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Wearable Kinesthetic System in Post-Stroke Rehabilitation: A Review of Sensor in Body Motions Detection

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***Abstract*—This paper presents a system with various kinematics parameters considered to capture and classify body gestures for user's recovery. The concepts involved are briefly explained in this paper. Basically, two devices concepts are explained, which are the Upper Limb Kinesthetic Garment (ULKG) and OPAL technologies. The method of literature search used is discussed in methodology, while detailed information from reviews on particular devices is analysed. Then, the performance and feedback from users are compiled to indicate usability on both devices under the results section. Both ULKG that used conductive elastomer (CE) and OPAL sensor are compared to figure out which sensor is more appropriate for users.**

***Index Terms*—Wearable Kinesthetic System; Post-Stroke Rehabilitation; Upper Limb Kinesthetic Garment (ULKG); OPAL Technologies; Conductive Elastomer (CE).**

I. Introduction

This paper aims to review articles about the wearable kinesthetic system for capturing and classifying both gestures in post-stroke rehabilitation. Stroke patients need a light, small, wearable instruments in several rehabilitation areas on the body. The purpose of the instruments is to collect data of gestures from post-stroke users. Therefore, it is necessary for them to be comfortable and convenient to wear and carry the instrument for daily physical activities.

Normally, coordinated human movements are smooth, but post-stroke patients seemed to be jagged on the affected part and need recovery aid to regain smoothness [1]. It is troublesome for them to do clinical visits frequently for physical therapy to analyse and provide suitable exercises for them. Therefore, a wearable sensor to collect and store data of gesture of users is needed. A material named conductive elastomer (CE) brought the possibility to set up the electrical sensor on stretchable fabric. It is electrically conducting and stretchable, unlike wiring system that limits movement of users [2]. The employment of CE does not change the mechanical properties of the fabric, and it confers the fabric piezoresistive properties related to mechanical solicitations. These properties are used in many sensorized fabrics, such as gloves, leotards and seat cover that monitor body postures and gestures [3].

Furthermore, with this technology, by using the same material in a single printing and manufacturing process, both sensor and connecting wires can be smeared. True comfort is archived by avoiding uses of metallic wires.

Meanwhile, OPAL sensor is a device that is suitable for post-stroke users too. OPAL wearable sensor is not as convenient as CE, but its usability cannot be ignored, because it is a well-developed technology by a company named APDM in Portland, United States. It includes accelerometer, gyroscope and magnetometer in the device [3]. The advantages of this technology are having a high sampling rate, able to access raw data, long battery life (up to 50 hours), easy to stream and log data. Moreover, it is also able to connect up to 24 OPALs on one network, which brings advantage to capture and classify gestures from the whole body [4]. Three main components of these devices are data acquisition, feature extraction and classification [3].

This paper is organised as follows. In the next section, the reviews based on previous findings are described and summarised. Finally, our work of this paper is summarised in the last section.

II. Research Methodology

This paper's literature search is limited to sources that are published after year 2000. Keywords that are used in the online search engine are "wearable sensor" and "post-stroke rehabilitation". Concepts and information for completing this project are obtained from different sources, like google scholar, IEEE webpage, Scopus and so on. First, related articles are read and understood; then, suitable information is extracted without 'copy and paste', which means, the ideas are presented in authors' own words. All the information is analysed and summarised to achieve the purpose of this paper. A total of 29 papers are reviewed for sufficient information.

III. Result and Analysis

There are three main components in a rehabilitation system for post-stroke patients. They are data acquisition, feature extraction, and classifier. The system is constructed to build a good rehabilitation system exercise for post-stroke patients.

