Wearable technologies for hand joints monitoring for rehabilitation: A survey

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Wearable Technologies for Hand Joints Monitoring for Rehabilitation: A Survey

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Abstract

Hand deformities often become a major obstacle in conducting everyday tasks for many people around the globe. Rehabilitation procedures are widely used for strengthening the hand muscles, which in turn leads to the restoration of functionality of the affected hand. This paper conducts a survey of various wearable technologies that can be used to accurately quantify the rehabilitation progress in terms of fingers' hand joint angles. Based on the data acquisition methods, these technologies can be mainly divided into six categories: 1) Flex sensor based; 2) Accelerometer based; 3) Vision based; 4) Hall-effect based; 5) Stretch sensor based; and 6) Magnetic sensor based. The main focus of some of the discussed technologies has been on various other domains, like gaming gloves, tele-manipulation etc., and thus their usage for rehabilitation of hand joints could be quite interesting. This paper analyzes the strengths and weaknesses of these wearable technologies along with some examples of their implementations. Based on our survey results, we propose a wearable glove for accurately measuring hand joint angles with enhanced features for better diagnosis and rehabilitation.

Keywords: Flex Sensors, Magnetic Sensors, Accelerometers, Hall-effect, Stretch Sensors, Hand Joints, Gloves, Dexterity.

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1. Introduction

Many acquired hand deformities, such as Osteoarthritis, fractures due to injuries, ruptured ligaments and dislocations, Rheumatoid Arthritis (RA) and Carpal Tunnel Syndrome (CTS) [1], continue to affect the lives of many humans around the globe. For example, it has been reported in [2] that up to 50% of the people suffering from RA lose their jobs within the first 5 years of diagnosis and the annual medical cost of an RA patient was estimated at £3,600 in 1992 and it became about £4,000 per annum since 2011 [2]. Similarly, it is believed that 3.8% of the general population suffers from CTS around the globe [3]. CTS is reported [3] to have been diagnosed in every 1 out of 5 persons who suffers from the pain and numbness in the hands, which represents the severity and sensitivity of this problem. The above-mentioned acquired hand deformities are generally cured by occupational therapy prescribed by hand therapists. Treatment for hand deformities is planned by doctors and clinicians after performing a complete check-up of the patient using radiative techniques, such as X-rays, or manual techniques, such as inspection of hand, health assessment questionnaires and examining a range of motion of all hand joints. The prescribed treatment mainly consists of physical therapy of hands to strengthen the muscles and thus recover the lost functionality of joints. One of the major goals of the treatment is to relieve pain and restore the functionality of hand for which hand therapists use joint protection exercises and work routines, as illustrated in Figure 1.

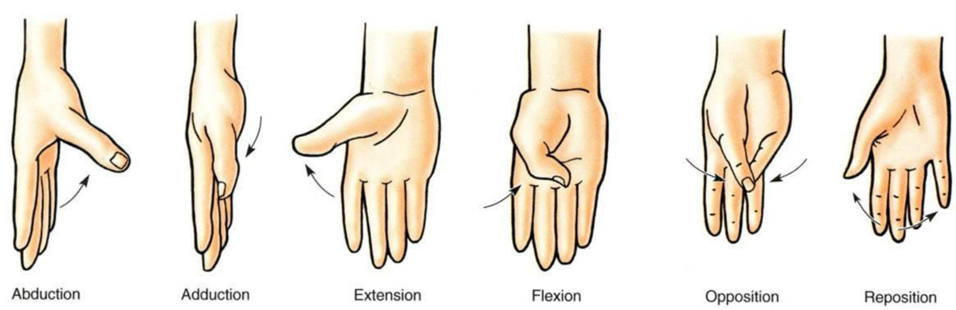

Figure 1: Various Hand Movements [4]

Traditionally, physiotherapists use Goniometers [5] (for hand angles measurement), hand strength dynamometers [6] (for hand grip force measurement) and assessment questionnaires to quantify disease progression and to monitor the rehabilitation process, i.e., the ability of the patient to perform different tasks. Statistical analysis techniques are then applied based on these outcomes to calculate patient's hand functionality level. The outcomes of this kind of manual procedure are easily influenced by the level of training and experience of clinicians as the patients data is recorded in manual form. Moreover, patients have to visit the clinic every time they want to check their progress, which not only makes the whole process very time consuming but also raises the burden on the healthcare costs.

The recent developments in wearable and Internet-of-Things (IoT) technologies can alleviate many of these issues by providing a more accurate, reliable and automated solution for quantifying the rehabilitation progress. These technologies can be broadly categorized into six types. (1) Flex Sensor based technology, in which different types of resistive bend sensors are embedded onto a stretchable glove and calibrated for accurate hand joint measurement. (2) Accelerometer based technology, in which accelerometers are similarly placed on a glove and calibrated for accurate readings. (3) Vision based technology, in which a glove is specifically designed with different colours to employ gesture recognition algorithms with cameras. (4) Hall-effect Sensor based technology, in which hall-effect sensors are used to accurately measure the flexion/extension and abduction-abduction motion of the fingers' proximal joints. (5) Stretch Sensor based technology, in which the sensor's deformation, i.e., stretching and squeezing, provides the accurate measurement of the hand and finger's motion and joint measurement. (6) Magnetic Sensor based technology, in which magnetic field sensors are used to track the position and orientation of the hand. All these techniques can be used to make a comprehensive wearable device, which can help in alleviating the inaccuracies caused by the above-mentioned manual approach of rehabilitation quantification. Moreover, the ability of the patient to independently measure and data log his/her rehabilitation progress using these automatic methods tends to increase the quality of diagnosis and the treatment.

In this paper, we provide an extensive survey of all these technologies along with some associated prototypes for hand joint monitoring. Our main objective is to identify the advantages and drawbacks of these technologies and the corresponding prototypes in order to recognize potential room for improvement in research in the domain of accurate hand joint measurement for rehabilitation quantification using the wearable technology. Moreover, based on the analyses, we propose a wearable device to accurately measure hand joint angles by utilizing the best possible features from all the mentioned technologies. The proposed device includes conductive ink based sensors for finger joints measurement along with an accelerometer for the measurement of wrist joint angles. Also, the inclusion of a smartphone app for easy user interface and automatic data entry can be used. We also recommend to use this wearable device to measure the level of dexterity of a patient's hand. This can be done by performing dexterity tests while donning the wearable and getting necessary readings [7].

