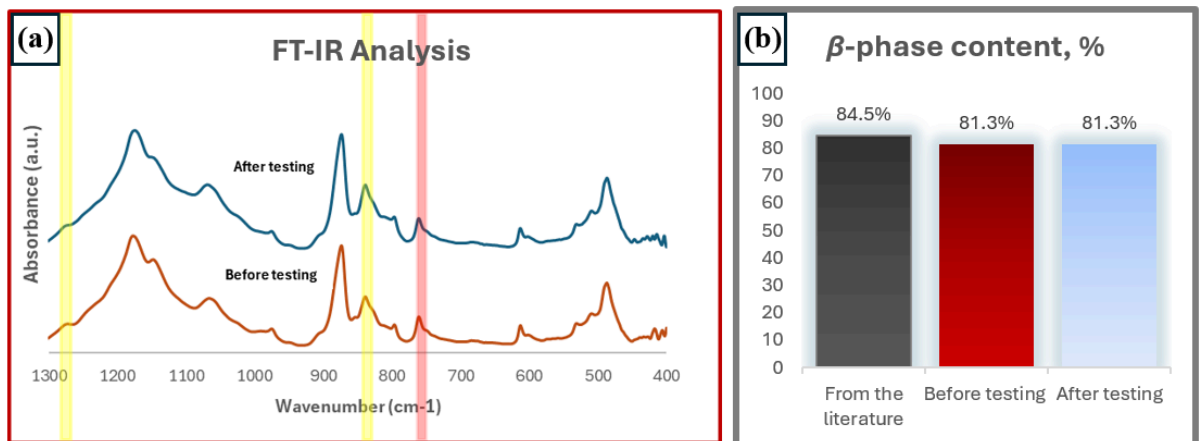
conditions. Processing conditions must be closely controlled in order to promote the development of  $\beta$ -phase.

To confirm the crystalline phases present, ATR-FTIR spectroscopy was employed. **Figure 8** combines the ATR-FTIR spectra of the film before and after mechanical testing with a bar-chart summary of the corresponding  $\beta$ -phase fractions. Two  $\beta$ -phase bands are clearly visible in both spectra:  $840\text{ cm}^{-1}$  ( $\text{CF}_2$  symmetric stretching) and  $1275\text{ cm}^{-1}$  ( $-\text{CF}_2-$  bending), whereas the  $\alpha$ -phase reference band at  $765\text{ cm}^{-1}$  remains weak. The preservation of these characteristic peaks indicates that the crystal phase distribution of the polymer is not degraded during cyclic loading. To calculate the  $\beta$ -phase, following equation is used:

$$F(\beta) = \frac{X_\beta}{(X_\alpha + x_\beta)} = \frac{A_\beta}{[(k_\alpha/k_\beta) A_\alpha + A_\beta]} = \frac{A_\beta}{1.26 A_\alpha + A_\beta}$$

where  $A_\alpha$  and  $A_\beta$  are absorbances at  $765\text{ cm}^{-1}$  and  $840\text{ cm}^{-1}$ , respectively, and the factor 1.26 compensates for the different absorption coefficients of the two phases.

As is evident from **Figure 8**, the  $\beta$ -phase content achieved was around 81%, high compared to PVDF films. High  $\beta$ -phase content was obtained through the deliberate introduction of the optimized concentration of PMMA (3%) into the PVDF (20%) matrix and a controlled cooling process employing liquid nitrogen and ice. For comparison, PVDF films reported in the literature tend to have  $\beta$ -fractions around 84.5%, validating that the material produced in this study is within a competitive range. These results guarantee success of the processing method in producing a highly piezoelectric PVDF film.

