A Novel Device to Monitor Mobilization of Fingers During Treatment for Stiffness of Tendons

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***Abstract*—Conceptualization and development of a novel device to monitor mobilization of fingers of a patient suffering from post-traumatic stiffness of the tendons is presented in this paper. Effectiveness of the treatment depends largely on this component of recovery and is unfortunately beyond the scope of continuous vigil by the doctor. The major post-operative procedure is to keep flexing and extending the fingers, either independently or with external support, usually with the other hand. The patient has to do this diligently and hence monitoring this exercise is of concern. The proposed novel idea is a monitoring system which keeps track of the movements of the fingers using linear ratiometric Hall-effect sensors (Allegro-1321) and magnets attached to the fingers. This can provide reliable data to the doctor to ascertain whether the patient is actually doing his part in effecting a speedy recovery for himself, thus improving the overall efficacy of the treatment.**

I. Introduction

With 27 degrees of freedom [1], the human hand comprising the deceptively complex system of bones and muscles in the fingers is paramount to the productivity of an individual. Robotic hands under development are made to replicate this tendon-sheath system to actuate the joints. An injury to this part of the body severely impairs an individuals' daily activities. Physical therapy and active orthosis are some of the methods of aiding the healing process in such cases.

In cases of inflammation(traumatic or post-operative) of tendons in the palm, wherein the tendons in the digits of the hand do not glide smoothly in it's sheath, surgical treatment may ensue. Complete recovery is not attained until the patient can independently flex and extend his fingers freely. This to happen, needs constant exercising of the fingers by means of physical therapy [2]. The requirement is that, the fingers have to be flexed(moved toward the wrist) and extended(moved so as to make the fingers straight) continually so as to assuage the stress in the tendons and repair it.

The success of surgery, especially in this case, is largely dependent on the physiotherapy component of post operative procedures, upon which the surgeon unfortunately has not much direct control on. Here is where the need for a monitoring system arises, so that the surgeon is allowed the luxury of remotely keeping track of the status of the healing process. In certain cases, as making the movements can be painful, the patient might not be willing to do the set of exercises and thus he hampers his own healing process. The monitoring system also has to be reliable by not allowing the patient to tamper with the data log or artificially create data logs.

Presently, there are no such devices available. However, devices providing external support for exercising the fingers after surgery have been reported. These are available in the form of exoskeletons [3], functional electrical stimulation [4] devices, and virtual reality based systems [5]–[7]. There is also a simple device by name therapeutic putty, using which the patient can massage his fingers and facilitate movement by applying pressure on the blob of putty of varying stiffnesses. With advances in healing, stiffer putty can be used. Another implementation [8] makes use of Wii™ Nintendo® for tracking 3D movements of the entire limb (elbow/shoulder). A commercial device [9] from Ectron, which is a robotic hand rehabilitation system has a patented mechanism that mimics the hand's natural grasping movement, making the patient's hand move with it. Some of these actively help movement, in contrast to others which are passive and are used only to monitor movement. A portable mechanical design [10] exists, but it cannot assure the surgeon of the validity of the exercise.

Presented herein is a monitoring system which is compact, ingenious, and low cost. It has been devised to use ratiometric Hall-effect sensors for proximity detection of fingers, so as to eliminate physical connection with the moving parts. This, liberates the fingers from any wired connections and hence will not allow for tedium to ensue. As the magnets are not heavy, they shall not impair the patient of any movements that he could otherwise do freely. As there is virtually no low frequency ambient magnetic field under normal conditions, the sensing accuracy is not jeopardized. This is a novel usage of Hall-effect sensors in the medical rehabilitation device industry.

II. Conceptualization of the Device

As with all wearable medical devices, there are several design criteria that have to be met, and in this case, compatibility to work in medical environments precedes all other requirements. Following is a list of features which are the result of discussions on the conceptualization and implementation of the device.

A. Physical Features

- An implicit requirement of any wearable medical device is that it has to be compact, light to handle, portable, and low power, implying that it shall be battery operated and

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hence adding no extra strain to the patient when he is carrying out the required procedures.
- Size, ergonomics, and ruggedness so as to work in hospital like conditions become significant factors in deciding upon the device design.
- An attachment to carry the magnets and the device is necessary. This may be in the form of a special glove with velcro straps around the wrist and thimbles to carry the magnets.