2. Flex Sensor Based Technologies

Flex sensors are passive resistive devices [8], which are commonly used to measure angle of deflections. Flex sensors are generally composed of carbon resistive elements, which are present within a flexible substrate. A bend in a flex sensor results in a change in carbon content in the substrate, which leads to a proportional change in the resistance of the substrate. Due to this characteristic, flex sensors are also commonly termed as analog resistors. Figure 2 shows a gesture recognition glove with flex sensors embedded on its fingers [9].

Figure 2: An Example of a Flex Sensor Based Glove [9]

Flex sensors can be manufactured based on the conductive ink or the fiber-optic technologies. Conductive ink sensors are fabricated by laying resistive ink on a substrate. As the flex sensor is bent, the resistive material is pulled apart and its resistance changes. In comparison to this, the fiber optic sensor consists of a plastic fiber optic, a light source and a photosensitive receiver. Light is sent from one end of the fiber optic cable and received at the other. When the optical fiber is bent, light intensity at the receiving end changes and thus the bending angle can be detected. Both conductive ink and fiber-optic based flex sensors have less hysteresis in resistance, but conductive ink based sensors are usually cheaper to manufacture than the fiber optic ones. The conductive ink based flex sensors can bear slightly higher temperature and humidity conditions while the fiber-optic based sensors have high repeatability. Table 1 shows a comparison of these two commonly available conductive ink based flex sensors.

Table 1: Comparison of Flex Sensors [10, 11]

Characteristics	**Flex Point**	**Spectra Symbol**
Life Cycle	>1 Million Bends	>1 Million Bends
Temperature range	-35°C to +80°C	-35°C to +80°C
Flat Resistance	100 to 500K Ohms	25K Ohms
Resistance Tolerance/ Nonlinearity	NA	30 %
Bend Resistance Range	1.5K to 40K Ohms	45K to 125K Ohms
Power Rating	NA	0.50 Watts Continuous
Hysteresis	7 %	NA
Resolution	<1 degree	<1 degree
Operating Voltage	5V to 12V	NA

2.1. Relevant Work

Flex sensor based technology [8] is the most widely used method in designing wearables associated with hands. Cyberglove III [12] is a flex sensor based glove used for gaming purposes and PC control. It has 18-22 sensors embedded on it with a reasonable accuracy of <1 degree. Kumar et al. [13] used a similar kind of glove, named DG5 VHand 2.0, for gesture recognition used with gaming consoles. These gloves provide reasonable alternatives for input devices for gaming consoles but are not suitable for hand rehabilitation since their sensors are not placed for measuring the corresponding joint movements. Recently, some researchers have explored the option of using the flex sensor technology for measuring hand joint movements. For example, Connolly et al. [14] proposed two flex sensor based gloves for hand joints measurement, namely 5DT Data Glove and X-IST Data Glove. The idea, presented in these two gloves, was extended by the researchers at the Tyndall Institute in Ireland, for the development of a more sophisticated wearable glove [15], which provides more accurate hand joint readings along with other parameters of hand deformity quantification.

Gallo et al. [16] proposed a low cost portable user interface for 3D visualization and manipulation of a medical image in a semi-immersive virtual environment, which helps the radiologists in the understanding of the shape and position of the anatomical structures. This 3D interface uses a Wiimote-enhanced wireless data glove as an input and thus provides an exploration of a 3D medical image in a virtual environment, such as rotation and movement of 3D reconstructions of anatomical parts, and position control of 3D cursor. The proposed interface used DG5 VHand 2.0 data glove [17], which consists of one bend flex sensor on each of the finger and an accelerometer for hand movement sensing and hand orientation deduction along the 3 main axes. Zimmerman et al. [18] proposed a hand to machine interface device, which provides hand's position and orientation information, and gesture recognition. It mainly consists of a glove, which uses analog flex sensors for measuring the finger bend, ultrasonics to measure the hand's position and orientation. Moreover, a small cable is used to establish a connection between these sensors and the driving hardware. A custom sensor glove is proposed in [19], which used passive-resistive flex sensors for the real-time measurement of the finger flexion in the individuals having reduced range of the motion of their hands and fingers. This glove is used to capture the daily routine rehabilitation activities performed away from the clinical sites. Saggio [20] proposed a novel array of flex sensors, which is integrated in a sensory glove and can perform the goniometric semi-automated measurements. These flex sensors are basically developed by coating resistive carbon elements on a flexible thin plastic substrate. These are low cost with long mechanical durability and can provide a good electrical stability over the time.

Zhang et al. [21] developed a low cost viable rehabilitation system for hand motion using the Augmented Reality (AR) technology. A self-designed low cost data-glove is used for the interaction between the real hand and the virtual environment and thus for the detection of flexion of the fingers and to control the movements of the virtual hands. A novel pneumatic glove, the PneuGlove [22], is used for hand rehabilitation after a stroke. It uses Flexpoint sensors for measuring the joint kinematics and thus is used for training of the grasp-and-release movements in a virtual reality environment. A detailed account of the flex-based sensors and the gloves using these sensors with their applications can be found in [8] and [23], respectively.

2.2. Discussion and Analysis

Flex sensors are very suitable for measuring hand gestures and a range of movement of joints due to their ease of placement on a glove, their larger life cycle, wide range of temperature of operation and finally, easy market accessibility. They have a thin, flexible membrane that can be easily placed on the glove over the knuckle of the joint under observation, providing a life cycle of greater than 1 million complete bends. The ability to operate in a wide range of temperature (-35°C to +80°C) makes them suitable for all environments. Flex sensors are also available in different sizes, which makes them quite a suitable choice for measuring different joints of hand.

Flex sensors also have some disadvantages, including the problem of repeatability and decrease in their accuracy over time. Also, the Flexpoint sensors show a non-linear trend for smaller angles, which makes their calibration quite difficult [8]. Bending a flex sensor with no protective coating for a relatively longer period of time can result in a permanent bend in the sensor that affects its base resistance, and requires a recalibration. Moreover, the flex sensors exhibit moderately slow response time due to their physical deformation [24]. For instance, the resistive flex sensor has a typical response time of 1 to 2 ms [8]. Another limitation of flex sensors is that they can only measure bending angles of bodies with one degree of freedom while accelerometers, vision based sensors and magnetic sensors can do the same in more than one degree of freedom.

3. Accelerometer Based Technologies

Accelerometers are used to measure the orientation of an object [25]. They are used collectively with gyroscopes and magnetometers to form an Inertial Measurement Unit (IMU), which provide quite accurate readings of orientation. The most commonly used accelerometers are Micro-electro-mechanical Systems (MEMS), which track the orientation based on the movement of a small proof mass on a silicon surface, suspended by small beams. The acceleration is measured based on the Newton's second law of motion, $F = ma$, in this setup as the beams act as springs. The second major type of accelerometers is based on the piezoelectric technology, where the acceleration changes in direct proportion to the applied force due to the piezoelectric effect, which states that a charge of opposite polarity appears on opposite sides of a certain crystal when crystals are compressed [26]. Table 2 shows a comparison of both of these accelerometers.

