

A Consumer-Grade IMU-Based System for Visualizing and Quantifying Finger Independence in Piano Training

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Abstract—This paper presents a low-cost sensor-based system to visualize and quantify involuntary finger motion during piano training. By utilizing five MPU6500 6-axis IMUs on each finger and an ESP32 microcontroller, we collect motion data while trained users press keys with either the thumb or pinky. We calculate total angular velocity to analyze and detect crosstalk between fingers. Our results show that even experienced pianists exhibit subtle involuntary finger movements, which can now be visualized and used for learning and corrective feedback.

Keywords—Finger independence, Crosstalk motion, Inertial measurement unit (IMU), ESP32, Piano biomechanics

I. INTRODUCTION

Finger independence plays a critical role in both keyboard instrument training and hand rehabilitation. Skilled piano performance requires the ability to isolate and control each finger with high precision, while rehabilitation demands similar neuromuscular control to restore functional hand movement. However, developing such fine motor control is inherently difficult due to the complex anatomical and neurological interconnections among the fingers [1-4].

Anatomically, fingers share flexor and extensor tendons, particularly between the ring and middle fingers, which limits their ability to move entirely independently. Neurologically, overlapping motor neuron pools and cortical representation in the brain also contribute to involuntary co-activation of adjacent fingers. As a result, even well-trained musicians may exhibit subtle, unintended finger movements—commonly referred to as “crosstalk”—during isolated finger actions such as pressing a single piano key [5-7].

For beginners and even experienced users, these involuntary movements are difficult to perceive and correct without direct feedback. Traditional teaching methods or self-practice may not offer enough resolution to reveal these micro-movements, limiting the effectiveness of finger independence training.

To address this challenge, we present a low-cost, consumer-grade sensing system built on the ESP32 microcontroller and MPU6500 6-axis IMU sensors (Fig.1). The system tracks motion data from all five fingers in real time and provides clear, time-synchronized visualizations of both linear acceleration and angular velocity. Most importantly, we focus on analyzing unintended movements in non-target fingers during specific motion tasks—namely, when the thumb or pinky is actively pressing a piano key.

By visualizing and quantifying finger crosstalk, our system enables both learners and instructors to better understand fine motor control performance. The approach provides a new pathway to improve finger independence through data-driven feedback and targeted training strategies.

