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PAPER

Modification of an IMU Based System for Analyzing Hand Kinematics During Activities of Daily Living

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ABSTRACT

The hand of a human being is the most commonly utilized body part in daily activities. Assessing the functional capability is highly challenging and important in medical applications purposes. This research aims to design and implement a sensor-based system for function assessment and movements analysis of the hand by calculating the angular velocity, acceleration and magnetic field for the joints of the fingers during the daily activities. The proposed system was applied to two groups of volunteers: The first group consisted of seven males, whereas the second group consisted of seven females, and the results were taken by calculating the acceleration, angular velocity, magnetic field during activities of daily living (ADL). This study showed the system is important in hand movement and control function evaluation. The thumb and index fingers have similar pitch orientations while interacting, while the middle finger employs a distinct range. Yaw variables are less noticeable, but the variation in roll angles between fingers is.

KEYWORDS

activities of daily living, hand kinematics, IMU, yaw- pitch and roll

1 INTRODUCTION

Hand kinematics is significant in a variety of contexts, including rehabilitation, athletics, ergonomics, and the animation industry. For kinematic evaluation in real-world situations, ambulatory monitoring of the entire hand configuration is particularly useful [1]. The ability of the human hand to grasp and move objects is critical for the development of activities of daily living (ADL) [2]. The hand's kinematic and muscular complexity, with over 25 degrees of freedom (DoF), is influenced by greater than 38 muscles, ligaments, and tendons [3]. The World Health Organization (WHO) estimates that 15 million people have strokes each year, with approximately two out of every three of these people surviving the stroke and requiring some form of motor rehabilitation [4]. Monitoring hand kinematics is required in medical domains such as rehabilitation and hand functionality assessment [5]. Physicians can properly detect the healing process in stroke patients' hands by collecting hand kinematics. As a result, in the rehabilitation field,

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a practical and reliable device capable of capturing multiple hand movement characteristics is needed [6]. In recent years, a large range of technology-assisted techniques to upper limb evaluation have been documented [7]. There are two types of hand capture systems on the market today: camera-based systems and datagloves. Although these approaches are useful for measuring hand kinematics, they have several drawbacks in terms of accuracy [8]. Camera-based systems may track hand curves or be directed by markers placed at the joints of the fingers [9]. The primary disadvantage of camera-based systems is that readings can only be taken in the volume where the cameras are located. A wide variety of hand-worn sensing equipment, including datagloves, is worn [10]. Their methods for gathering kinematic data are different. Sensors based on a resistive bend and optical fiber are two widely used sensing techniques, with the latter providing the best accuracy. Both systems have drawbacks relating to the sensor location. Both assess the relative orientation of articulating segments by placing the sensor at the joint of interest [11]. The instrumented gloves with inertial and magnetic measurement systems (IMMS) have been shown to be precise in establishing the positions of body segments without the need for additional sensors or cameras [12]. The suggested system develops a system for measuring and analyzing hand function. The system consists of five inertial measurement unit sensors. The sensors were connected to the microcontroller, and the electrical components were connected to each other. These sensors assess and analyze hand movement during the activity of daily living (ADL). This can be done by achieving the objectives that follow:

- Implement the electronic system by using the hardware components IMU sensor (Gyroscope, triaxial accelerometer, magnetometer), microcontroller, and software programming.
- Apply the proposed system to a group of volunteers to assess and analyze the kinematics of their hand movements during daily activities.
- Collect data in Excel program.

Several items have previously been developed for hand function assessment and analysis. In the last few years, many technologically assisted methods for assessing the upper limb have been reported in the literature. There are reviews that provide overviews of quantitative assessment tools that have been used on a specific population of people with upper-limb problems. In (2012) Ninja P Oess, et al. [13], designed a low-cost instrumented glove that may be utilized to measure hand function in clinical settings and rehabilitation situations. Four individuals who had impaired hand function as a result of a cervical spinal cord injury (cSCI) were tested to see if the glove was viable for real-life use. The results showed that the glove's dependability was evaluated and gave high values for the ICC (0.84 to 0.92) and a precision error of about +5°. In (2014) Henk G Kortier, et al. [14] evaluated hand function by assessing hand kinematics. A 3D reconstruction of finger and thumb joints has been proposed. Inertial sensors attached to the hand, fingers, and thumb used to create an accurate 3D model of the hand for use with prosthetics and other medical equipment. In this study, five healthy male volunteers with no known hand conditions, ranging in age from 21 to 53, took part. In regard to static precision, dynamic range, and repeatability, this study found that IMMS are relevant for ambulatory assessment of human finger and hand kinematics when compared to current data gloves. It enables low-cost sensors to estimate multi-degree-of-freedom joint motions. In (2018) Bor-Shing Lin, et al. [15] offered a system of modular data gloves for capturing hand kinematics correctly and reliably. A motion-capture board (MCB), five flexible finger units (FFUs), an arm board, and a host system were included in the development of the device.

The outcome demonstrated that the data glove was very well received by the participants. In (2019) Christina Salchow-Hömmen, et al. [16], designed hand neuroproteins with the hand sensor system integrated as part of a feedback-controlled device for patients with hand motor impairments. The base unit on the posterior of the hand, the forearm wireless IMU, and five or more sensor strips with three IMUs each made up the system. The findings of the research were that the acquired accuracy (RMSE about 1 cm) is enough for the neuroproteins' control. The researchers used the suggested hand sensor method specifically to locate the best stimulation locations in electrode arrays. In (2019) Angel Cardenas, et al. [17], constructed a wearable device for intention detection and quality evaluation to help people involved in the rehabilitation of extremity motion. The researchers created a glove-based system in which inertial measurement unit (IMU) sensors work in tandem with flexible sensors to reduce the number of IMU sensors. Using a fuzzy logic data analysis technique improved the system's categorization capabilities. The hand may be thought of as an open kinematic chain that begins at the wrist joint and ends at the finger joints [18]. A total of 27 degrees of freedom (DoFs) are involved in the mechanism of the hand, including 2 DoFs at the wrist and 25 DoFs on the linkages between the fingers [19]. Most hand functions are represented by six categories of movements: an opposing pinch, a spherical (span) grip, a hook (or snap), and a palmar grab (also called as a tip or precision pinch, a lateral (key) pinch) [20]. The kinematics of human hand movements may be tracked and studied using a variety of techniques, including Kinect system, optical motion capture and instrumented data gloves [21].