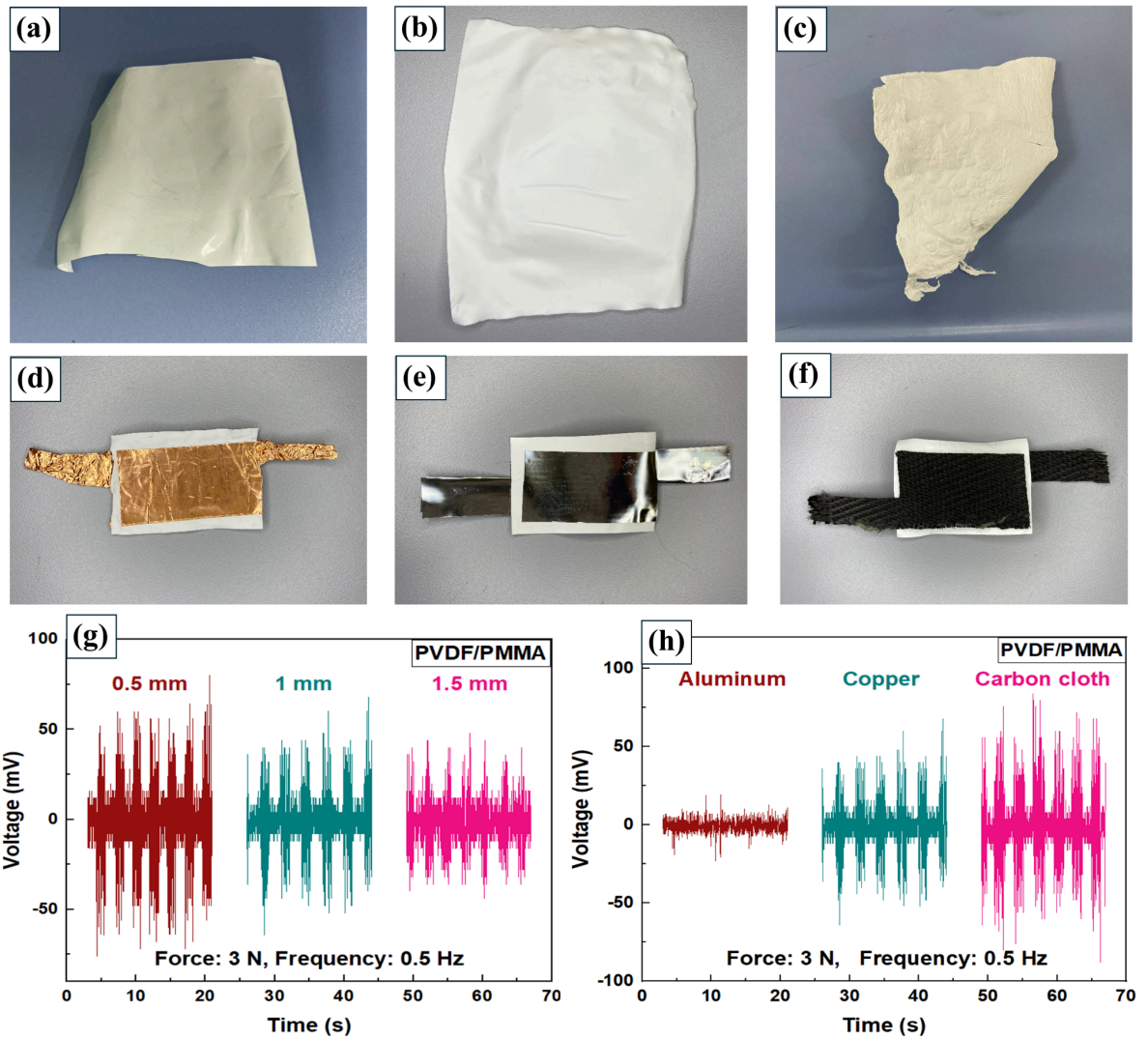


**Figure 8.** (a) FTIR analysis of the film before and after the testing (b)  $\beta$  - phase content comparison of the film with literature

### 4.1.3 Electrode Choice

The next parameter affecting the output of the piezoelectric sensor is the choice of electrode material. A suitable electrode can significantly enhance the performance of the piezoelectric sensors. From commonly used electrodes, the three materials were considered to find the one which is optimal in terms of output and durability: aluminum, copper and carbon cloth, **Figure 9d-f**. The sensors were prepared from 1 mm-thick films. As it is clear from the results of output voltage testing in **Figure 9h**, sensors with aluminum electrodes produced the lowest output, measuring approximately 20 mV, which was insufficient for practical applications. Copper electrodes performed better, generating an output of around 100 mV, as previously noted. However, the best performance was achieved with carbon cloth electrodes glued with silver paste, which produced an output of 150 mV. The conductivity of copper is higher than the conductivity of carbon cloth, however, the adhesive glue used in the copper and aluminum tapes has reduced the conductivity of these materials.

Aside from greater electrical return, carbon cloth also offered mechanical advantages over metal foils. Aluminum and copper foils crumpled and folded when applied, forming non-uniform surfaces, whereas carbon cloth was more flexible and deposited smoothly in the PVDF film. This flexibility ensured maximum contact and uniformity in sensor response. Furthermore, the higher thickness and woven nature of the carbon cloth make it highly resistant compared to thin metal foils that are fragile and prone to wear and tear. The toughness and flexibility as well as higher output make carbon cloth the better option for the electrodes.

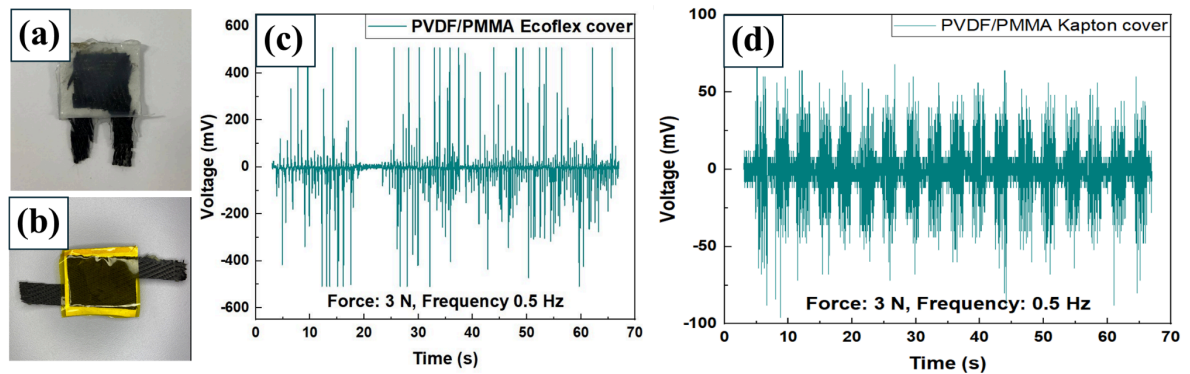


**Figure 9.** PVDF film with different thicknesses: (a) 0.5 mm, (b) 1 mm and (c) 1.5 mm. Piezoelectric sensor with different electrodes: (d) copper, (e) aluminum and (f) carbon cloth. (g) Output voltage of PVDF film and copper electrode sensors with different thicknesses. (h) Output voltage of 1 mm PVDF film with different electrodes.