Table 2: Piezoelectric Accelerometer Performance Compared with ADXL105 [14]

Property	**Piezoelectric**	**MEMS (ADXL105)**
Range	Up to 2000 g	5 g
Sensitivity	100 pC/g	250 mV/g
Noise Density	0.02 mg	0.225 mg
Temperature Range	274°C to 2508°C	240°C to 858°C
Frequency Range	0.1 Hz to 4800 Hz	0 Hz to 10000 Hz
Resonance	16 kHz	Around 7 kHz

3.1. Relevant Work

Just like the flex sensor based gloves, the main application of accelerometer based hand gloves is in gaming and gesture recognition. KeyGlove [27, 28], shown in Figure 3, Gest [29] and Acceleglove [30] use accelerometers to provide gesture recognition capabilities for PC control and gaming consoles. The accuracy of these gloves is up to a few degrees, which makes them not too suitable for precise measurement of hand joint angles, which is a requirement for rehabilitation. Hsiao et al. [28] proposed a data glove embedded with 17, 9-axis IMUs. These IMUs contain a 3-axis accelerometer, a 3-axis gyroscope and a 3-axis magnetometer to gauge acceleration, angular velocity, and magnetic field, respectively. These sensors are placed on both the front and back of the glove. The sensors are calibrated using an inertial motion sensor to check the correctness of raw data. The acquired readings are validated by goniometers and servo motors and show an error of approximately 0.98 degrees. This glove was also used for clinical testing for dexterity results and showed very clear and precise readings. However, it requires a flexible printed circuit, which is an expensive technology for a consumer product.

The accelerometers have also been used for gesture recognition, which is used in many applications, such as human computer interaction and sign language translation. Bui et al. [32] developed a MEMS accelerometer based

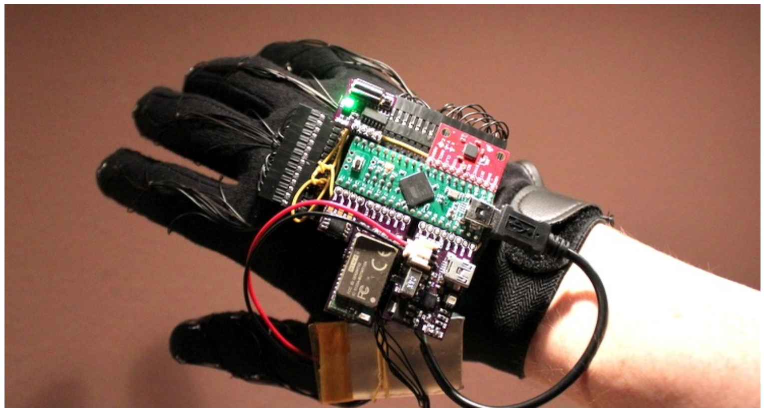

Figure 3: An Example of an Accelerometer Based Glove [31]

glove for gesture recognition. It consists of six MEMS accelerometers, i.e., one of them is placed at the back of the hand alongside the other five sensors at the front of the hand, which considerably improves the process of recognition. However, it can only perform gesture recognition in two dimensions. In order to overcome this limitation, Kim et al. [33] developed a data glove KHU-1, which consists of three tri-axis accelerometer sensors and thus can perform a 3-D rule based hand motion tracking and gesture recognition. The signal produced as a result of the process of sensing is transmitted to a computer via a wireless channel using Bluetooth technology, which is used for further processing and recognition process. Similarly, Zu et al. [34] presented three models, which used the MEMS 3-axes accelerometers to recognize, seven hand gestures including right, left, up, down, cross, tick and circle. The sensed acceleration of the hand is transmitted via a Bluetooth channel to the computer and gesture recognition is performed based on a comparison of gesture code with the already stored template in the computer.

Hernandez-Reboller et al. [35] presented an interactive computer game AcceleSpell, which helps in learning and practicing finger spelling. This game is based on a decision tree based recognition algorithm and the AcceleGlove glove. AcceleGlove utilizes six 3-axis accelerometers placed at the fingers and back of the palm to provide the angular position of each axis upon a query from the PC. OFlynn et al. [36] developed an Inertial Measurement Unit (IMU) smart glove microsystem based on sensors, processors and wireless technology used for human computer interaction. It consists of 16 9-axes IMUs, where each one includes a 3-axis accelerometer, a 3-axis gyroscope and a 3-axis magnetometer and provides a realtime measurement of a range of hand joint movements including the measurement of flexion/extension, adduction-abduction and complex hand movements. A detailed review of the utilization of the accelerometer based sensors in wearable devices can be found in [37]. Similarly, a review of wearable sensors and systems used in rehabilitation can found in [38].

3.2. Discussion and Analysis

The accelerometer based technology for tracking hand joint movements, explained above and the prototypes associated with it also has some advantages and shortcomings. The advantages include less hardware requirement and a better data rate as accelerometers give digital output and thus, do not require analogue to digital conversion. Also, accelerometers are relatively cheaper and have a longer lifespan. Moreover, accelerometers generally have a faster response time compared to that of the flex sensors. For example, the KC-2105 accelerometer has a response time of $<$ 100ns [39].

The disadvantages of this technology include the tricky placement of the sensors on the glove. For assessing the movements of every hand joint angle, accelerometers have to be placed in between each finger joint. This is quite challenging due to the fixed shape and dimensions of the accelerometers. Moreover, accelerometers provide their readings with reference to the gravitational acceleration, i.e. g. This results in a lot of noise in the readings and hence requires noise reduction algorithms, which in turn require tedious initial calibration along with inaccuracies in readings in the presence of magnetic devices.

4. Vision Based Technologies

Using imaging cameras for recognizing hand gestures, is a growing research trend these days. Real-time hand tracking devices are used to capture the freeform motion of the hand and the captured images are then used to measure the hand joint angles and a range of movements using image processing techniques as illustrated in Figure 4. Hand gesture recognition can be primarily modeled by using 3D model based or appearance based techniques. The 3D model method is primarily based on a 3D kinematic model of the hand [40]. The required parameters for palm position and joint angles can be obtained from this 3D information using volumetric models. The main idea is to deduce hand parameters by comparing the possible 2D appearance as projected by the 3D hand model and the input image from the camera. The appearance-based techniques use images or videos as their input and the required parameters are extracted using a template database instead of using a spatial representation of the gesture [40]. Color body markers [41] have also been used to track motion of the hand by using particle filtering and multi scale color features [42].