2 METHOD

The proposed system, which connects all of its components, was created to account for technical advancements with respect to the instrumented glove. The development of the system was to record hand movements during ADL. Five inertial measurement unit sensors, and LCD monitor were all included in the electrical circuit and all of them were connected to the microcontroller to process the system. The suggested system was used to assess and analyze hand movements by using five IMU sensors positioned on the rings around fingers. Additionally, an LCD monitor was used to display the output of sensors, and the SD card module saved and processed this data. Using a microcontroller, these components and the input/output (I/O) modules were made accessible. The system was powered by a mini UPS-PoE power source and a lithium battery. The output voltage is switched between 3.3 and 5 volts DC for the (IMU) and it is arranged via a voltage regulator. The suggested system's block diagram is shown in Figure 1 and the flowchart of experiment work shown in Figure 2.

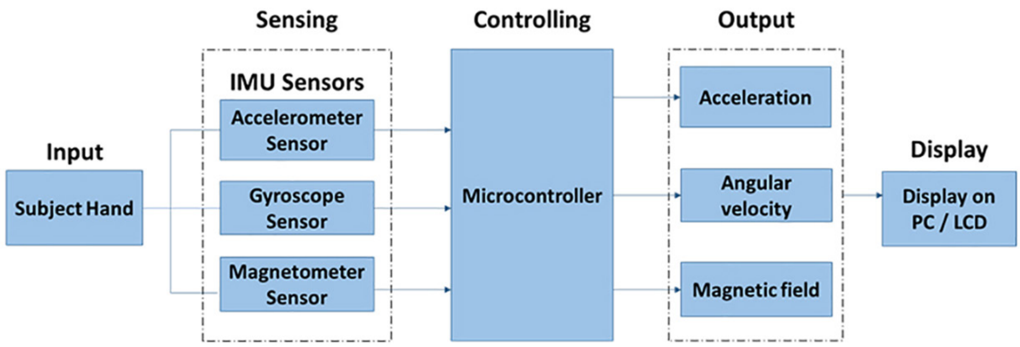

Fig. 1. Suggested system block diagram

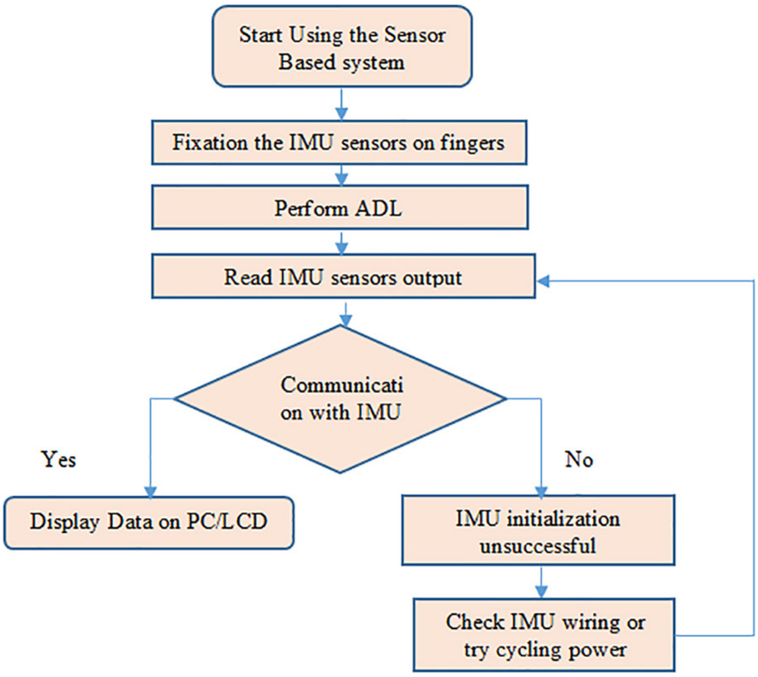

Fig. 2. Flowchart of experiment work

3 THE PARTICIPANTS

This study included fourteen volunteers who provided written informed permission after being approved by the Research Ethics Committee of Al-Nahrain University's Biomedical Engineering Department. The individuals who participated had been divided into two distinct groups based on their gender, with Group A being the first group with seven males with a mean age of 35.14 ± 6.5 years, a mean height of 178.57 ± 7.3 cm, and a mean weight of 90.57 ± 12 kg. Even so, in contrast, the opposing group (Group B) was seven females, with a mean age of 34.28 ± 8.5 years, a mean height of 165.71 ± 6.3 cm, and a mean weight of 65.14 ± 12.8 kg. Demographic information of volunteers is listed below in Table 1.

Table 1. Demographic information of volunteers

Subjects	Age (Year)	Height (cm)	Weight (kg)	BMI $\left(\frac{kg}{m^2}\right)$
Group A (Male)				
Case 1	25	173	75	25.1
Case 2	28	172	80	27
Case 3	35	180	92	28.4
Case 4	42	190	105	29.1
Case 5	45	188	98	27.7
Case 6	34	170	106	36.7
Case 7	37	177	78	24.9
The Mean	35.14 ± 6	178.57 ± 7.3	90.57 ± 12	28.41 ± 3

(Continued)

Table 1. Demographic information of volunteers *(Continued)*

Subjects	Age (Year)	Height (cm)	Weight (kg)	BMI $\left(\frac{kg}{m^2}\right)$
Group B (Female)				
Case 8	29	158	50	20
Case 9	22	160	48	18.8
Case 10	38	165	70	25.7
Case 11	33	175	85	27.8
Case 12	43	175	77	25.1
Case 13	48	165	68	25
Case 14	27	162	58	22.1
The Mean	34.28 ± 8	165.71 ± 6.3	65.14 ± 12.8	23.5 ± 3

4 HARDWARE DESIGN

The circuit components were connected to achieve the desired function of each one. The suggested system's electrical circuit is shown in a schematic diagram of the system in Figure 3. Each component's construction, purpose, and interface with the microcontroller have all been covered. Figure 4 illustrates the main hardware elements. Also, software is integrated into the hardware system, which is a component of the whole system.