#### 4.1.4 Protection Cover

For the protection and elongation of the durability of the sensors, two covering materials were evaluated: Kapton tape and Ecoflex (**Figure 10a-b**). When Ecoflex was used as a protective layer, the sensor exhibited behavior characteristic of a triboelectric sensor, producing high, inconsistent peaks (**Figure 10c**) instead of the expected steady piezoelectric response. It happened as a result of contact between the sensor surface and the Ecoflex, resulting in the adventitious triboelectric effect that was not desirable. Kapton tape, however, was discovered to leave its initial function with the sensor but with slightly no change at

approximately 150 mV (**Figure 10d**). With it, the tape was more consistent in masking off the sensor as a defense tool without compromising function.



**Figure 10.** Sensors covered with (a) ecoflex and (b) kapton. The voltage output of (c) ecoflex and (d) kapton covered sensors.

## 4.2 Sensor testing

### 4.2.1 Noise elimination

When connecting the sensor to the Arduino system, an issue with consistent background noise arose, as shown in **Figure 11a**. This noise persisted even when the sensor was inactive, making it difficult to obtain reliable readings. To address this, several methods of noise cancellation were tested.

The first approach involved isolating the sensor using an aluminum cover, followed by isolating tape. As shown in **Figure 11b**, these measures significantly reduced the background noise. Additionally, the isolation prevented the sensor from reacting to random movements in its surroundings, further improving the setup's stability.

However, despite these improvements, the sensor's output voltage remained inconsistent. To address this, a 7.5 M $\Omega$  resistor was added to the circuit. The resistor helped stabilize the sensor's output by reducing high-frequency noise and providing a consistent pathway for the signal to ground. This adjustment minimized interference and improved the accuracy of the sensor's readings. As shown in **Figure 11c**, the sensor output became noticeably more consistent after implementing this change, ensuring reliable data for further analysis.

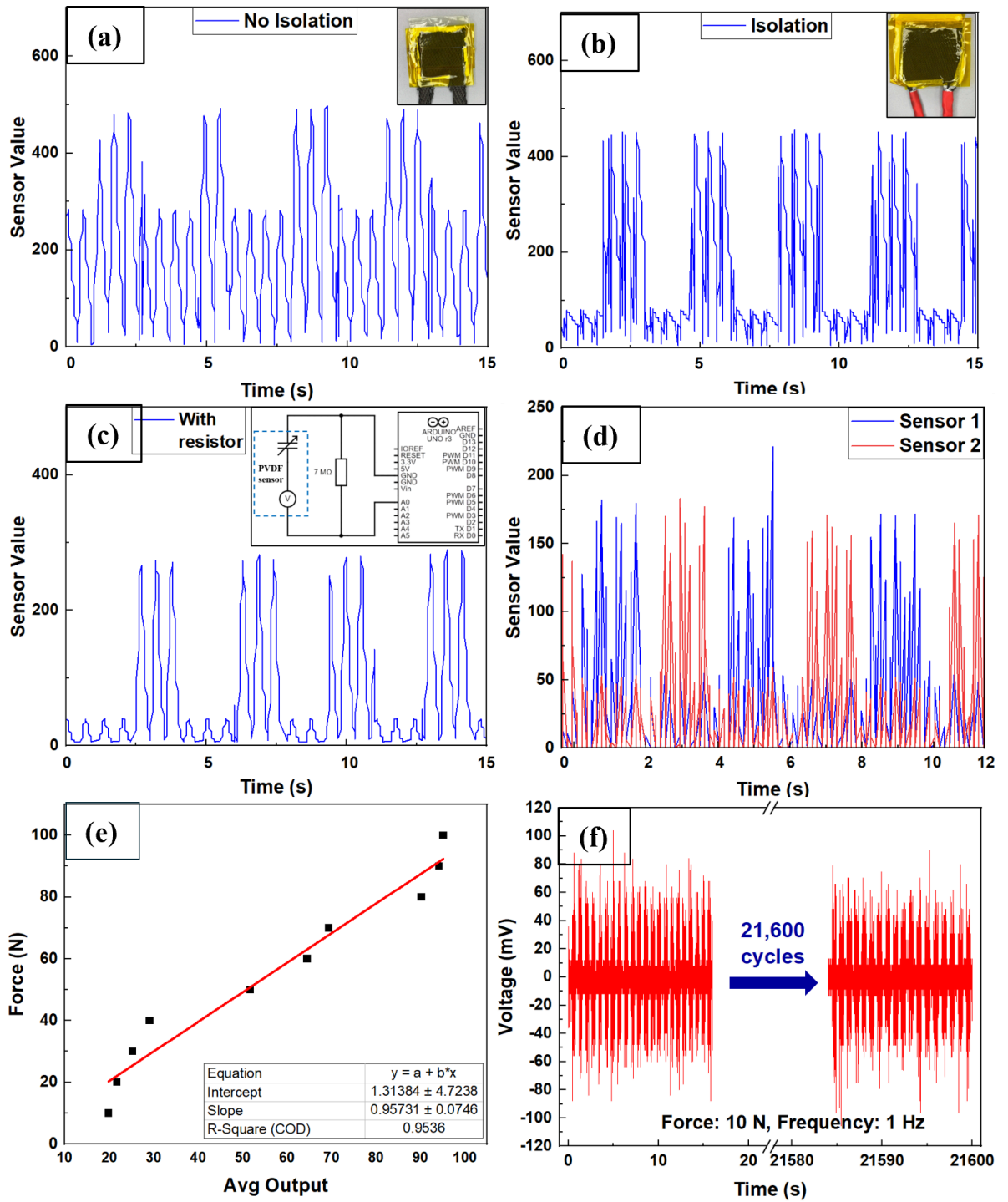
Since the platform requires multiple sensors to work simultaneously to provide data about the child's standing posture and balance, a test was conducted by connecting two