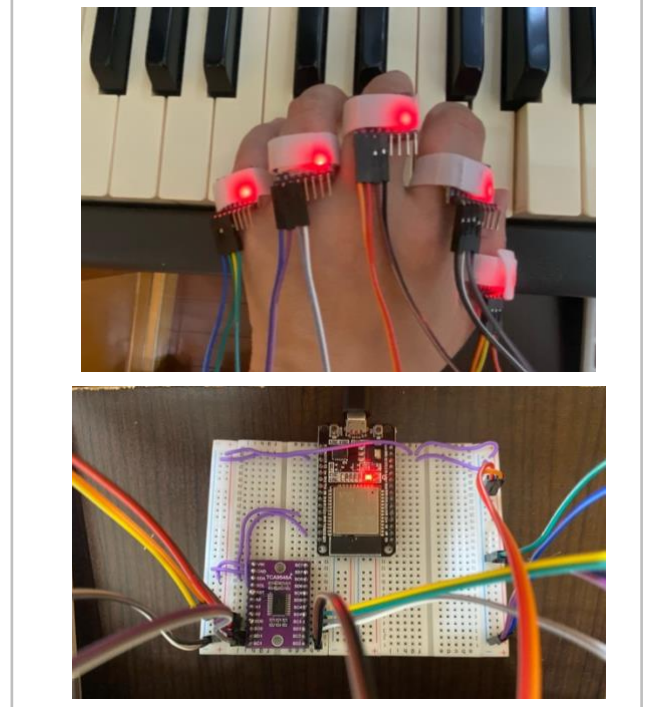


Fig. 1. The ESP32 and MPU6500 module in use

II. SYSTEM DESIGN

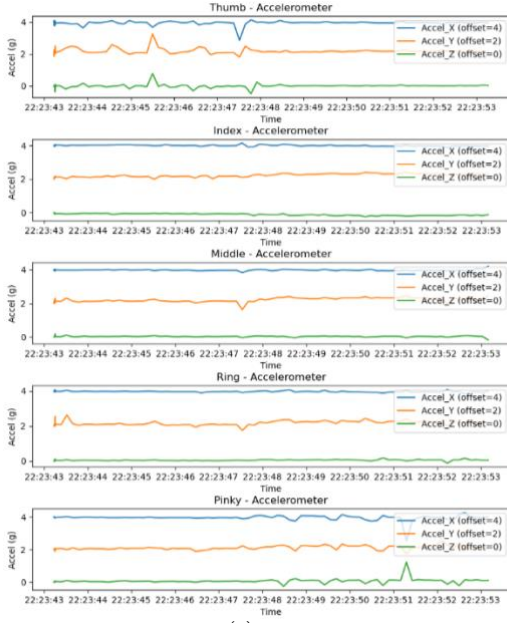
To capture fine-grained finger motion in a cost-effective and scalable manner, we developed a sensing system based on the ESP32 microcontroller and five MPU6500 inertial measurement units (IMUs), each combining a three-axis accelerometer and a three-axis gyroscope. One sensor is securely mounted on the distal phalanx of each finger on the left hand (thumb, index, middle, ring, and pinky), enabling individual tracking of linear acceleration and angular velocity across all six axes.

The ESP32 board serves as the central data acquisition unit. It polls each MPU6500 sensor via I²C multiplexing, ensuring synchronized data sampling across all five fingers. The sampling rate is set to 100 Hz to capture sufficient temporal resolution for detecting short, rapid finger movements commonly observed during piano performance.

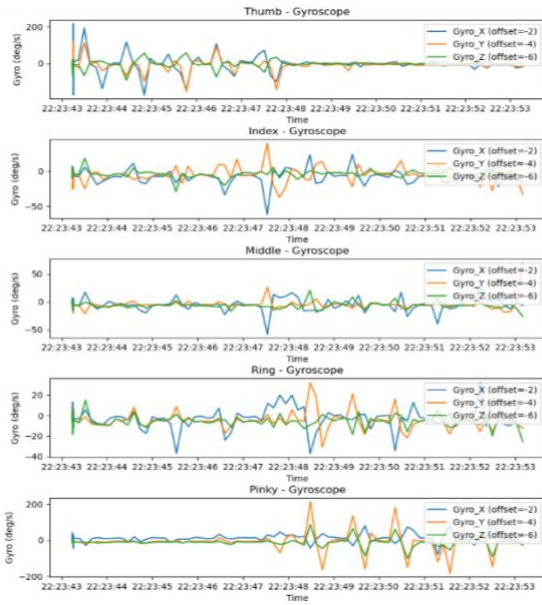
Each sensor's data includes three channels for acceleration (X, Y, Z in g units) and three channels for gyroscope readings (X, Y, Z in degrees per second).

All data are transmitted in real time through a serial USB connection to a Python-based host computer. A custom script decodes incoming serial data, timestamps each packet, and logs the results to a structured data frame. This data is then saved to an Excel file for further analysis, including offset calibration, visual plotting, and inter-finger comparison.

The system also includes a live preview plotting interface that provides instant visual feedback during data collection (Fig.2), assisting both users and researchers in confirming sensor functionality and recording quality. By employing low-cost, off-the-shelf components and an open Python software stack, the system is both accessible and extensible for broader applications in music training, motor control studies, or rehabilitation scenarios.



(a)



(b)

Fig. 2. Live preview plotting interfaces: (a) accelerometer, (b) gyroscope.

III. EXPERIMENT SETUP

To evaluate finger independence and detect crosstalk motion, we designed a targeted experiment simulating a common piano training task. A single subject with over ten years of classical piano training was instructed to place their left hand over a keyboard in a natural curved posture, as if prepared to play.

The experiment was divided into two five-second segments within a 10-second data capture window. In the first segment, the subject was asked to press a single piano key five times using only the thumb. In the second segment, the task was repeated using only the pinky finger. All other fingers were instructed to remain relaxed and stationary. This design isolates the thumb and pinky—both anatomically unique and more independent—and allows for observation of involuntary responses in the remaining fingers.

Data were recorded continuously across all six axes for each of the five fingers, producing a synchronized motion profile for the entire hand..

IV. SIGNAL PROCESSING AND VISUALIZATION

Prior to visualization, the raw sensor data underwent baseline offset calibration. The initial sensor readings were subtracted from subsequent data to normalize each axis to a zero-reference starting point, eliminating minor bias due to sensor alignment or resting tension.