B. Medical Features

- One of the basic features needed is a time log, having information about what time of the day has the patient done the exercise and how often in a week has it been repeated and so on, to track and control the progress of recovery.
- Since movement of the fingers is a painful process while injured, the patient has to be given incentive to move, without actually aiding movement directly. This incentive can be in the form of an audio and/or visual coaxing. This calls for real time feedback and instructions to correct and encourage motion. Audio-visual warning and indication will make for a good support for helping recovery.
- Also, wired sensing makes matters tedious and can lead to undesirable consequences. It is best to leave each finger independent of wires running from it to the wrist and independent of each other as well, so as to allow free-form movements without hampering the counting.
- This device will be put to best use if the patient has no way to bypass or hack the counter. The sensing has to be reliable as well as rugged, demanding a novel methodology.
- Logging of data required for a subjective assessment of the rate of healing of individual flexor and extensor tendons.
- Extraction of certain features like average, standard deviation, and ensemble of the finger movements.

C. Interfaces

- The user interface should be minimal consisting of a power button, a wake-up button, a display/video screen, and a beeper/speaker.
  - power button: This is used for powering up the device.
  - wake-up button: When the patient does not carry out the exercise for a determined period of time, the device automatically powers down to save power. To wake up from this sleep state, this button is used.
  - display/video screen: The display shall be used to warn the user if he is not performing the exercise properly, to show the number of counts, and for coaxing the patient to carry out the exercises.
  - beeper/speaker: In addition to coaxing, this feature can also be used for issuing warnings.
- Providing facility to store the data for post-processing and easy reading using commonly available systems like PC, PDA, and mobile is paramount. Usage of memory cards like MMC or SD cards has been proposed as an efficient way of storing the data. This enables the surgeon to easily keep track of the progress made due to the vast popularity of these cards and the associated readers.
- In order to provide flexibility in the use of the device, menu driven settings like: threshold setting for edge detection, power-down time, naming the data-file, and RTC time resetting may be incorporated with the help of a keypad.

III. Implementation Details

An ATmega32 Microcontroller and an Allegro-1321 ratiometric linear Hall-effect sensor has been used to make measurements. At present, a microSD card available in the laboratory is used to store the data. However the amount of data that will be collected for a one hour session will be approximately 100 kB. With an on-chip 10-bit ADC, the Hall sensor outputs can be digitally recorded and processed to make decisions regarding the validity of counts and effectiveness of the exercise. The block schematic is as shown in Fig. 1.

A. Choice of the sensor and sensed quantity

Due to the medical constraints on this device, it has been proposed to use Hall-effect sensors for measurements. Magnetic field sensing has been used by Shima, et al., [11] for measuring finger-tapping movements. Using accelerometers placed on the fingers would be a possibility, but it would mean loss of reliability of data due to the sensor being removable. Image processing techniques are also a possibility, but it would turn out to be too complicated and cost-inefficient. Using IR transmitters and sensors placed on the fingers would mean passing wires to the fingertips which would not be a viable option in a hospital environment. Considering all these factors, using hall sensors with tiny magnets attached to the fingertips seems appropriate and practical.

B. Placement of the sensors and sampling

Under normal conditions, the patient can flex quickest in about a second. Therefore a sampling frequency of 50 Hz is chosen. Two sensors are placed at the two extremities of the movement, one on the base of the palm, the other at a fixed distance from the fingertip in the extended position. These two sensors are to be excited in an alternating fashion, thus certifying that the finger has been completely flexed. An image of the experimental setup is shown in Fig. 2.

C. Timing and data storage

A Real Time Clock IC is used to keep track of time, independent of the Microcontroller and this is used for time-stamping the data. DS 1307, a 64x8 serial I^2C interface device is used in this case. At each point in time when the patient commences the exercise, the time and corresponding number of counts is to be stored in the microSD card interfaced with this system. A GPL licensed library for the SD-card interface with ATmega controllers [12] is used. This will allow for the