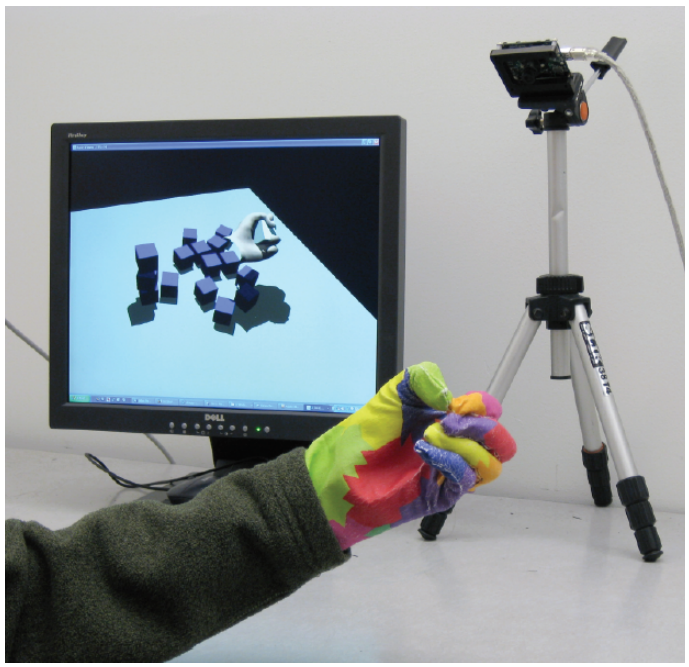

Figure 4: An Example of a Vision Based Glove [43]

4.1. Relevant Work

Kapuscinski [44] used the skin colored section of the captured image to *intensity-normalize* it with the desired hand region. This way the gesture can be recognized using a Hidden Markov model. YCbCr color model was used by Yu to differentiate skin colored pixels from the background of the image [45]. Malima [46] used the red-green ratio of the image to detect the skin colored portion. This way the hand's center of gravity is determined, which in turn allows us to find the location of the finger tips that is usually the farthest point from the center of gravity point of the hand. A circle can then be drawn around the center of gravity to determine the desired gesture by counting the number of white pixels outside the circle. Jackin [47] used a similar gesture recognition procedure, but instead of converting Red, Blue and Green (RGB) to Hue, Saturation, and Value (HSV), as done by Malima [46], they used RGB as input. This technique is reported to achieve an accuracy of 100%. Koh [48] considered the shape and color of an image for the identification of rough contour of the hand. Fang [49] employed the Adaptive Boost algorithm to detect the hand from the input image. In addition to detecting a single hand, this algorithm can also detect overlapping hands. Rekha et al. [50] detected the palm and finger structure by drawing blobs and ridges and the recognition rate was found to be about 98% accurate.

Zabulis et al. [51] proposed a vision-based hand gesture recognition system used for human computer interaction. It is based on a probabilistic framework, which detects the image regions belonging to human hands efficiently using multiple information clues. The process of real-time tracking can handle multiple hands moving in different trajectories in front of the camera. The authors [51] proved the efficiency and effectiveness of the proposed approach using several experimental results. Cameiro et al. [52] developed a Rehabilitation Gaming System (RGS), i.e., a vision based motion capture system, which can be used for the rehabilitation of the stroke patient. Placidi et al. [53] proposed a virtual glove, which unlike the traditional mechanical gloves, uses the video cameras for capturing and tracking movements of the hand. It uses a numerical hand model to calculate the physical and geometrical parameters using some boundary constraints, i.e., joint angles and dimensions. The proposed system is low cost and easy to use. Similarly, Ma et al. [54] developed a five-fingered haptic glove, which is adaptable to any size of the fingers and can provide accurate tracking the complex finger joint motion. It uses least squares fitting of circles methods for the analysis of the kinetic model of hand and fingers motion. It can be used for the rehabilitation of the hand as well as in virtual reality based systems. A detailed account of the applications of the vision-based hand gestures can be found in [55].

4.2. Discussion and Analysis

3D Model Based approach is computationally quite intensive and thus, using it for real-time data acquisition, requires high performance computational resources, such as processing speeds and memory. Performance evaluation for hand gesture recognition techniques can be done by evaluating the percentage of error in recognition. Table 3 compares the accuracy of different vision based hand gesture recognition techniques.

Table 3: Comparison of Vision Based Hand Gesture Recognition Techniques

Available Hand Gesture Recognition Techniques	**Accuracy**
Hand gesture recognition by Hit-Mass Transform and Hidden Markov Model [45]	98%
YCbCr color model with Artificial Neural Network (ANN) [46]	97.4%
Detection of skin region by Red/Green ratio [47]	98%
Hand gesture recognition through Perceptual Color Space [48]	100%
On-premise skin colored modeling method [49]	82.6%
Adaptive Boost Algorithm for hand detection [50]	98%
Hand Gesture recognition using PCBR and 2-D WPD techniques [43]	91.3% static 86.3% dynamic
Two hand segmentation with Haar-Like feature and adaptive skin color model [56]	89% to 98%

A few studies have also compared the accuracy of vision based techniques with sensor based techniques. Table 4 shows the results of one such experiment, conducted by Baatar et al. [57], involving 5 male and 5 female participants.

Table 4: Experiment conducted to determine the accuracy of Vision based techniques

	Sensor based hand gesture recognition	**Vision based hand gesture recognition**
Accuracy	84%	91%
User Preference	40%	60%

5. Hall-effect Sensor Based Technologies

Hall-effect sensors [58, 59] are used for the accurate measurement of the flexion/extension and adduction-abduction motion of the proximal joint of the fingers. These sensors are based on the phenomenon of the magnetic field, which is characterized by its polarity and the flux density. When a magnetic field is applied across a hall-effect sensor, its magnetic flux density starts increasing. As this density crosses a pre-set threshold, the sensor detects it and generates an electrical signal as an output voltage known as hall voltage. The generation of this electrical signal based on the applied magnetic field is known as the hall effect. Figure 5 depicts the Humanglove having 20 hall-effect sensors, which is mainly used to measure the flexion/extension of the fingers and thumbs as well as their adduction-abduction motion.