Figure 1: OPAL Sensor [4]

A. Data Acquisition

For data acquisition, to connect the computer with the signals from the outside world, a DAQ hardware device is used. Signal conditioning circuitry, an analogue-to-digital converter (ADC), and a computer bus are the three main components of a DAQ device to measure a signal from outside world [5]. A DAQ device or wearable sensor, called OPAL produced by APDM (Portland, OR, US), is used to record the movements of post-stroke patients. The OPAL sensor includes an accelerometer, gyroscope, and magnetometer. Different parts of the patients' body can be mounted on with the OPAL sensor. For example, patients' chest, shoulder and leg. The long axis of the body segment is exactly aligned by the y-axis of the sensors [3]. There are seven to eight OPALs used on upper limb. Each OPAL sensor is 48.5 x 36.5 x 13.5mm, weighs 22 grams, and has a sampling rate of 40Hz [4].

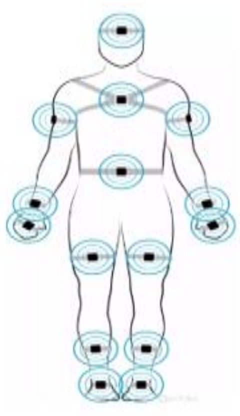

Figure 2: Position of wearable sensor mounted on the patient's body [4]

B. Feature Extraction

In feature extraction, accelerometer and gyroscope are selected to record the subject's movement. The input data will filter the wrong data that will give false or wrong information to the classifier and reduce the accuracy. Accelerometers collect the changes of acceleration. It is a mechanical sensing unit, which consists of a test mass attached to a mechanical suspension system concerning a reference frame. Inertial forces cause the mass to deflect according to the Newton's Second Law. The gyroscope collects the rotation about an axis. The different axis of gyroscope measures different axis of rotation. These sensors can control the conditions accurately [6]. In OPAL sensor, the triaxial gyroscope is combined with a triaxial accelerometer to measure rotational velocities and inertial force. The translational acceleration recorded by the accelerometer is double integrated, and angular velocity measured by the gyroscope is integrated to estimate the orientation of body segment of patients [7].

C. Classification

In the exercise classification stage, the software is to classify the data collected. Software with its high accuracy and minimal computational complexity in activity recognition is needed [8]. In OPAL, a decision tree is chosen. The decision is a useful and accurate tool in the classification of data, description of data and generalisation of data. Multiple fields that decision tree can work, such as statistics, pattern recognition, decision theory, signal processing, machine learning, and artificial neural networks [9]. Based on the results of the decision tree, the wrong information can be extracted, and the exercise rules are formed. Finally, the improper movement is identified and extracted by the exercise rules. Figure 3 shows the example of the angle information that has been classified.

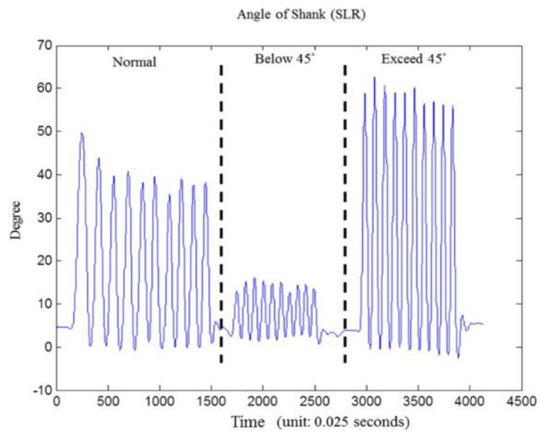

Figure 3: Angle information for improper movement detection of shank angle during the SLR (straight leg raise) exercise, from left to right: standard normal movement, below 45 degree, and exceed 45 degree [3]

1) Problem/Disease: Post-stroke using Conductive Elastometer (CE) Sensor

Electrical conductivity and mechanical stretchability are both found in CE. Stretchable electronics, stretchable energy harvesters and stretchable sensors are three main application fields of CE.

i. Stretchable electronics
   - Includes stretchable display units, memories and stretchable logic gates. Those devices have their own structures, but they are generally organised with few components like interconnects, transistors, light-emitting diodes (LEDs) and dielectrics.

ii. Stretchable sensors are divided into two categories.
   - Chemical sensors: To sense chemical properties in gas or liquid phase.
   - Physical sensors: To sense properties related to physical quantity, such as temperature, stress and strain.

iii. Stretchable energy harvesters include thermoelectric energy harvesting due to the global warming issue. Moreover, there are solar energy harvesting and also piezoelectric energy harvesting [10].