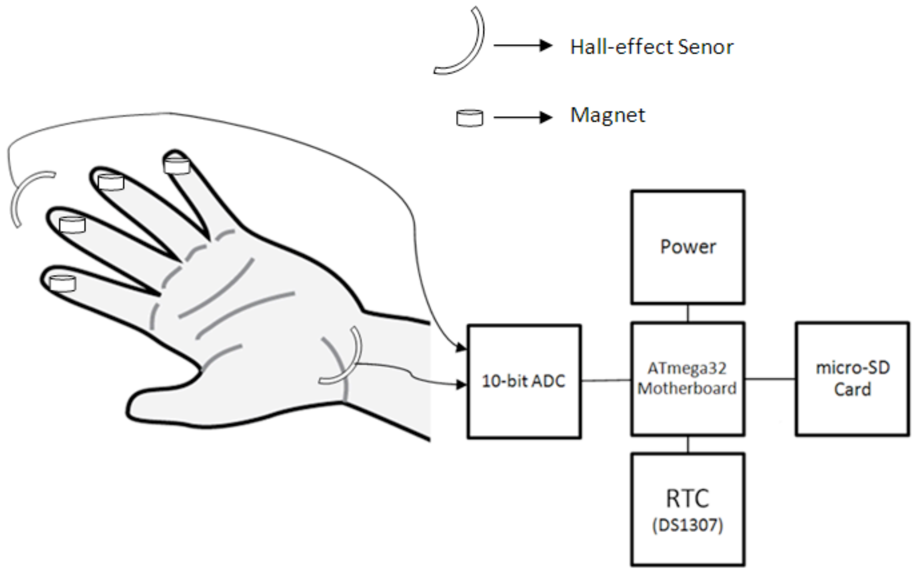

Fig. 1. Block Diagram

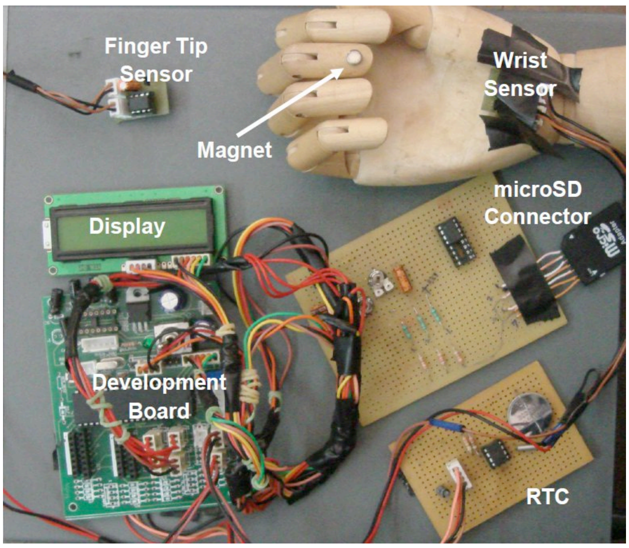

Fig. 2. The experimental apparatus

post-processing of the data recovered from the patient when he periodically goes for check-ups or even remotely consults the doctor by sending him the datalog file.

D. Recording and Decision Making

Since continuous data checking would be unnecessary, a threshold of magnetic field(Gauss) is used to detect the proximity of the finger to the Hall-sensor. As the two sensors continually keep sending data through the ADC, it is checked for being in the range of around the threshold, between 10 G to 15 G above the ambient condition. This threshold is measured to be a value corresponding to a distance of 2.5 cm away from the sensor in the direct axis of measurement. As soon as the system detects a crossing of this threshold, the direction of crossing, either rising or falling is checked over a range of 20 samples. This is to eliminate noise and false crossings. If more than 15 samples fall under this monotonic change, then it is either a rising or falling edge, which corresponds to the finger approaching or receding away from the sensor. Once the type(rise/fall) of crossing has been confirmed, a counter is started to measure the time for which this event extends, until another crossing is detected. This enables the system to keep track of each time durations of the movement and hence the sum of this will be the total time taken for one iteration of the exercise. The edges are used to determine the temporal order of the events.

Detection of a rising edge on a sensor following a falling edge on it before a rising edge on the other sensor is logged implies that the fingers have not approached the other sensor and hence the flexing or extending has not been done completely. This is recorded as an error and is announced on the display, and the count is not updated for that iteration until the other sensor sees a rising edge. Also, as soon as one complete iteration of the exercise is detected, time-stamping of the count is done and all the relevant time data along with the time-stamp is stored in the microSD card. This is done as soon as the count is validated in order to secure the data.

If no edge is seen on ADC for a duration more than 10 seconds, it means that the patient has stopped exercising. The system has to be powered down to save power. To come out of the sleep mode, the patient/attender has to press a wake up button, which is an external interrupt for the ATmega32, to restart the device.