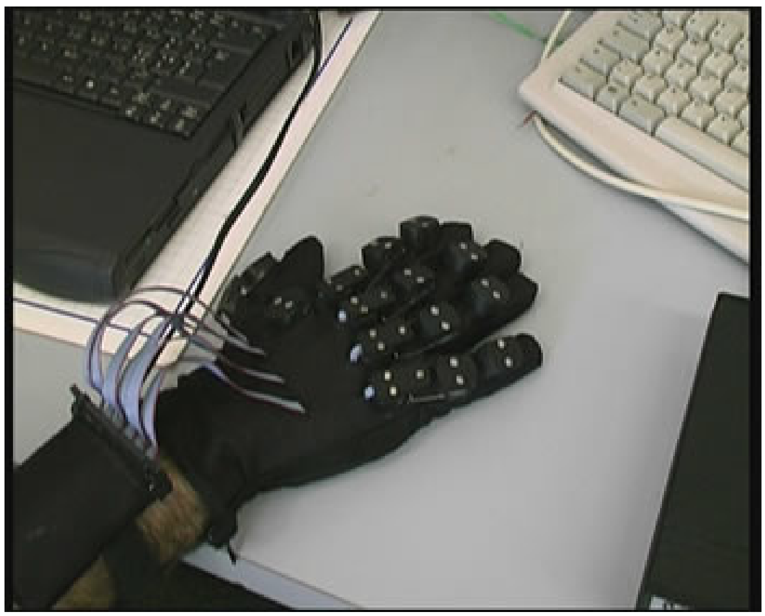

Figure 5: An Example of a Hall-effect Sensor Based Glove [60]

Based on the type of the output signal, these sensors are characterized namely as analog and digital. In the analog sensor, the output signal is of continuous nature and is directly proportional to the strength of the applied magnetic field. The increase in the strength of the applied magnetic field increases the corresponding output voltage until it saturates due to the limitation applied on it by the power supply. Similarly, in the case of digital sensors, it works as a switch, i.e., if the magnetic field crosses a pre-set value, the output of the sensor switches from state “OFF” to “ON”. Moreover, based on the utilization of the magnetic poles (north and south), the digital hall-effect sensors are categorised as unipolar and bipolar sensors.

5.1. Relevant Work

The hall-effect sensor based wearable technology is widely used for tracking various motions of hands and fingers in many applications, such as robotics, health-care and wearable computers. Humanglove [61] is a hall-based sensor glove, which is used for measuring the flexion/extension and abduction-abduction of the four fingers and thumb. It is embedded with 20 hall-effect sensor that are used for the above-mentioned measurement and is available in 3 sizes. It is calibrated for the new user using the Graphical Virtual Hand (GVH) software, which captures the actual movement of the hand by its equivalent animated hand [62]. Hall-effect sensors are integrated in the hand exoskeleton exerciser, which is used for the rehabilitation of patients who loose the muscular control of their hands [63]. Huang et al. [64] proposed a wearable rehabilitation robotic hand that can be worn on the forearm. Hall-effect sensor is embedded at the axis of the joints for the measurement of the angles. A wearable artificial hand is proposed in [65], which is used for prosthetics and humanoid robotics applications. In order to sense and measure the angular movement and position of the hand joints, it uses six hall-effect based sensors (SS495A, Honeywell, USA [66]). Due to their small sizes and the contactless working principle, these sensors enable the smooth working of the system by avoiding the frictional forces.

Hall-effect sensor grid is used on the fingernail to convert it into a touchpad, named as FingerPad, and a magnet at the thumb enables it to work as a touch pad [67]. Similarly, Phillips et al. [68] proposed a transducer, which is used for the monitoring of the patients undergoing the rehabilitation of the flexor tendon of the hand fingers. It uses the hall-effect sensor to capture the movement and stretching of the fingers. Chouhan et al. [69] presented a glove for gesture recognition that can be used by the hearing and speech impaired people. This system uses the hall-effect based sensor along with other sensors to capture the hand and finger orientation and gestures.

Eilenberg et al. [70] presented an adaptive muscle-reflex controller for anklefoot prostheses, in which a linear hall-effect sensor (Allegro A1395 [71]) is used for the estimation of the ankle joint angle, which ranges from -0.19 to +0.19 radians. Similarly, Arami et al. [72] proposed a hall-effect based sensors system for the accurate measurement of the knee flexion-extension. These sensors are integrated into a smart knee prosthesis, and are used to simulate the actual patterns of walking.

5.2. Discussion and Analysis

Hall-effect sensors are low cost. Moreover, they are not effected by environmental impurities due to their strong sealed packaging and thus can bear severe conditions. The operating frequency for such sensors is up to 100kHz and are thus very good for a high speed operation. These sensors can work in a wider range of temperature and thus can measure a wider range of magnetic fields. These sensors maintain their quality and are usable for an unlimited period of time and thus can perform repeatable operations.

As described above, these sensors work on the phenomenon of magnetic field, so there is always a possibility of the interference of this magnetic field with the external magnetic field, which can change the resulted output. This in turn may result in the degradation in performance by compromising the accuracy of the sensed signal. Moreover, the response time for the hall-effect sensors is slower compared to that of the accelerometers and it typically ranges from 1 to 6μsec. For example, the VF360NT sensor exhibits a response time of 1.5μsec [73].

6. Stretch Sensor Based Technologies

Stretch sensors [74] are used to measure stretch, bend, pressure and force and are widely used for tracking hand movements in applications ranging from soft robots, Virtual Reality (VR) gloves, biometric displacement reading and other physical applications. These sensors are typically resistors with resistance values depending on the sensor's deformation, i.e., stretching or squeezing. The deformation of the sensor is directly proportional to its resistance, i.e., its stretching increases its resistance, whereas its squeezing decreases its equivalent resistance [75]. In order to perform different stretch sensor based operations, we need to adapt the same methodology, which is used for the measurement of the resistance of a variable resistor. These sensors are available in different sizes, sensitivities and elasticities based on their intended applications. Figure 6 illustrates a soft stretchable bending sensor placed at a hand's finger.