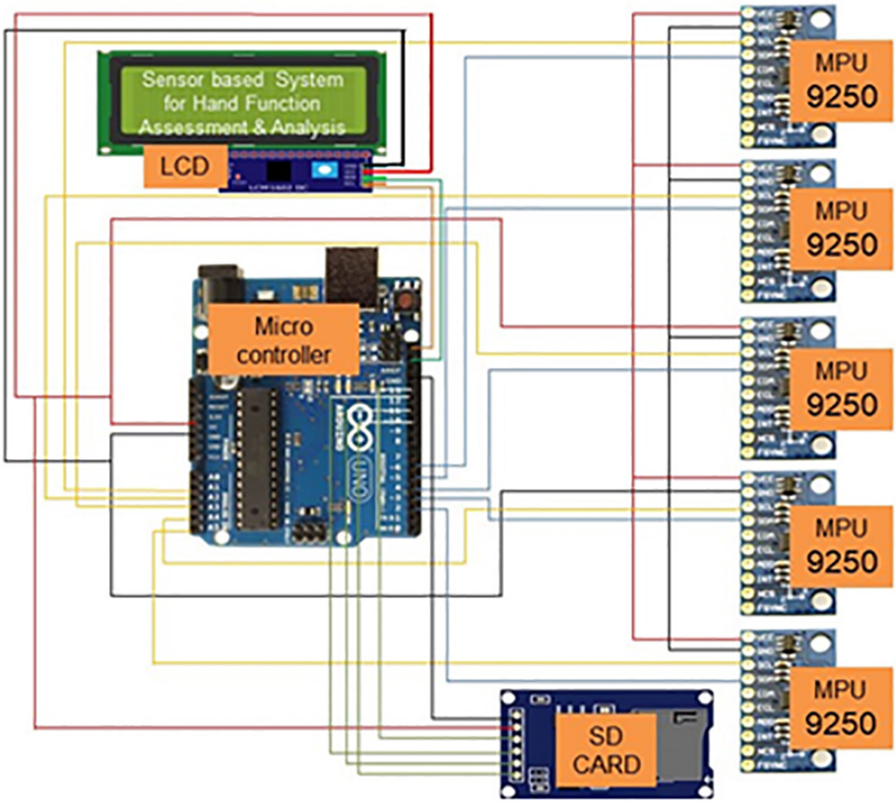

Fig. 3. The system's schematic diagram

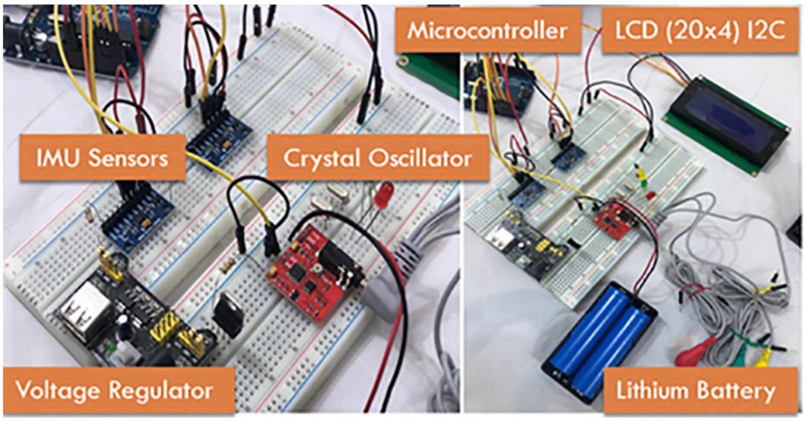

Fig. 4. Hardware components for the proposed system

4.1 Inertial measurement unit (IMU) MPU9250 sensor

The MPU-9250 has Gyroscope, accelerometer, and magnetometer outputs which are all digitalized using nine 16-bit analog-to-digital converters (ADCs) [22]. In this research, five IMU sensors were used and connected to an Arduino, and they were fixed on a flexible ring of variable diameter, where each sensor was placed on a finger between the metacarpophalangeal joints (MCP) and proximal interphalangeal joint (PIP) as shown in Figure 5. This IMU sensor contains ten pins, only four of which were used to connect to the microcontroller. VCC was connected to (+5V) in Arduino via a red cable, GND was always connected to GND via a black cable, and SCL and SDA were connected to one of the analog pins on the Arduino board. The schematic diagram of IMU sensor with Arduino circuit was done using a web-based diagramming Smart-Draw application as shown in Figure 6.