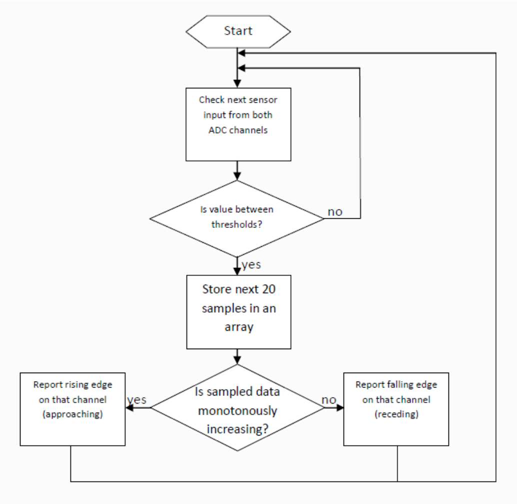

Fig. 3. Flowchart

E. *Power and size specifications*

The device is expected to have a large battery life(to last for one complete course of physiotherapy), and the size and weight has to be medically acceptable. A single 23AE 12 V alkaline battery [13] is chosen as the power source. This offers a weight of 8 grams and a size 28.9 mm long with 10.3 mm diameter. With a nominal capacity of 55 mAh, it is expected to last for about 100 hours, which translates to 4 weeks at 4 hours of exercise-time per day.

The current PCB version with SMDs has a dimension approximately 8x5x5 cm^3 making it fit comfortably on the patients forearm. This is displayed in Fig. 4. The attachment for the memory card holder and the battery carrier for the RTC are on the bottom side of the PCB. It can be observed that there is still scope for miniaturizing the device, possibly with a piggyback arrangement. The sensors are placed at the base of the palm and behind the outstretched fingers in separate attachments.

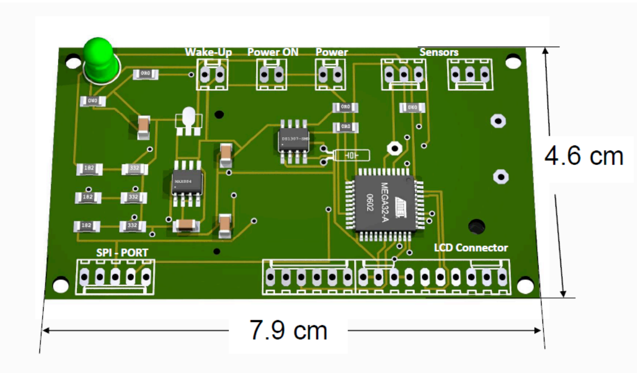

Fig. 4. PCB design Version-1: a 3D rendering

IV. Testing and Calibration

The idea is to essentially transform the magnetic-field data into a relevant distance plot so as to ascertain the closest distance of approach of the magnet and hence the finger to the sensor. This calls for calibration of the sensed voltage versus distance using the magnetic-field data. As per the sensor characteristics, it is linearly related to the magnetic-field in the region of sensing.

Due to the size constraints mentioned earlier and to minimize the interference from the adjacent magnets on the fingers, the magnets cannot be larger than the size of a fingernail. The magnets used here have a dimension of 6 mm in diameter and 3 mm in height and hence the magnetic-field variation around it will not have a linear variation with distance for distances of concern. Therefore some knowledge of the magnetic-field variation around the magnet in use is essential. For the sake of information, the magnet has a weight of 0.64 grams.

A. *Magnet Calibration*

In the course of testing, the ratiometric sensor was powered with a standard 5 V supply and as per the design, for ambient magnetic field, the output was 2.54 V. The sensor has an output sensitivity of 5 mV/Gauss. This amounts to a resolution of about 1 Gauss/bit. For distances closer than 0.5 cm along the axis of the sensor, saturation of the ADC was observed, implying that the field is higher than 500 G. On the other hand, for distances farther than 5 cm, no variation was detected. The magnet used here is directionally specific, in that, even 1 cm radially away from the direct axis of measurement, the field variation was negligible.

The choice of the magnet as an exciter has both advantages and disadvantages. The sensing happens only in the small cylindrical volume of about 3 cm in height and 1 cm in radius around the direct axis of the sensor. These spatial dimensions are perfectly suited for sensing the approaching of a finger. However, for the given dimensions of the magnet, the field vs distance variation is not linear for the distances where sensing is necessary.