Based on the process of their fabrication, the stretch sensors are broadly characterized as of three types [76], namely fabric stretch [77], constructed stretch [78] and the knit stretch [79] sensors. The fabric stretch sensors are made up of stretchy fabrics, which are coated with a conducting polymer named polypyrrole. Table 5 presents the specifications of some of the fabric stretch sensors, which help in selecting an appropriate sensor based on its

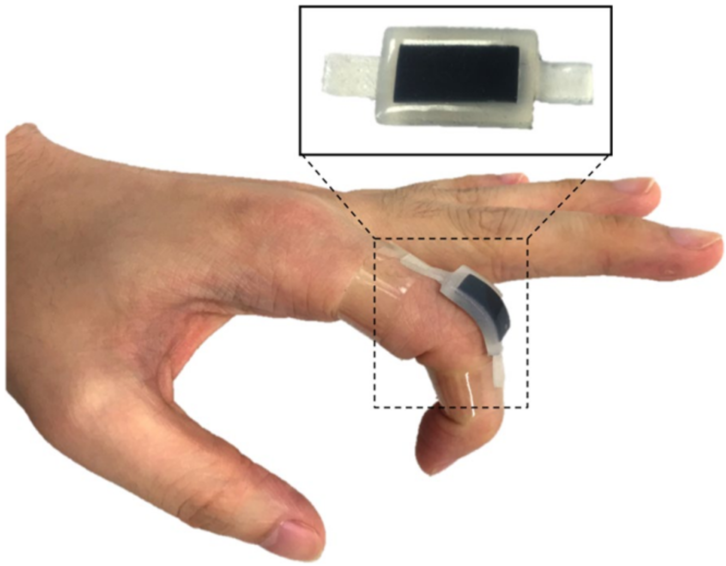

Figure 6: A Soft Stretchable Bending Sensor Placed at a Hand's Finger [74]

utility in a particular application. The constructed stretch sensors are devel-

Table 5: Specification of Some of the Fabric Stretch Sensor [77]

Batch Number	**Resistance (Range in Ohms)**	**Size**
RL-5-123-T-24	1100 to 1300	9"×11"
RL-5-109-GL	1500 to 2000	9"×11"
RL-5-129	8×10^5 to 1×10^6	9"×12"
RL-5-137	5×10^5 to 1×10^6	10"×11"
RP-3-125-1B	1100 to 1300	9"×17"
RP-3-125-2B	120 to 145	9" × 15"

oped using various techniques based on changing their conductive properties, i.e., as a result of, knitting and stitching with resistive thread and a mixture of conductive fiber with stretchy fabric glue. Similarly, the knit stretch sensor is a 3×6 cm hand knitted rectangular conductive/resistive wool obtained from a conductive thread, which can be embedded on any glove. If a circular sewing machine is used, it will result into a circular knit stretch sensor [80].

6.1. Relevant Work

Stretch sensor based technology is widely used for measuring the stretch, bend and force in soft robots and VR gloves, which are used for the rehabilitation process. Toomey et al. [81] carried out study on the usage of Dielectric Electroactive Polymer (DEAP) along with the stretch sensor in human healthcare. The authors explored the integration of soft material and the sensors for the real-time monitoring and mapping of the human body. A fabric-based, flexible and stretchable tactile sensor is proposed in [82]. Next, Bianchi et al. [83] presented a sensing glove for hand monitoring by integrating the kinaesthetic and stretchable tactile sensing gloves proposed in [82]. The stretchable tactile sensing glove consists of a knitted piezoresistive fabrics and is used to measure bending. Only five sensors, one placed on each of the fingers enables the reconstruction of the 19 Degrees of Freedom (DoF) hand models. A virtual reality-based system is proposed for the analysis of accurate hand functionality in [84]. In the proposed system, the authors used a glove for capturing the movement/motion of the hand, which was equipped with the stretch sensors and has been used to trace the positions of the joint exertion. Lee et al. [85] fabricated a stretchable strain sensor for the detection of tensile as well as compressive strains. This sensor is successfully used in the human wrist and finger motions. It can also be used to measure the pressure with high sensitivity.

Tognetti et al. [86] developed a prototype, which involves the knitted and woven e-textile stretch sensors and is used to monitor the rehabilitation progress of the knee joint. Similarly, Shimada et al. [87] used a stretch sensor in the closed-loop system for the restoration of standing in paraplegia. Shen et al. [74] presented a soft stretchable bending sensor and two sensor gloves. Due to their low cost and customizable size, they are widely used in wearable devices. A detailed account of the stretch sensor based technologies for the rehabilitation purposes can be found in [88].

6.2. Discussion and Analysis

Due to the stretching ability, stretch sensors are customizable in size and can fit any application. For example, in the case of non-stretchable data gloves, the size of a glove is kept larger than the size of the hand so that the sensors can fit into it. Thus, this gap between the hand and glove can produce errors in the sensor's output. Whereas, in the case of stretchable glove, i.e., the glove having stretchable sensors, we can use the size of a glove same as that of a hand and hence, can minimize the error caused by the non-stretchable gloves.

One of the drawbacks of knit stretch sensor is that it follows the axis of the knit structure and thus a free-form sensing pattern cannot be created. The other drawback of the stretch sensor is that the sensitivity of these sensors changes with the size of the sensor and hence is not constant. Moreover, these sensors exhibit slower response time, typically in milliseconds, compared to that of the hall-effect sensors and accelerometers. Also, the lifetime of these sensors is less compared to the hall-effect sensor based technology.

7. Magnetic Sensor Based Technologies

Magnetic sensors [89, 90, 91] are primarily based on the phenomena of magnetic fields to detect the position of an object and have been widely used in aerospace, geology and medical sciences [89]. Based on the technologies used for the magnetic field sensing, the magnetic sensors are of various types, such as, search-coil magnetometer [89], optically pumped [92, 93], fluxgate [94], nuclear precession [90], Superconducting Quantum Interference Device (SQUlD) [95, 96], magnetodiode [97], magnetoresistive [98], magneto-transistor [99], fiber-optic magnetometer [89] and magneto-optical [100, 101]. For example, the search-coil magnetometer works on Faradays law of induction. It consists of a coiled conductor and moving/rotating the coil in the magnetic field changes its corresponding flux, which generates a voltage between its leads. The signal detected by a search-coil magnetometer depends on various factors, such as, number of turns and area of coil, the strength of magnetic field and the permeability of the material of coil. Table 6 presents the sensitivity ranges for various magnetic sensors [90].

7.1. Relevant Work

Magnetic sensors have been used for detecting the position of the object in many applications, such as, aerospace and healthcare. Pabon et al. [102] presented a data-glove having goniometric sensors. Due to their insensitivity towards the user's hand, these sensors do not require any calibration. Moreover, this data-glove uses the magnetic sensor to track the position and orientation of the user's hand. Kortier et al. [103] presented a data glove, which is based on Inertial and Magnetic Measurement Systems (IMMS) and provides estimates of the 3D kinematics of fingers and hands. It uses the magnetic and inertial sensors that are placed on various segments of the

Table 6: Sensitivity Ranges for Various Magnetic Sensors

Magnetic Sensors	**Sensitivity Range**
Search-coil magnetometer	2×10^{-5} nT, No upper limit
Optically pumped	10^{-3} nT to 10^{5} nT
Fluxgate	10^{-2} nT to 10^{7} nT
Nuclear precession	10^{-1} nT to 10^{5} nT
SQUlD	10 fT or 10^{-5}nT
Magnetoresistive	10^{-2} nT to 10^{3} nT
Magnetotransistor	10^{9} nT to 10^{11} nT
Fiber-optic magnetometer	10^{-2} nT to 10^{6} nT

hands and fingers and thus enables the accurate measurement of the corresponding kinetics. A bidirectional force feedback dataglove is proposed in [104], which is based on pneumatic artificial muscles. This dataglove uses the anisotropic magnetoresistive sensors, which provide the measurement of all the four degree of freedom for each of the fingers such as abduction-adduction in Metacarpophalangeal (MCP) joint, and flexion and extension in Distal Interphalangeal (DIP), MCP and Proximal Interphalangeal (PIP) joints. Due to its light weight and portability, it is widely used in the rehabilitation of the hands. A detailed account of the tracking of human motion for the rehabilitation purposes based on magnetic sensors can be found in [105].