sensors to the Arduino. As shown in **Figure 11d**, this setup was successfully implemented, demonstrating that multiple sensors can be integrated for future work on the balancing platform.

#### **4.2.2 Force and Durability Testing**

As shown in **Figure 11e**, there is a clear positive correlation between the applied force and the output voltage. This occurs because the piezoelectric sensor generates more charge under greater mechanical stress, directly translating into higher voltage output. The relationship confirms the sensor's responsiveness to varying force levels, validating its suitability for pressure sensing applications.

For durability testing, the sensor was subjected to a 10 N force at a frequency of 1 Hz for 21,600 cycles. The results showed no significant variation in performance, **Figure 11f**, indicating that the sensor maintains its functionality even after prolonged use under repetitive stress conditions.

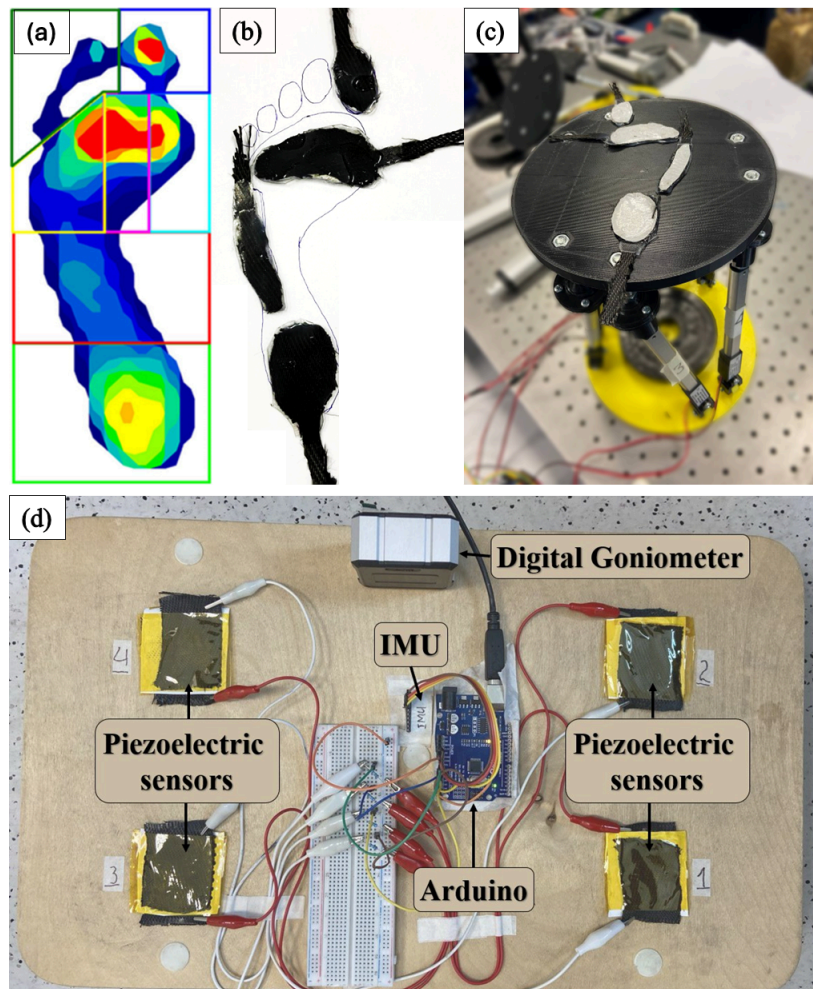


**Figure 11.** Arduino connection: sensor value for (a) no isolation (b) isolation (c) with resistor 7.5 MΩ (d) two sensors. (e) Force testing. (f) Durability testing.