A plot of variation of the magnetic field along the axis of measurement for the distances mentioned earlier is shown in Fig. 5. The saturation point of the ADC is seen at a distance of 0.4 cm from the sensor. It is observed here that the magnetic field varies roughly as an inverse square with distance due to the point-like physical dimensions of the magnet in relation to the distances measured.

B. *Timing Calibration*

From measurements of the speed and scale of movements possible by recovering patients, it has been deduced that the time quantization need not be lower than 20 ms. This translates to a sampling frequency of 50 Hz. Although considered not essential, timing information for individual events of movements can be acquired to provide a quantitative assessment of the rate of healing of individual flexor and extensor tendons. With this in mind, the sampling frequency has been set to 50 Hz for ensuring optimal time resolution with reliable data logging with enough samples to work with, for checking the rising or falling edge conditions.

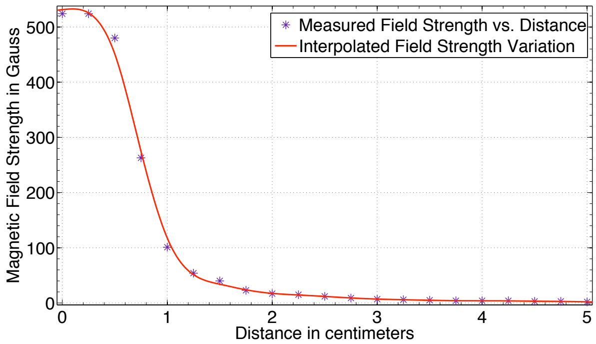

Fig. 5. Magnetic Field along direct axis vs Distance

V. Results

A sample of the typical data captured on the wrist sensor and the fingertip sensor is shown in Fig. 6. Every pulse in the figure represents an extremity in the movement, either at the wrist or at the outstretched position of the finger. The width of each pulse signifies the time duration for which fingers have been positioned close to the sensor and the rise-time and fall-time are proportional to the speed of movement. As the exercise demands, this process is repetitive and alternating between the two extreme positions, hence the two sensor data are time-shifted with respect to each other. The figure also contains the recording of an erroneous activity by the user. The mistake committed by the user is that one of the sensors(the fingertip sensor) has been approached twice in succession before he has moved his fingers towards the wrist indicating that the exercise is not done properly. The figure also shows the missing pulse on the wrist sensor during the same period. This information can be processed to extract certain vital features of the healing process [14].

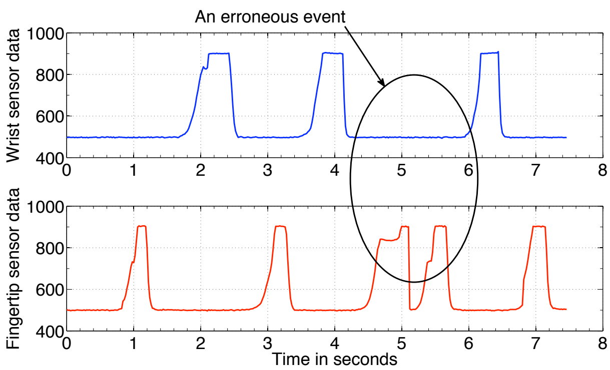

Fig. 6. Sample data signals from the ADC

The results presented above is on a laboratory prototype. The device to be deployed in clinical trials is under fabrication. Considering the care taken in the design and development of the device, it is expected that it will be comfortable and easy to use.

VI. Applications

With the dependence of human productivity on the health of his fingers, the utility of this device in physical medicine and rehabilitation is vast. It has been tested with an orthosis for tracking movements reliably. The magnets used here have the right intensity distribution so as to give a definitive measure of the counts and the quality of the physiotherapy done. It is believed that this shall considerably reduce the recovery time of the injury. This device can also be used for treatment of non-traumatic stiffness of tendons especially in the case of aged people.

VII. Conclusions

A device to monitor the mobilization of fingers during the healing process of the tendons is presented in this paper. The device is conceptualized and developed in close association of orthopedic surgeons and academicians in the engineering field. The general features of such a device are identified and many of them are implemented. The weight and size of the device is thoroughly minimized. With a reduced size of the controller housing and display, it is possible to make the device akin to a wristwatch.

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