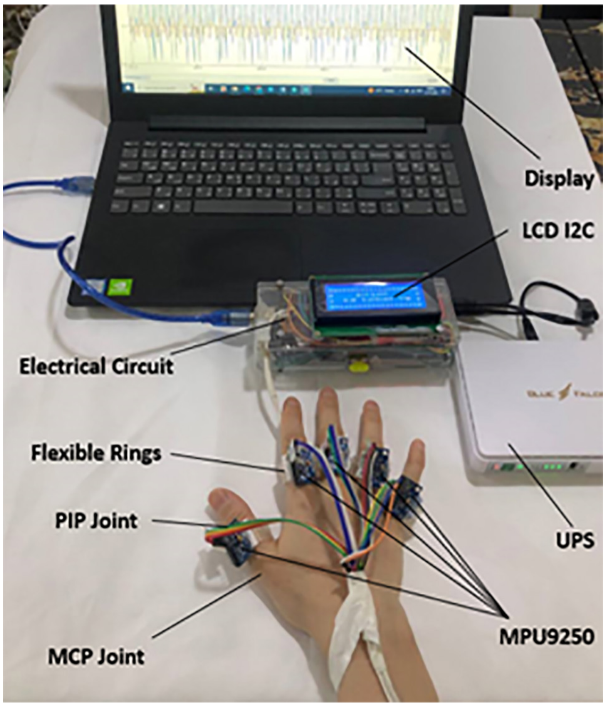

Fig. 5. Proposed system design

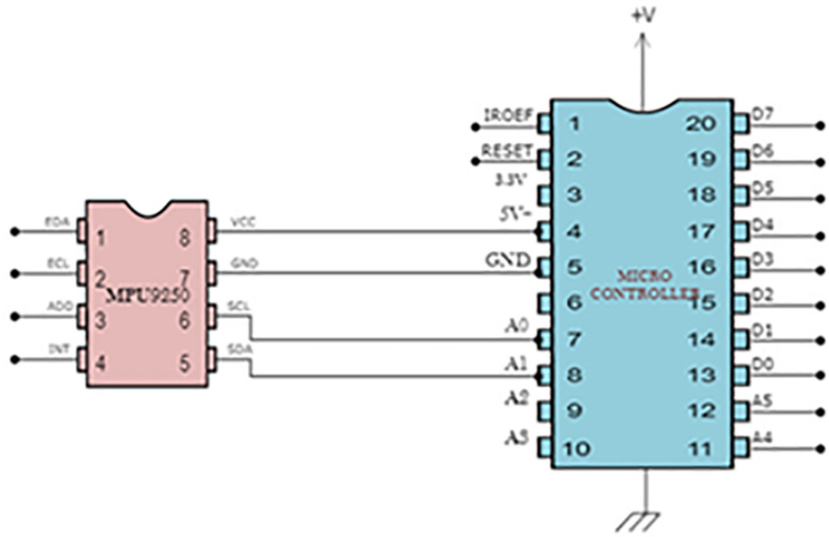

Fig. 6. The schematic diagram of IMU sensor with Arduino circuit

4.2 I2C (20 × 4) LCD display module

In the proposed system, an I2C LCD module was used as an output display to show the output from the sensors (IMU sensors). I2C interference LCD display module has 4 pins (VCC, SCL, SDA, and GND). First, to test the LCD, the LCD and Arduino microcontroller circuit was connected by connecting the VCC pin of the I2C LCD display module to the 5V pin of the Arduino microcontroller, the SCL pin of the I2C LCD to the Arduino's D1 pin, the SDA pin to the Arduino's D0 pin, and always the GND pin to the GND pin [23]. The schematic diagram of I2C LCD with Arduino was done by using a web-based diagramming Smart-Draw application as shown in Figure 7.

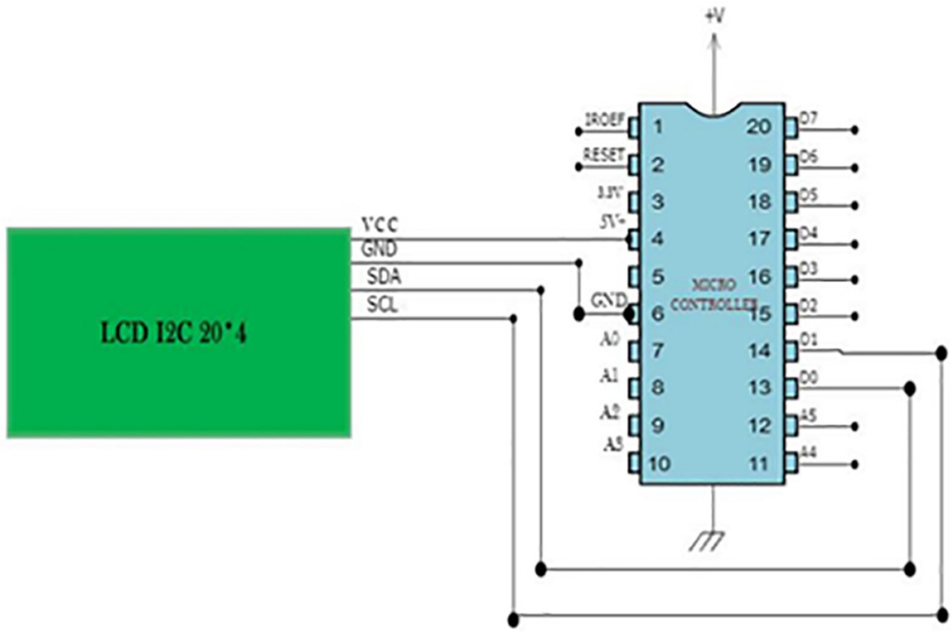

Fig. 7. The interfacing of I2C LCD with Arduino

4.3 Data storage system

The suggested system utilized an SD card to store the output data of all sensors that were used in the system, and this helped to restore the information at any time needed [24]. The SD card pin was linked to Arduino microcontroller pins: the VCC pin was coupled to the 5V pin of the Arduino, the GND pin of the SD card adapter was coupled to the GND pin of the Arduino, the MISO pin coupled to the D2 pin, the MOSI pin was coupled to the D3 pin, the SCK pin coupled to the D4 pin, and the CS pin of the SD card coupled to the D5 pin of the Arduino. SD card module with microcontroller interface was done by using a web-based diagraming Smart-Draw application as shown in Figure 8.

4.4 Power source for the system

A mini-UPS-PoE power supply was used to power the system. It enables a voltage regulator to arrange the output voltage [25]. It maintains consistent operation for a long time to protect the system. Another type of power supplies used in this proposed system is a lithium battery used to power the IMU sensor. Because the IMU sensor operates at 3.3V, it accepts 5V from two lithium batteries held in a battery holder with a voltage regulator that reduces this voltage to 3.3V for each of the IMU sensors.