CE is produced by using graphite mixture and silicon rubber. Sensors are integrated into Lycra fabrics directly by using CE because it is a human's movement capable garment. Throughout the designing process of spreading mask based on the joints that need to be monitored, important information from garments is obtained. There are two different examples of kinesthetic interfaces, which are upper limb kinesthetic garment (ULKG) and sensing glove [11].

Figure 4: Upper limb kinesthetic garment (ULKG) [11]

Figure 5: Sensing glove prototype [11]

2) Upper Limb Kinesthetic Garment

i. ULKG are used for capturing postures of shoulder, elbow and wrist from the user. It is done for easing post-stroke users to continue their recovering exercises at home [12].
ii. ULKG collects data from joints of the upper limb (shoulder, elbow and wrist joints) by locating 20 sensors around the shirt. Segment series which compound the bold track is used to represent all sensors while the wiring system is build up by thin gallery [13].

Figure 6: ULKG prototype [13]

i. The Figure below shows the mask used to realise ULKG. Set of sensors connected in series are represented by bold black tracks, s_i, while the connection between electronic acquisition system and sensor set are represented by thin track, R_i [11].

Sensing glove

i. Sensing glove is used to capture data of gesture and posture by hands and fingers [12].
ii. A mask is utilised to print conductive elastomers sensor on a glove made of Lycra fabric, known as the sensing glove [13].
iii. It is not necessary to connect the glove to other electronic devices, such as smartphones and tablets [13].
iv. The capability of sensing glove depends on the optical fibre Bragg gratings (FBGs) sensors. The developed glove can provide numerical data about the hand postures' angles in real time [14].

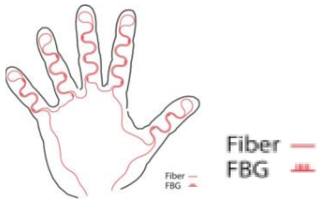

Figure 8: FBG sensor positioning proposal [14]

Smart fabrics, such as Lycra fibre, which is directly used by CE to monitor patients' health-focused disciplines in a natural contest for an extended period. For example, bio-monitoring, rehabilitation, telemedicine and so on. To increase the effectiveness of monitoring gesture and posture by using wearable kinesthetic systems, piezoresistive sensors are printed on the fabric too [15].

Figure 9: Printed piezoresistive sensor for wearer [15]

A wearable sensing system to capture data from human gesture and posture that can be worn comfortably can be realised by sensing fabrics, even if it is worn for an extended period. Sets of polypyrrole (PPy) and carbon filled rubber (CFR) sensors are integrated into a glove and a leotard, linked to an electronic unit that handles the pre-filtered data gained by the sensors [16].

We have attributed:

i. Three degrees of freedom for shoulder
   - adduction-abduction
   - flexion–extension
   - rotation
ii. two degrees of freedom for elbow
   - pronation-supination
   - flexion-extension
iii. one degree of freedom for each inter-phalangeal joint of hand
iv. two degree of freedom to each metacarpophalangeal joint and trapezium-metacarpal joint
v. Consideration of relative movements between metacarpal bones is made too. [16]

Figure 10: Sensing glove [16]

Figure 11: Leotard [16]

A motion capture system is used to monitor human motion. It can measure data accurately, but conventional sensors positioned on the garment by a strap, or other methods caused them to be inconvenient and uncomfortable to be used. Textile solutions, like Lycra fibre, solve the problem because it can integrate sensing system well with clothing; it allows users to be more comfortable during usage. The change in fabric's electrical resistance when tested on human's elbow and knee bend under different angles [17].