## 4.3 Device Testing

### 4.3.1 Sensor Placement

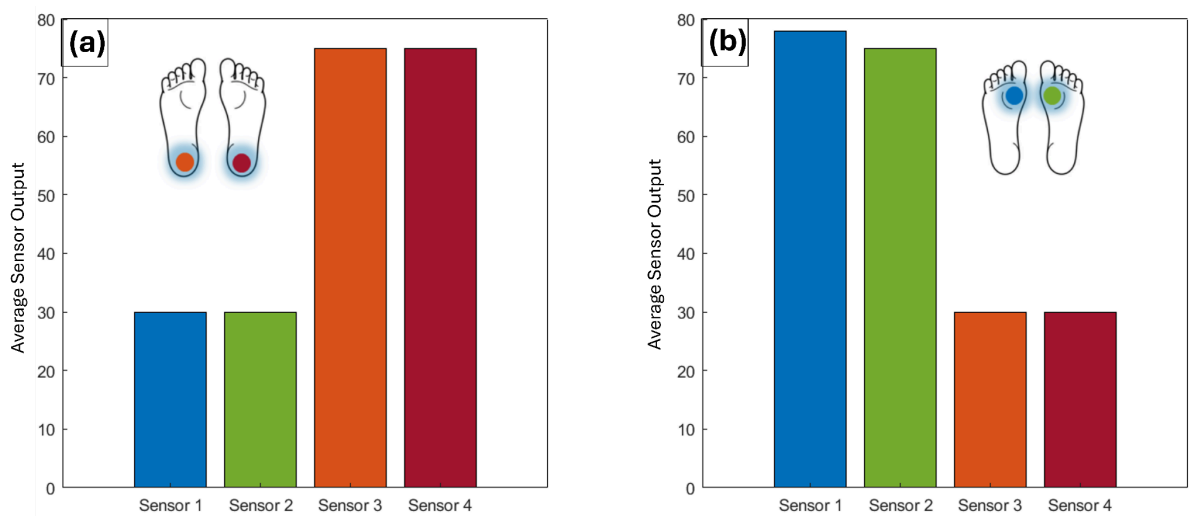
We initially chose sensor locations by looking at typical pressure maps of five-year-olds' feet, where the highest forces concentrate under the heel, the middle metatarsal region and the big toe (**Figure 12a**). With those hotspots in mind, our plan was to use four sensors per foot—at the heel, metatarsal area, hallux and arch—each cut to fit an average 18.5 cm foot and mounted on the balancing Platform (**Figures 12b–c**). However, to focus our limited time on perfecting the sensors themselves rather than full device testing, we simplified the layout: now each foot carries just two sensors, one at the rear (heel) and one at the front (metatarsal), **Figure 12d**. As can be seen, the balancing platform has been replaced by the balancing board.



**Figure 12.** (a) The pressure distribution in normal feet. (b) Sensor placement. (c) Sensors are placed on the Stewart Platform (initial idea) (d) Sensors are placed on the balancing board (actual work).

### 4.3.2 Validation of Simultaneous Sensor Functionality

The proper functioning of the sensors is further confirmed by the results shown in **Figure 13**. When the subject stands on tiptoes, the front sensors produce noticeably higher readings. On the other hand, shifting weight to the heels causes the rear sensors to show significantly increased outputs. This clear response demonstrates that the sensors effectively detect shifts in pressure distribution across the foot, confirming that the system is suitable for conducting different balance assessments. Moreover, the consistent and symmetrical sensor outputs suggest that the sensors are correctly placed and do not interfere with each other's measurements.