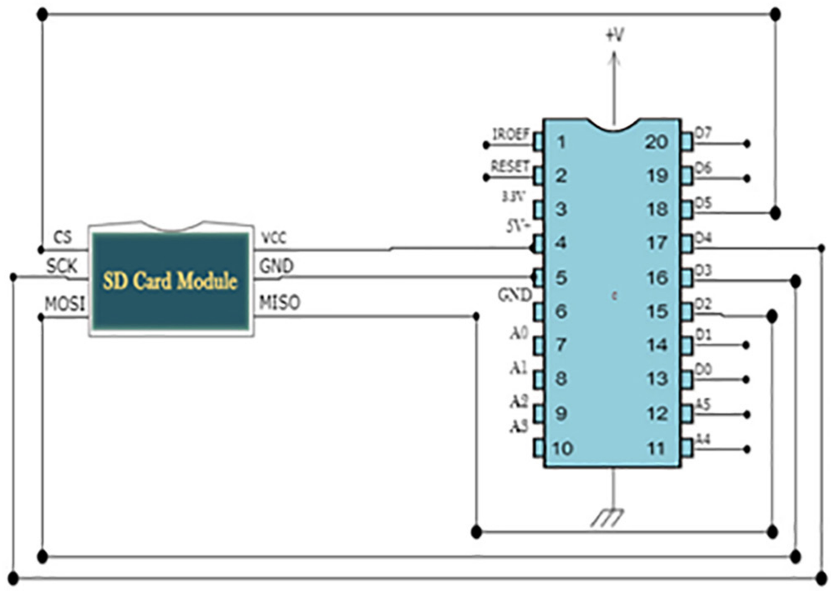

Fig. 8. SD card module with microcontroller interface

5 MEASUREMENT PARAMETERS

After completing the assembly of all the components of the system, it was tested on users to take the necessary steps on the volunteers for all movements through the ADL. The results were measured by calculating the magnetic field, angular velocity, and acceleration for each movement of the daily activities, and the most important of these movements included in this study are (Flexion of the thumb and fingers, drinking water, using a key to open a door, using a phone, using a pen to write) as shown in Figure 9.

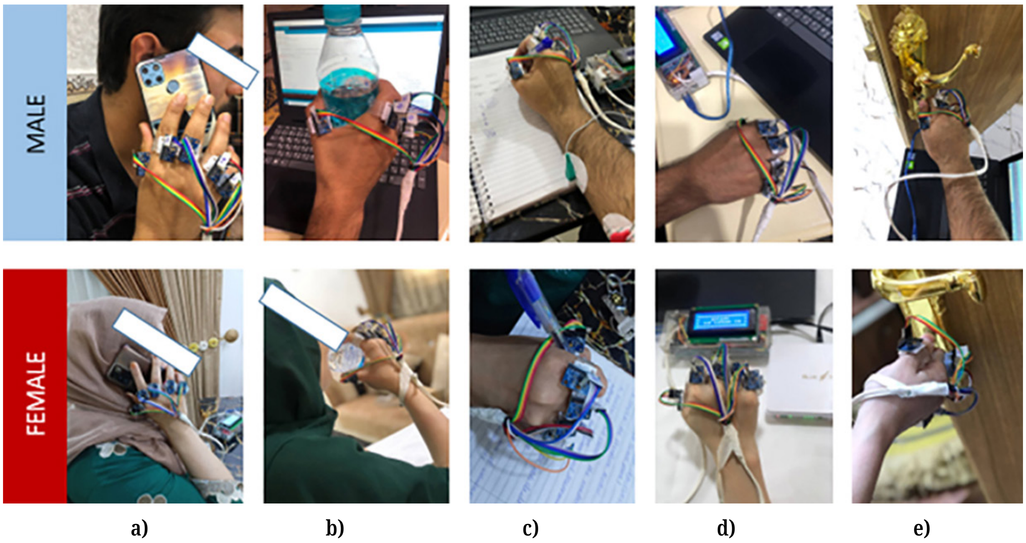

Fig. 9. Movements for ADL tasks. a: Using phone, b: Drinking water, c: Using pen, d: Flexion of fingers, e: Using keys to open a door

In addition, three angles were measured for each of those movements of ADL. The angles that are used to describe a finger's orientation are the same angles used to define airplane orientation as shown in Figure 10. Pitch, roll, and yaw are angles that revolve around the lateral, longitudinal, and vertical axes, respectively. The pitch of the finger describes the height at which the tip of one's finger points. The roll angle specifies the orientation of the palm of the hand. The yaw defines the direction in which the fingertip points [26].

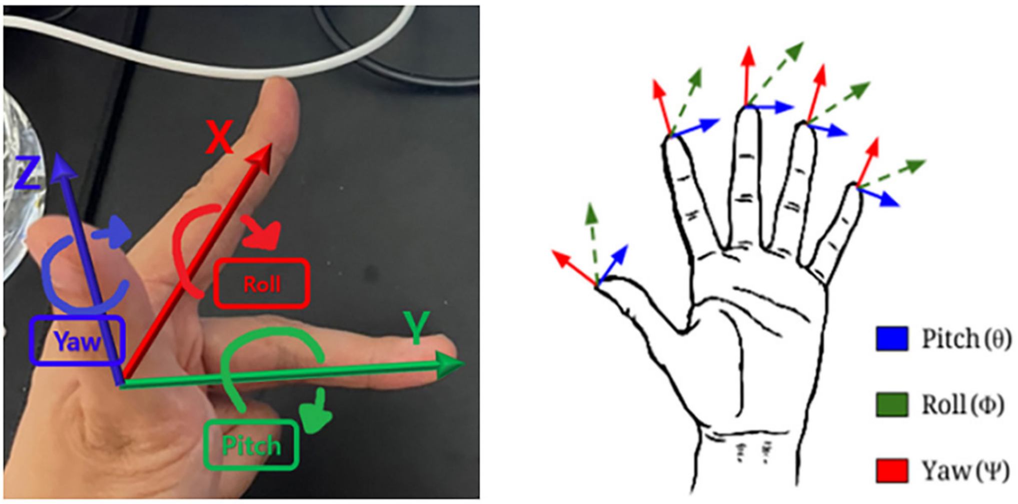

Fig. 10. Angles describing finger orientation (pitch, roll, and yaw) [27]