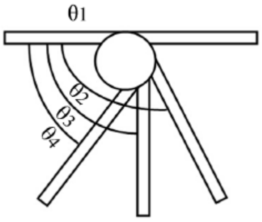

Figure 12: Illustration of different bending angles of knee and elbow joints [17]

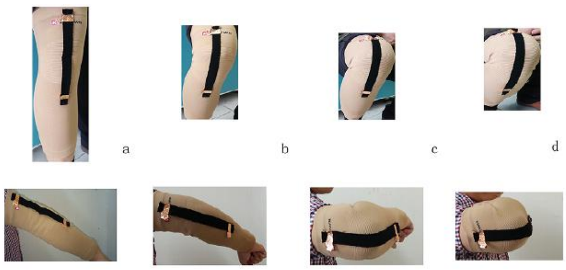

Figure 13: Bending tests of human knee and elbow joints [17]

D. Performance of Textile Strain Sensors

Strain sensors are used in garments, which functioned to detect human motions. Sensitive strain sensor based on nanocomposite of silver nanowire (AgNWs) network and PDMS elastomer, which is more flexible and stretchable would be a good choice for numerous strain sensors for the selected sensor used in fabrication. The performance of sensor as shown in Figures 13 and 14 [18][19].

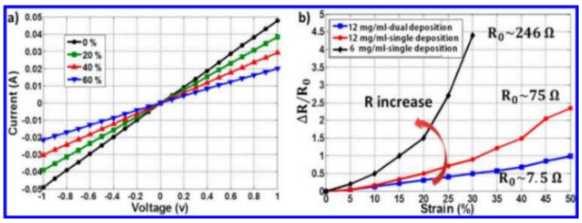

Figure 14: Electromechanical response of the sandwich-structured AgNWs-PDMS nanocomposite strain sensors to strain supplied [18]

(a) current-voltage curves of the strain sensor for different levels of strains;

(b) relative change of resistance versus strain for the sensors with different levels of initial resistance.

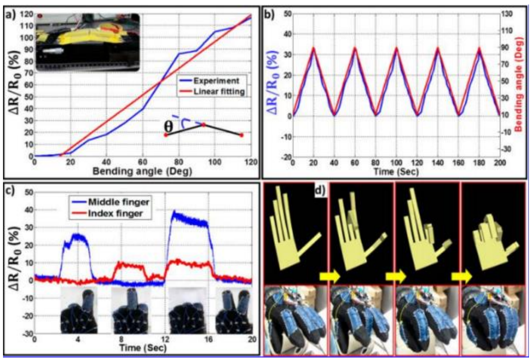

Figure 15: Human motion detection by the sandwich-structured AgNWs [19]

where PDMS nanocomposite strain sensors:

(a) Response from the sandwich-structured strain sensor to the bending angles (0° to 120°);

(b) Response from the strain sensor under repeated bending and relaxation cycles (10° – 90°);

(c) Motion detection of the index and middle fingers;

(d) Control of avatar fingers in the virtual environment using wireless smart glove system

The arrangement of strain sensors on upper-limb kinesthetic garment and regions of elongation for characteristic movements is shown in Figure 16.

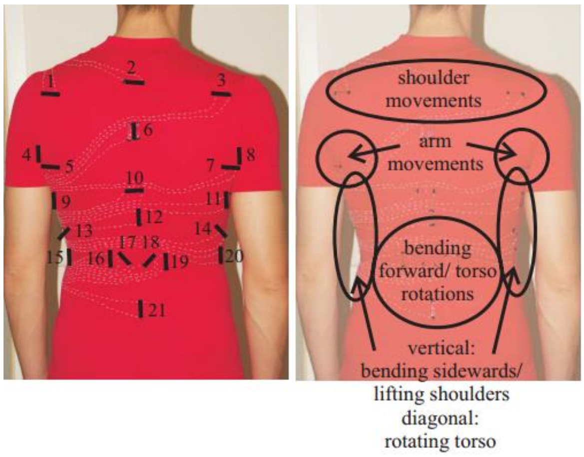

Figure 16: Placement of 21 strain sensors in upper-limb kinesthetic garment and regions of elongation for characteristic movements.

Due to its flexibility, the circuit will not be easily broken down, and strain sensor can convert the analogue signals (stretching of fingers) into digital signals (resistance). Thus, precise outputs can be determined by using strain sensors, and strain sensor circuit can be printed on the garment by using smart fabric ink [21].