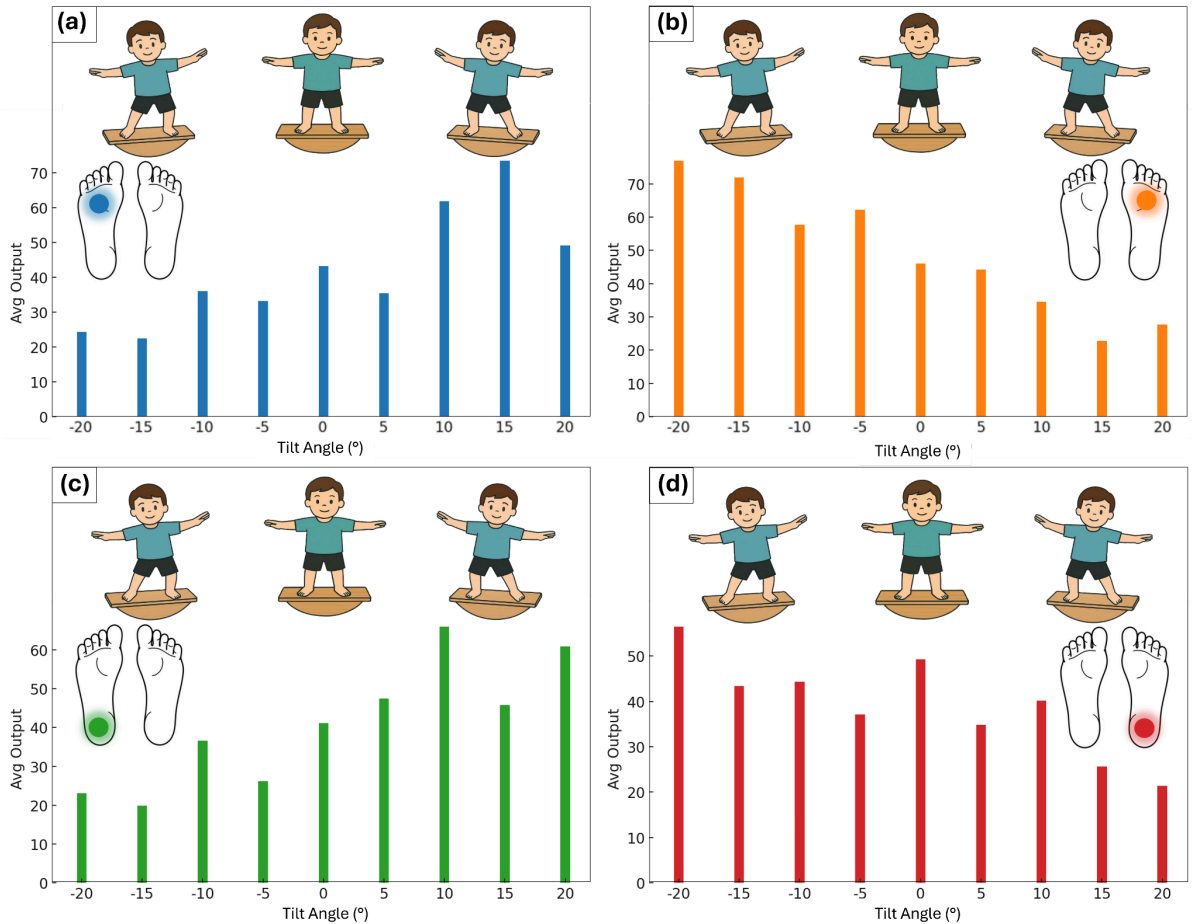


**Figure 13.** The average output when the person is standing on their (a) tip toes and (b) heels.

### 4.3.3 Roll Angle and Sensor Output Correlation

Each bar in **Figure 14** represents the average pressure recorded at different tilt angles, and there's a neat, consistent pattern: as the tilt angle increases to one side, the pressure reading on the opposite leg's sensor goes up. This confirms that the sensor system captures how people adapt foot pressure to shifts in the platform's tilt. Looking closer at the figure, when the board tilts to the right (a negative angle), you can clearly see that the left leg sensors (**Figure 14a, c**) consistently show higher readings. This increased pressure on the left side isn't random—it's the person's natural response to shifting their weight in order to counterbalance the board and avoid a fall. In simple terms, as the platform leans to the right, our body instinctively moves our weight to the left to help maintain balance. Conversely, when the board tilts left (positive angle), the right leg sensor picks up this extra load, showing us the reverse effect (**Figure 14 b, d**).

From **Figure 14**, it can also be seen if the person balancing might be leaning on one side too much. This information can be important for the detection and rehabilitation of autistic individuals, considering their challenges in balancing. For many on the autism spectrum, differences in sensory processing can influence how they perceive their body and manage balance. This may lead to, when a platform tilts, then exhibiting a new pattern of weight distribution, possibly requiring a more powerful or more exotic corrective force. These findings have promising potential for future research. By including autistic participants in our testing, we can build valuable knowledge about how their balance strategies differ from neurotypicals. This can ultimately lead to more targeted and effective rehabilitation therapies, as well as improved detection methods for balance-related problems within the ASD group. In the future, we can extend our research by incorporating autistic participants so that we can learn more about their unique balancing patterns. We can compare these with neurotypical individuals and potentially discover new information regarding how sensory differences impact balance and stability. This can give us the information that will be helpful in developing more individualized therapy approaches and even detect balance problems at an earlier point for people on the autism spectrum.



**Figure 14.** Correlation between tilting angle (varying from  $-20^{\circ}$  to  $20^{\circ}$ ) and sensor output for sensor located at: (a) left metatarsal, (b) right metatarsal, (c) left heel and (d) right heel.

#### 4.3.4 Case study: Child balancing

A case study was carried out to further test the platform involving a healthy 3-year-old child weighing approximately 14 kg. The child stood on the platform and attempted to maintain balance while the tilt angle varied. As expected, the child adapted his foot pressure depending on the direction of the tilt.