The inverse tangential of the acceleration (ACC) data can be used to compute pitch, roll, and yaw angles [27].

$$Pitch(\varphi) = \left(\frac{ACCx}{\sqrt{ACCy^2 + ACCz^2}} \right) \times \left(\frac{180}{\pi} \right) \tag{1}$$

$$Roll(\varphi) = \left(\frac{ACCy}{\sqrt{ACCx^2 + ACCz^2}} \right) \times \left(\frac{180}{\pi} \right) \quad (2)$$

$$Yaw(\psi) = \left(\frac{ACCz}{\sqrt{ACCx^2 + ACCy^2}} \right) \times \left(\frac{180}{\pi} \right) \quad (3)$$

Where:
ACCx: Acceleration in the x-axis.
ACCy: Acceleration in the y-axis.
ACCz: Acceleration in the z-axis.

The orientation of the thumb as well as index fingers in relation to the dorsal aspect of the hand was estimated using a magnetometer paired with an IMU sensor on the fingertip. The efficiency was shown in the experiment by performing several movement tasks. By integrating gyroscope data, it is possible to estimate how an orientation will vary over time. The area of gravity and geomagnetic field obtained by the accelerometer and magnetometer can adjust for movement. For intervals longer than a few seconds, the orientation cannot be reliably predicted. Drift problems, fortunately, may be remedied by combining data from magnetometers that measure the geomagnetic field. The geomagnetic field is thought to constitute a disturbance as shown in Figure 11, and magnetometers can be used to measure the comparative orientations of the magnet and fingertips. When it is possible to add more magnetometers, the magnets' size and strength may be reduced [28]. However, magnetometers should be properly separated from one another. The magnetometer's detected differential magnetometer field is substantially larger than the noise. The geomagnetic field's impacts can be reduced by using the gyroscope, accelerometer, and magnetometer together.

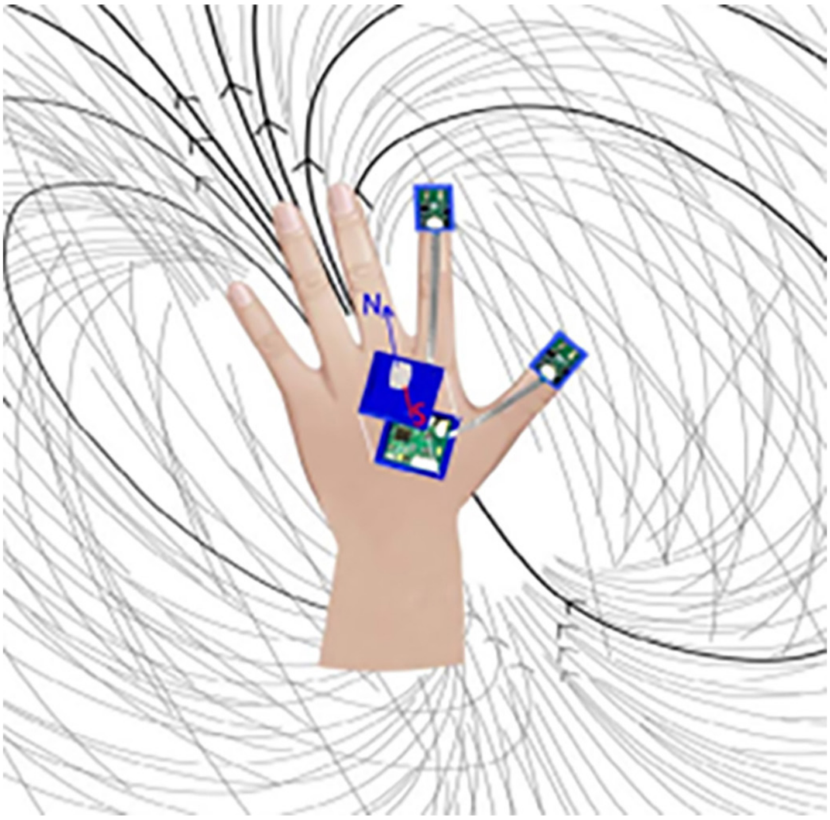

Fig. 11. Magnetic sensor-based estimation of hand-finger pose [28]

6 THE RESULTS

The results of flexion of fingers, drinking water, using a key to open a door, using a phone, and using a pen to write for the two groups was shown in Figures 12–16.

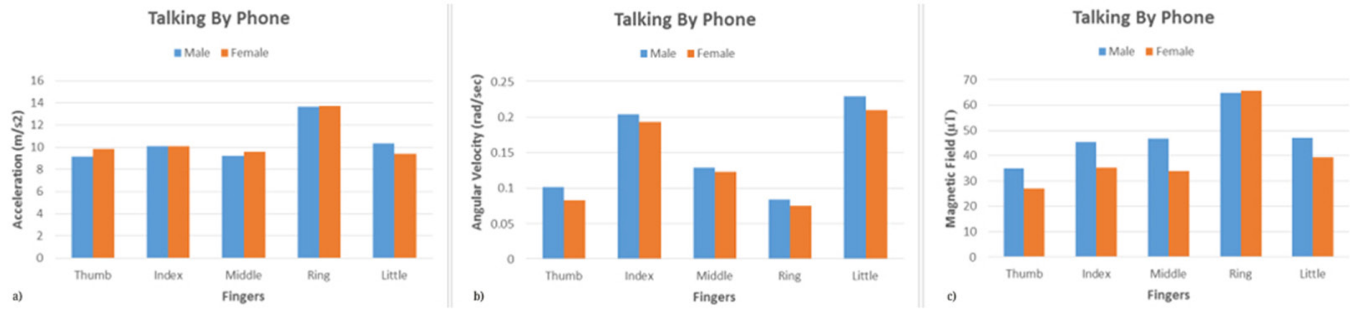

Fig. 12. (a) Acceleration, (b) Angular velocity (c) Magnetic field during talking by phone