To quantify rotational activity, as shown in (1), the system computed a combined angular velocity magnitude—referred to as $Gyro_Total$ —for each finger at each time point:

$$Gyro_Total = \sqrt{GyroX^2 + GyroY^2 + GyroZ^2} \quad (1)$$

These values were plotted over time, with color-coded lines for each finger. The result was a clear visual representation of which fingers exhibited active movement and when.

To detect micro-movements (indicative of crosstalk), we defined a threshold of 20 deg/s. Any non-target finger exceeding this threshold during the active phase of the thumb or pinky was flagged as exhibiting involuntary motion. A reporting module calculated three indicators per non-active finger: the number of threshold-exceeding events (Micro-movement Count), the average $Gyro_Total$ during those events, and the maximum angular velocity observed (Fig.3).

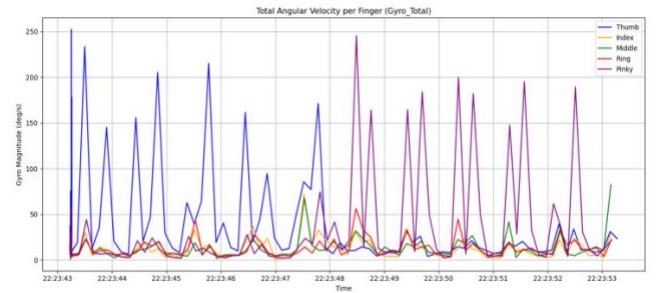


Fig. 3. $Gyro_Total$ per finger

V. RESULTS AND DISCUSSION

The visualization and analytics confirmed the presence of finger crosstalk, even in a highly trained subject (Fig. 4).

During the thumb activity phase (0–5 seconds), the ring and middle fingers exhibited repeated, measurable involuntary motion, with the ring finger showing the highest Micro-movement Count. During the pinky activity phase (5–10 seconds), not only the ring and middle fingers but also the thumb and index fingers displayed elevated angular velocity, suggesting broad inter-finger influence when the pinky is engaged.

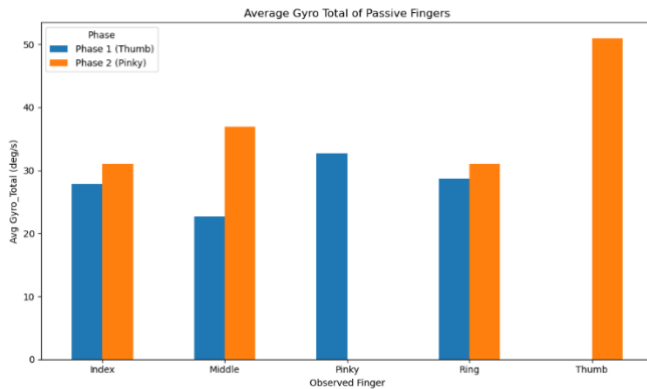


Fig. 4. crosstalk visualization

These results align with physiological expectations. The flexor and extensor tendons controlling the ring and pinky fingers are partially shared, making them especially prone to synchronized movement. Neurological crosstalk due to overlapping cortical representation and shared motor units further contributes to involuntary activation.

Importantly, these subtle motions would likely go unnoticed by the naked eye. The proposed system provides a new capability to objectively assess finger independence, helping musicians identify and reduce unwanted motion during targeted training.

VI. CONCLUSIONS AND FUTURE WORK

This paper presents a practical and affordable system for analyzing finger independence through real-time motion

tracking and visualization. By integrating low-cost IMU sensors with a consumer microcontroller and Python-based analysis tools, we demonstrate that even subtle involuntary movements can be visualized, quantified, and used as training feedback. Our findings confirm that even experienced pianists are subject to finger crosstalk, particularly when engaging the thumb or pinky. The system's ability to detect and report such motion offers a valuable tool for both learners and educators.

Future developments will include: (1) Expanding to bilateral (both-hand) analysis, (2) Applying machine learning to automatically classify motion patterns, (3) Integrating real-time feedback via visual or audio alerts, and (4) Conducting longitudinal studies to measure training impact over time. This platform has strong potential in music education, fine motor skill research, and rehabilitation domains.

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