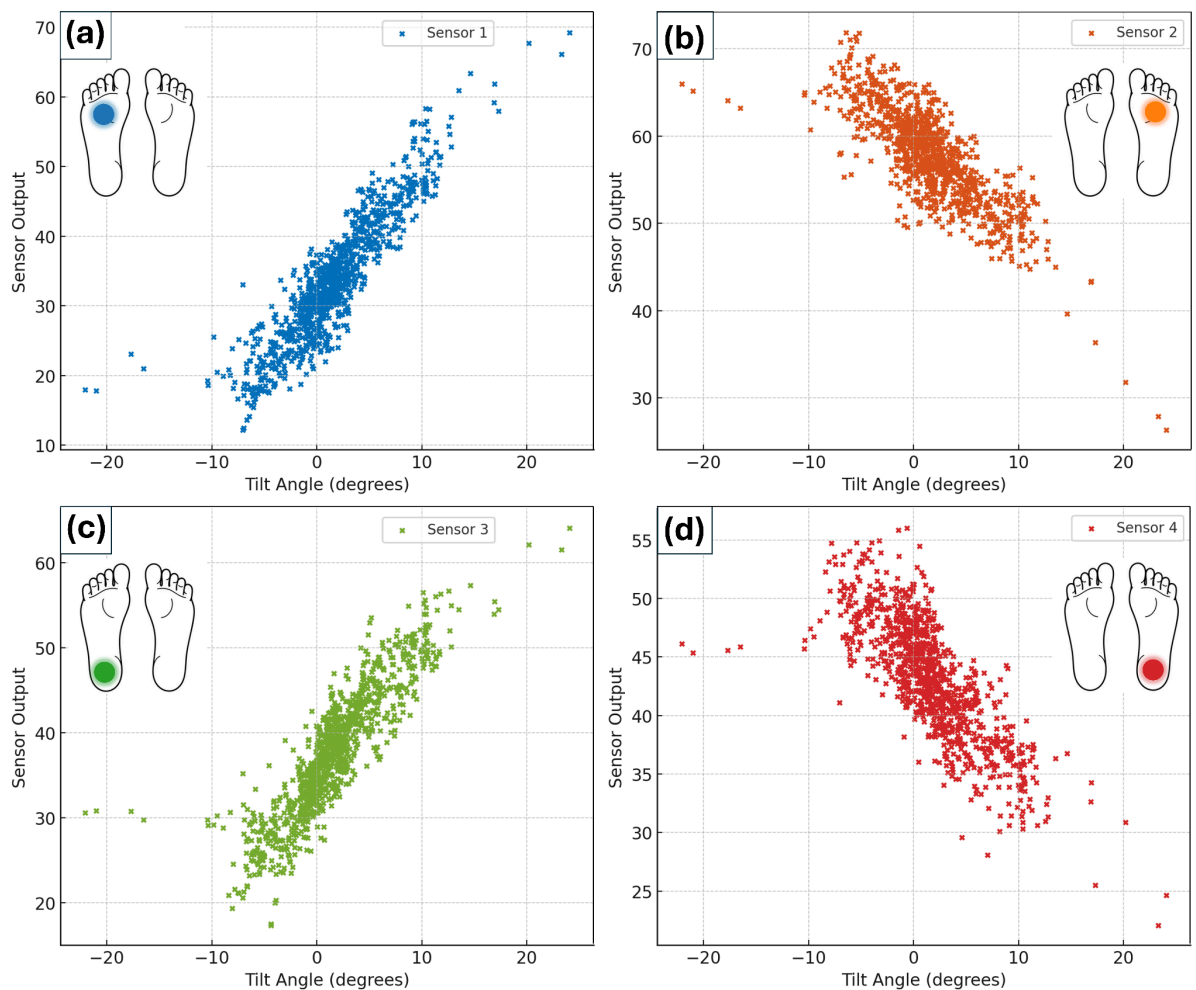
As shown in **Figure 15**, when the platform tilted to the right (positive tilt angle), the child instinctively applied more pressure on his left leg to counterbalance the movement. This behavior is reflected in the sensor outputs: at a  $15^{\circ}$  tilt, Sensor 1 (**Figure 15a**) reached around 60 units, and Sensor 3 (**Figure 15c**) reached about 55 units. Meanwhile, the right-side sensors (**Figure 15b, d**) recorded lower outputs at the same angle. Conversely, when the platform tilted to the left (negative tilt angle), the child shifted more pressure onto his right leg. At just  $-10^{\circ}$ , Sensor 2 (front right) reached around 65 units, while Sensor 4 (back right) was around 55 units. This stronger pressure response on the right side compared

to the left is because the child found it slightly more difficult to balance when tilting left during the test, resulting in more platform oscillations. These results clearly align with the expected behavior shown in **Figure 14**. The figure confirms a strong relationship between tilt angle and foot pressure adjustments, supporting the platform's ability to track balancing in real time.

This video demonstrates the child's balancing behavior on the platform:

[https://drive.google.com/file/d/1slk7vGDesstlP4Cu6vNIhMflu8NT6D\\_G/view?usp=sharing](https://drive.google.com/file/d/1slk7vGDesstlP4Cu6vNIhMflu8NT6D_G/view?usp=sharing)

This case study demonstrates that the platform can successfully capture force distribution patterns during balancing and detecting irregularities. It shows potential for future studies comparing neurotypical children with children on the autism spectrum. By identifying specific balance strategies and unique pressure patterns, this system could become a useful tool for early detection and personalized rehabilitation strategies for individuals with sensory and motor challenges.



**Figure 15.** Balancing pattern of a 3-year-old child: Sensor outputs vs Tilt angle (a) left metatarsal, (b) right metatarsal, (c) left heel and (d) right heel.

## 5 Conclusion

Children with ASD can benefit significantly from therapies aimed at improving motor skills, speech development, and overall engagement. However, many existing rehabilitation devices fall short due to their lack of real-time data collection, dynamic interaction, and feedback capabilities, which limits their usefulness in therapy. This project addresses these problems by developing piezoelectric sensors for integration into a robotic platform designed to support ASD rehabilitation.