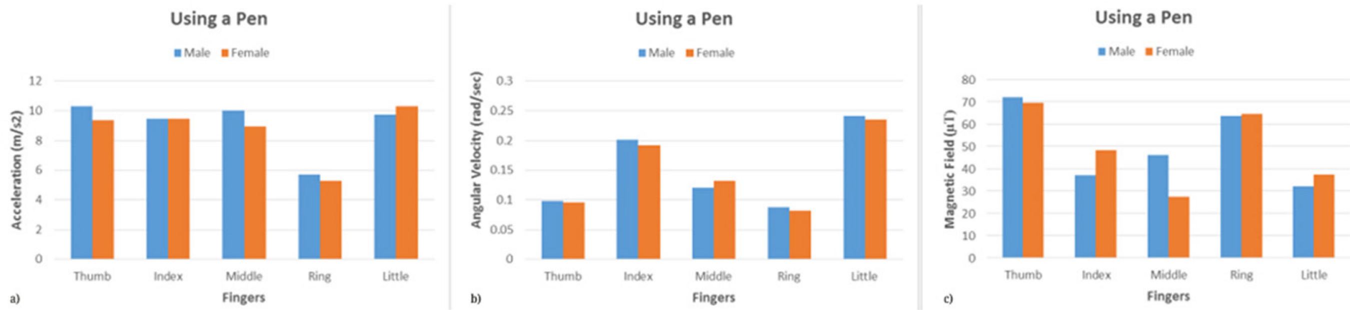

Fig. 13. (a) Acceleration, (b) Angular velocity (c) Magnetic field during using a pen

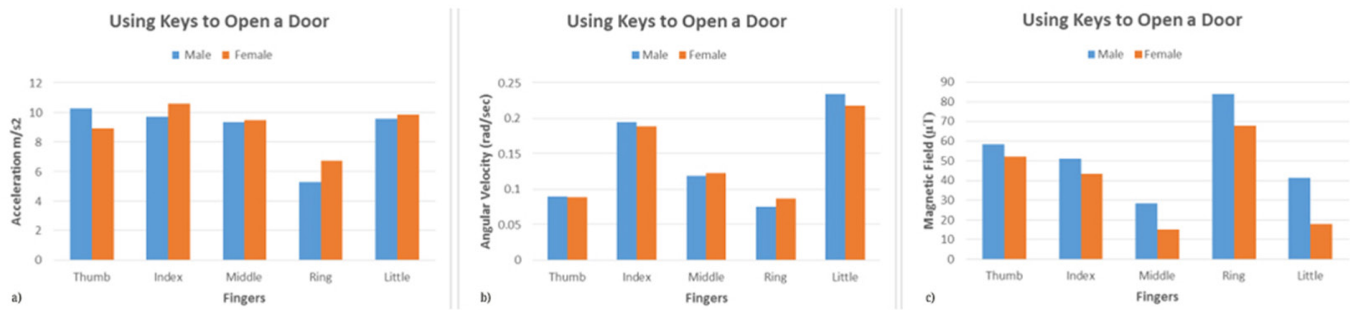

Fig. 14. (a) Acceleration, (b) Angular velocity (c) Magnetic field during using key to open a door

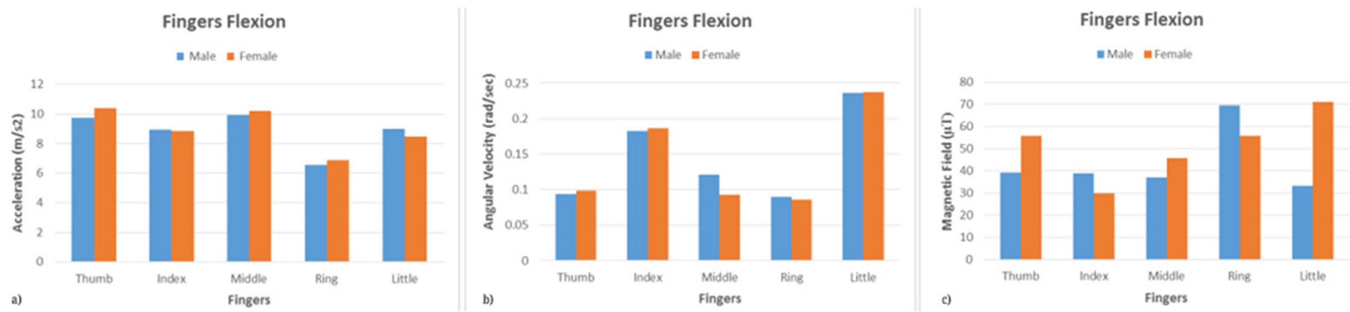

Fig. 15. (a) Acceleration, (b) Angular velocity (c) Magnetic field during fingers flexion

Fig. 16. (a) Acceleration, (b) Angular velocity (c) Magnetic field during drinking water

Recording the pitch, yaw, the roll angles of the fingers when interacting with normal daily tasks are explained in the following tables (see Tables 2–6) for the two groups.