A Pneumatic Glove, namely PneuGlove, and an immersive virtual reality environment [22] is used for the hand rehabilitation training after stroke. It uses the magnetic trackers in order to track the position of the head. Moreover, a flexion sensor is used for the measurement of the joint kinematics in this environment. Ma et al. [106] proposed a VR based training system, which is used for the therapy of the stroke patients. It mainly consists of VR games, which enable a patient with upper limb motor disorders to do physical exercises and thus serves as a rehabilitation system. In order to track the movement of the patient's hand, arms and upper body, it uses four Ascension MotionStar wireless magnetic sensors [107]. Altun et al. [108] used the magnetic sensors for the recognition of daily human activities. A detailed account of the usage of magnetic sensors for human activities recognition and monitoring, and behavior classification can be found in [109].

7.2. Discussion and Analysis

There are many advantages and drawbacks of the magnetic sensors. One of the main advantage is the variability in their sizes, which make them a wider utility in many applications. One of the drawbacks of the magnetic sensors is that their sensitivity changes with their size, which results into change in power and cost, i.e., it is directly proportional to all these parameters. In order to use them for the hand joint monitoring and rehabilitation, the smaller size, low cost and less power consuming magnetic sensors are preferred, which lack in their sensing ability as compared to the ones with the larger size. Moreover, the magnetic sensors exhibit a slower response time compared to the accelerometers and the flex sensors.

8. An Optimal Rehabilitation Glove

We believe that all the above-mentioned technologies need to play together in order to develop an optimal rehabilitation glove in terms of accuracy, cost and reliability. Table 7 presents a comparison of various wearable technologies presented in Sections 2 to 7 of this paper based on their accuracy, performance, cost and the lifetime, which are the most important parameters while designing a rehabilitation glove. It is important to note that the accuracy parameter considers for both the sensing ability and the response time of a wearable technology, i.e., the desirable accuracy would mean to precisely and efficiently detect the movements. The green, yellow and red circles represent the level of behavior of the technologies for each of the parameters. It can be clearly seen that the flex sensor and accelerometer are the most optimal technologies based on these parameters since they do not exhibit any worst (●) behavior. The flex sensor based technology provides the best accuracy and lifetime, while the accelerometer based technology provides the best performance and cost.

Table 7: Comparison of Various Wearable Technologies for Rehabilitation Glove (🟢 : Desirable, 🟡 : Nominal, 🔴 : Worst)

Technology	Accuracy	Performance	Cost	Lifetime
Flex sensor based	🟢	🟡	🟡	🟢
Accelerometer based	🟡	🟢	🟢	🟢
Vision based	🟡	🟡	🔴	🟡
Hall-effect based	🔴	🔴	🟡	🟢
Stretch sensor based	🟡	🟡	🟢	🔴
Magnetic sensor based	🔴	🟡	🟡	🟢

Based on the above-mentioned observations, we propose a wearable rehabilitation glove, depicted in Figure 7, which utilizes Flexpoint bend sensors [110] to measure the joint angles, the ADXL345 accelerometer [111, 112] at the wrist and pressure sensors at the fingertips to measure the grip strength of the hand, since grip is also a major measure of dexterity. We chose the Flexpoint bend sensors at hand joints due to their decent accuracy, easy cal-

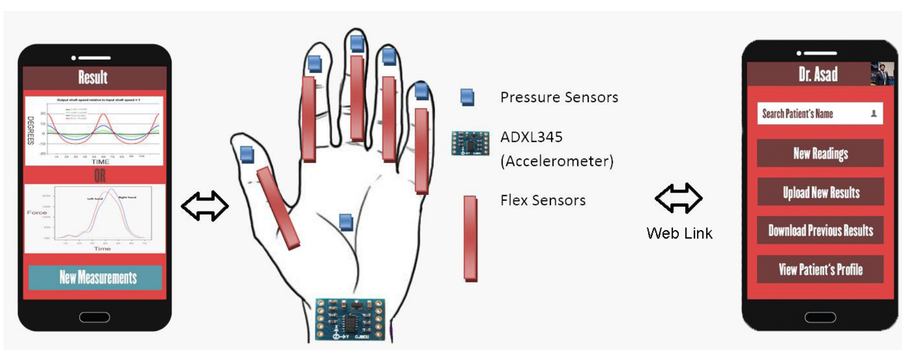

Figure 7: Proposed Glove

ibration and easy placement on the glove. Moreover, these sensors are available in multiple lengths, which allows us to use them according to the joint length requirement. An accelerometer is proposed to be used for the wrist because the wrist movement has two degrees of freedom of movement, which cannot be measured accurately using bend sensors. We also propose to include a smartphone application, interfaced using Bluetooth, with the glove for easy user accessibility. The app mainly allows data management of disease progression and sharing of data with therapists and other patients. Moreover, the app also facilitates the therapists in keeping record of all patients. This setup is expected to facilitate a comprehensive diagnosis process and thus more effective treatments.