The final sensor design consisted of a 1 mm PVDF film with carbon cloth electrodes adhered using silver paste and protected by Kapton tape. This configuration delivered stable output voltages up to 150 mV, combining high sensitivity, mechanical flexibility, and long-term durability. The protective Kapton layer maintained consistent piezoelectric performance while avoiding triboelectric interference.

For real-time data acquisition, the sensors were integrated into an Arduino-based system. Initial noise challenges were addressed through a combination of shielding techniques, including aluminum foil wrapping and resin insulation, as well as circuit optimization. The introduction of a 7.5 M $\Omega$  resistor significantly stabilized the output signal by filtering high-frequency noise, enabling cleaner analog readings.

The gathered data demonstrated a strong relationship between angular displacement and foot pressure distribution. Additionally, prior testing confirmed a linear correlation between the applied force and the sensor output, enabling direct estimation of the force exerted at each angle. Using this relationship, the sensor readings can be converted to approximate force values, allowing the generation of a force vs. roll angle plot. Since the output-to-force relationship is linear, the measured voltage can be directly interpreted as applied force, simplifying real-time analysis. This data was applied in a case study, where a subject was asked to freely balance on the platform. The sensor readings revealed moment-to-moment postural adjustments, highlighting points of instability, compensatory responses, and balance control strategies. **Figure 16** shows the updated Gantt chart of the project.

Altogether, the developed system provides a robust, self-powered platform capable of capturing biomechanical data. It offers an adaptable and low-maintenance solution for individualized rehabilitation in ASD, paving the way for data-driven therapeutic interventions and personalized motor training programs.



**Figure 16.** Gantt chart for “Self-powered sensor integrated platform for ASD rehabilitation”.

### 5.1 Future work and challenges

For future work, it will be important to apply for ethical approval earlier. During this project, one of the major challenges was obtaining approval from the Nazarbayev University Institutional Research Ethics Committee (NU IREC). Our application was rejected because they considered working with children, especially those with ASD, too complicated for a capstone project. As a result, we could not visit correction centers or collect real-world data from a wider group of children with ASD.

At the same time, efforts should be made to improve the sensors by making them more durable and better able to handle heavier loads. Other improvements could include adjusting the sensor placement, increasing the number of sensors, and improving signal filtering. Another important step would be to study balance behavior differences between

typically developing children and those with ASD to identify patterns that could support early intervention. Based on these findings, the long-term goal would be to create a set of balance exercises or interactive activities that use real-time sensor feedback, making rehabilitation more engaging and personalized.

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## Appendix A. Source Code.

### A1. Code for single sensor connection with arduino

```
// Constants
const int piezoPin = A0; // Analog pin connected to piezoelectric sensor
void setup() {
  Serial.begin(9600); // Initialize serial communication at 9600 baud
}
void loop() {
  int sensorValue = analogRead(piezoPin); // Read the analog value
  if (sensorValue > 5) { // Threshold to filter small noise
    Serial.println(sensorValue); // Print values only above noise level
  }
  delay(10); // Short delay for stability
}
```

### A2. Code for several sensor connection with arduino

```
// For two sensors in same graph
const int piezoPin1 = A0; // Analog pin connected to the first piezoelectric sensor
const int piezoPin2 = A1; // Analog pin connected to the second piezoelectric sensor
void setup() {
  Serial.begin(9600); // Initialize serial communication
}
void loop() {
  // Read raw analog values from both sensors
  int sensorValue1 = analogRead(piezoPin1);
  int sensorValue2 = analogRead(piezoPin2);
  // Print the values to the Serial Monitor
  Serial.print("Sensor 1: ");
  Serial.print(sensorValue1);
  Serial.print(" Sensor 2: ");
  Serial.println(sensorValue2);

  delay(10); // Small delay for real-time plotting
}
```

### A3. Code for saving data from arduino using python

```
import serial
import csv
from datetime import datetime
PORT = 'COM3'
BAUD_RATE = 9600
OUTPUT_FILE = 'sensor_time_data.csv'
try:
    ser = serial.Serial(PORT, BAUD_RATE, timeout=1)
    print(f"Connected to {PORT} at speed {BAUD_RATE} bod.")
except Exception as e:
    print(f"Ошибка: {e}")
    exit()
with open(OUTPUT_FILE, 'w', newline="", encoding='utf-8') as csvfile:
    writer = csv.writer(csvfile, delimiter=',')
    writer.writerow(['Time', 'Sensor Data'])
    print("Data collection... Press Ctrl+C to stop.")
    try:
        while True:
            if ser.in_waiting > 0:
                line = ser.readline().decode('utf-8').strip()
                if line:
                    time_only = datetime.now().strftime('%H:%M:%S.%f')[:-5]
                    writer.writerow([time_only, line])
                    print(f"Time: {time_only}, Data: {line}")
```

```
except KeyboardInterrupt:
    print("\nData collection is stopped by the user.")
except Exception as e:
    print(f"Mistake: {e}")
finally:
    ser.close()
    print(f>Data is save in file: {OUTPUT_FILE}.)
```