Table 2. Mean angles for each finger during using phone

Fingers	Pitch (deg.)		Roll (deg.)		Yaw (deg.)	
	Male	Female	Male	Female	Male	Female
Thumb	68.28	63.54	21.03	26.2	–5.34	–3.7
Index	70.46	70.29	19.52	14.8	1.46	–12.77
Middle	71.29	83.47	5.45	–3.83	–17.88	–5.319
Ring	66.61	71.28	21.09	11.12	9.72	14.91
Little	43.52	54.57	–0.69	34.87	46.51	–5.65

Table 3. Mean angles for each finger during fingers flexion

Fingers	Pitch (deg.)		Roll (deg.)		Yaw (deg.)	
	Male	Female	Male	Female	Male	Female
Thumb	5.06	5.03	–23.39	–37.21	–66.04	–52.38
Index	–79.80	–78.47	–5.99	–7.18	8.27	9.02
Middle	–62.66	–72.97	–14.74	–9.38	22.52	–14.12
Ring	–60.08	–65.73	7.59	7.84	28.79	22.85
Little	–11.39	–17.74	70.79	57.33	–15.31	–26.5

Table 4. Mean angles for each finger during drinking water

Fingers	Pitch (deg.)		Roll (deg.)		Yaw (deg.)	
	Male	Female	Male	Female	Male	Female
Thumb	51.05	61.34	25.62	20.77	0.01	0.005
Index	55.37	58.29	27.45	21.44	–0.005	–0.006
Middle	56.87	59.55	20.8	14.72	–0.007	–0.007
Ring	60.2	53.03	28.1	29.92	0.002	0.005
Little	28.04	51.08	13.49	13.82	0.017	0.0108

Table 5. Mean angles for each finger during using a key to open a door

Fingers	Pitch (deg.)		Roll (deg.)		Yaw (deg.)	
	Male	Female	Male	Female	Male	Female
Thumb	17.22	17.77	–18.71	–22.05	–64.15	–61.1
Index	–18.45	–15.42	–43.13	–47.23	–41.16	–38.71
Middle	–22.34	–14.34	–48.99	–41.03	–32.37	–45.48
Ring	12.03	28.86	–39.73	–37.02	–47.79	–39.53
Little	13.94	33.34	48.41	19.675	–38.25	–49.91

Table 6. Mean angles for each finger during using a pen

Fingers	Pitch (deg.)		Roll (deg.)		Yaw (deg.)	
	Male	Female	Male	Female	Male	Female
Thumb	–14.1	–18.67	–24.49	–30.39	–0.018	–0.016
Index	–27.9	–18.05	–48.98	–56.81	–0.008	–0.008
Middle	–33.98	–19.96	–53.17	–57.22	–0.004	–0.008
Ring	–14.65	–15.84	–70.26	–66.02	–0.004	–0.005
Little	7.62	5.18	69.08	36.66	–0.006	–0.016

7 DISCUSSION

The study's findings give information and new perspectives on the user's fingers above and beyond their daily activities. For designers looking to create new forms of interaction that take input from finger orientation, a baseline study revealed whether there are appreciable variations in acceleration, velocity, or magnetic field for various hands, fingers, and tasks for different users. For the various ADL activities, the finger had a substantial main effect. The smallest angle, similar angle orientation, and least difference angle between male and female were assessed for each ADL that all volunteers had performed, as listed in Table 7 below:

Table 7. Angles evaluation

ADLs	Smallest Angle	Similar Angle Orientation	Less Difference Angle (Male / Female)
Using Phone	Yaw	Pitch in Index	Pitch
Fingers Flexion	Pitch	Pitch in Thumb	Pitch
Drinking Water	Yaw	Yaw in Middle	Yaw
Using Key	Yaw	Pitch in Thumb	Yaw
Using Pen	Yaw	Yaw in Index	Yaw

A comparison between the design of the proposed system with other methods presented by various researchers was determined. Christina Salchow-Hömmen, et al. (2019) proposed a transportable IMU-based sensor system for detecting fingertip positions in real-time in a feedback-controlled hand. Five sensor strips were attached to the segments of the fingers and the base unit was linked to the hand's back. A biomechanical hand model was used to define the relationships between segment orientations and locations and accounts for the 23 primary rotational degrees of freedom (DoF) of the hand and finger joints. The system's precision was assessed using inertial measurements from the IMUs mounted to the fingers and hand back. Yang, Z., Yan, S., and van Beijnum (2021) developed a compact sensor configuration consisting of three IMUs and a magnet for estimating the postures of interested fingertips related to the hand. The relative orientations were determined by integrating relative angular velocity and combining it with relative orientation estimates throughout time periods when the complete hand moved or turned as a single entity. Several experiments were conducted to illustrate the performance, with two IMUs placed on the thumb and index fingertip to adjust for direction drift. However, IMU-based systems in previous methods had a number of significant limitations, such as each finger segment must have an IMU. In such a case, calculations become more complex due to the estimation of an excessive amount of useless information, and sensor-to-segment calibration predicts the uncertainty of segment lengths and error parameters. Finally, the proposed approach provides a viable strategy for hand-finger movements, outperforming earlier techniques that used an additional IMU on intermediate finger segments in addition to the finger kinematic model.

8 CONCLUSION

Modification of an IMU-based system was estimated for analyzing hand kinematics during activities of daily living. The device provided precise results of the magnetic field, acceleration, and angular velocity by using an IMU sensor that has three embedded sensors (magnetometer, accelerometer, and gyroscope). These output results were used to calculate the three angles of finger movements (pitch, roll, and yaw). The thumb and index fingers have similar pitch orientations while interacting, whereas the middle finger employs an entirely distinct range. The disparities between fingers according to the yaw variables are less noticeable. The variances between fingers are primarily due to the difference in roll angles. Hand morphology can explain these various behaviors, which are mostly caused by movements that cause a wide range of motions. The suggested system directly measured angular velocity, acceleration, and magnetic field and had no "line-of-sight" issues. It was also more portable and usable outside of the lab, which bodes well for everyday and long-term home monitoring. In the future, a hand sensor system may be combined with fingertip force detectors that detect item contact, delivering more information when a human grasps and holds an object. Future studies might try to minimize the weight and size of the sensor system to further lessen the device's influence on motions with the motor-impaired hand.

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