The major hardware required to implement the proposed wearable includes Flexpoint bend sensors of lengths 1″ and 2″, for DIP joint and for PIP and MCP joints, respectively. These flex sensors along with the Flexiforce pressure sensors are placed on a lycra hand glove at the joints and fingertips, respectively. These flex sensors are calibrated using a calibration setup [113], which consists of a wooden board, rotating platform and a servo motor. The wooden board is fixed horizontally on this rotating platform, which is operated through the servo motor. A metal hinge is placed on the upper end of the motor's shaft and the sensor is placed as a cantilever beam on this metal hinge, as shown in Figure 8. This setup thus allows the sensor to bend at di-

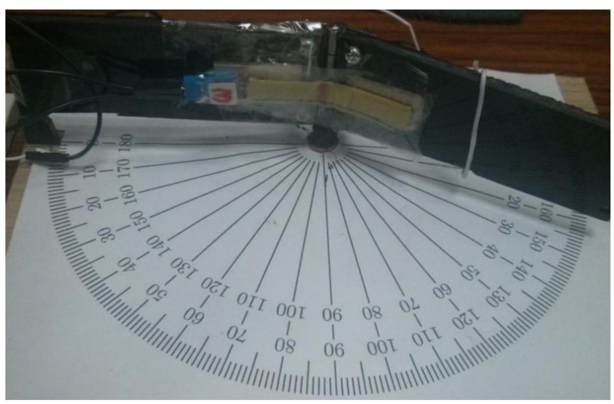

Figure 8: Setup for the Calibration of Flexpoint Bend Sensor

fferent bending rates and angles. For a single degree change in the angle, the corresponding resistance is measured and the polynomial relationship acquired from the calibration is then implemented in the microcontroller, such as ATega32 [114]. The relationship between the angle and resistance measurements for a 2″ unidirectional and a bidirectional flex sensors is depicted in Figure 9. Similarly, the Flexiforce A101 [115] pressure sensors are also used at the joints and fingertips for measuring the values of the pinch pressure of the hand and fingers, respectively. They are made up of polyester with a linearity error of $\pm < 3\%$, repeatability of $\pm < 2.5\%$ and a response time of $< 5\mu$sec.

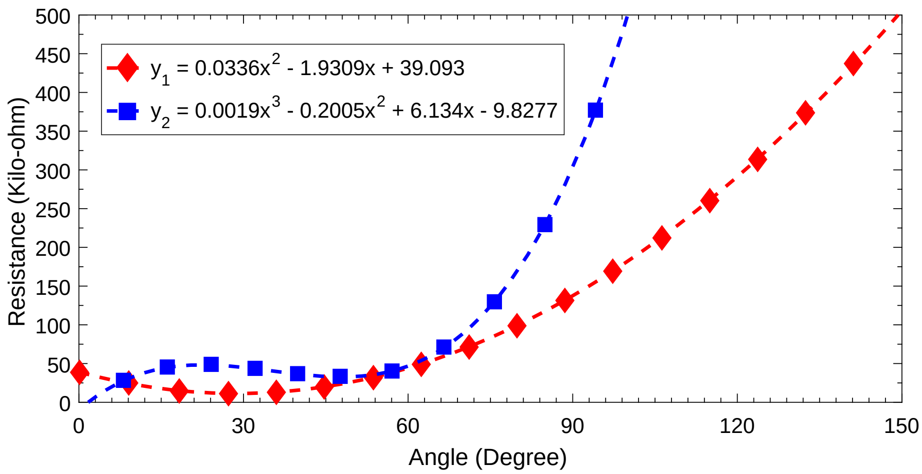

Figure 9: Resistance-angle Relationship for a 2″ Unidirectional and a Bidirectional Flex Sensors

During the interfacing of the microcontroller with the sensors, the input impedance of the microcontroller changes the resistance of the sensors, which effects the accuracy of the sensors. Thus, to cater far this issue, the raw data from these sensors is conditioned using a voltage buffer, which is implemented using the LM324 Operational Amplifiers (Op-Amps) [116]. The flex sensors are connected to the input of the Op-Amp, whereas, the microcontroller is connected to the output port of Op-Amp. Thus, this setup caters for the inaccuracy issue of the sensors caused by the input impedance of the microcontroller.

Finally, a Bluetooth low Energy (BLE 4.0) [117] module is used to interface the glove with a smartphone application for user accessibility. The app is used for the record keeping of disease progression and sharing of data with therapists and other patients. A board with ATMega32 and BLE chip embedded, like the Blend Micro [118] or RFduino [119], can also be used for the development of the proposed glove rather than using individual models for the microcontroller and the Bluetooth. Figure 10 depicts the design and layout of the android app, whereas Figure 11 shows a prototype of the developed system.

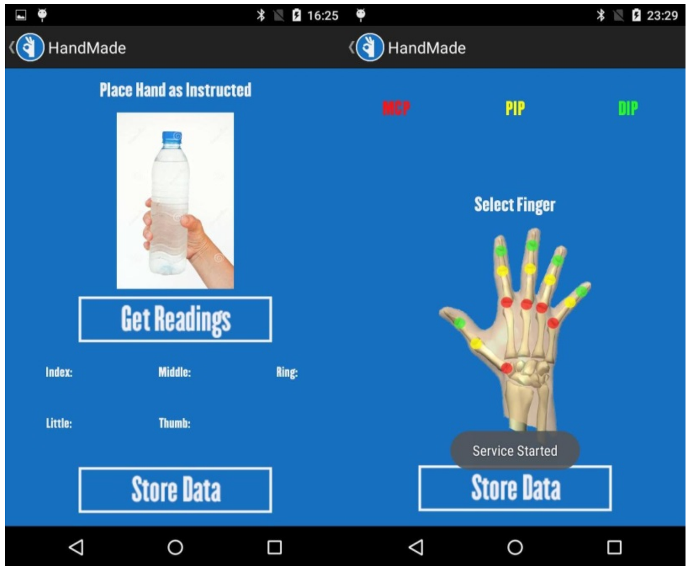

Figure 10: Design and Layout of the Android App

Figure 11: Design of the Proposed Glove

The proposed system exhibited quite promising results for overcoming the major shortcomings of conventional methods of hand joints monitoring and thus has the potential to revolutionize the field of hand therapy. The high accuracy allows us to keep track of even the slightest increase or decrease in the range of motion of hand joints. The smartphone connectivity allows sharing the live progress with therapists and other patients, which greatly facilitates the rehabilitation process.

9. Conclusions

In this paper, we presented a survey of all the major wearable technologies available to measure hand joint angles for rehabilitation process of various hand deformities. We broadly categorized them in six categories i.e. Flex sensor based, Accelerometer based, Vision based, Hall-effect based, Stretch sensor based and Magnetic sensor based. We critically analyzed all these categories and mentioned their advantages and drawbacks. Finally, based on various vital parameters, such as, accuracy of sensor's sensitivity, size, cost and implementation, we proposed an optimal solution, which provides a cost-effective, easy and innovative alternative to the current methods of measuring hand joint angles for the rehabilitation. Our proposed device uses conductive ink based sensors for finger joints measurement and an accelerometer for the measurement of wrist joint angles. It also uses a smartphone app, which provides an easy user interfacing and automatic data entry. We also recommended to use this wearable device to measure the level of dexterity of a patients hand, which can be done by performing dexterity tests while donning the wearable and getting necessary readings.

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