E. Performance of conductive elastomer (CE) Sensors

Motion recognition by using conductive elastomer is based on the strain sensor technology [18][19], directly printed on garments as reference [13][21]. Conductive elastomers (CE) are polymer-based materials, which exhibit electrical conductivity. Patients are assigned to carry out the following rehabilitation exercises [20].

List of rehabilitation exercises under test [20]:

i. External rotation with elbow flexed at 90°
ii. Extension and flexion of the elbows
iii. Prone-supination of the forearms
iv. Functional: combing one's hair
v. Functional: eating
vi. Abduction and adduction of the upper limb in the frontal plane
vii. Abduction and adduction of the upper limb in the sagittal plane

Table 2
Performance of Conductive Elastomer in Sensing Glove [13].

	MP	PI	DI
Real	45	45	0
Estimated	45	45	0
Real	45	22.5	22.5
Estimated	45	25.31	15.47
Real	45	45	45
Estimated	45	42.19	45
Real	75	75	25
Estimated	80.16	67.5	32.34
Real	60	0	0
Estimated	60.47	0	8.44
Real	22.5	22.5	22.5
Estimated	22.5	22.5	22.5

where:

- MP represents metacarpophalangeal joint;
- PI represents proximal interphalangeal joints;
- DI represents distal interphalangeal joint of the forefinger.

This shows that the average error percentage in detecting the angle is only about 4%.

F. Performance of Product Concept Neurological Rehabilitation system

This system is to show the satisfaction of upper-limb kinesthetic garment (ULKG) users and helps to correct the users if their therapies are wrong [20].

Figure 18: The feedback interface. Traffic lights signal the start of an exercise; bars grow to show progress; the face smiles or frowns depending on the correctness of the execution [20]

G. Performance of OPAL

Post-stroke patients are required to wear the OPAL and carry out the Codman's rehabilitation exercise. Codman shoulder exercises are more commonly called pendulum exercises. These exercises allow patients' shoulder joint to move without using the muscles in patients' shoulder [9].

Figure 19: Shoulder rehabilitation exercises [24]

Accelerometer and gyroscope, which are inside the OPAL, record the input data, and the decision tree analyses the data to classify the correct and wrong motion of the post-stroke patients.

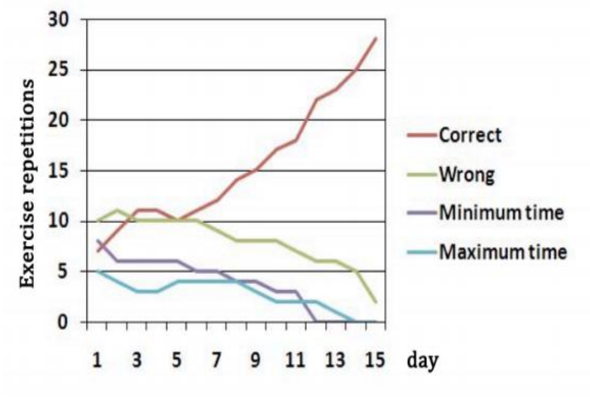

Figure 20: Daily evolution of the patients' rehabilitation during the tests [23]

The system can prevent the consequence of inadequate physical recovery. With the guides of the system, post-stroke patients can enhance the performance of the rehabilitation exercise.

IV. Result and Discussion

OPAL sensor and Conductive Elastomer (CE) sensors are advanced in the detection of body motions. At the same time, both sensors have their own advantages and disadvantages. CE sensor, with strain sensor built-in, has the advantage of high flexibility and stretchable [26][27]. This ensures that the circuit with strain sensor will not break down easily. Besides, due to CE sensor is directly printed on the upper-limb kinesthetic garment; it is comfortable to users when in contact with body skin [30]. The OPAL sensor has the advantage of high battery life, which can last for 50 hours. OPAL sensor also eases the system to stream and log data. Its data sampling rate is high to ensure the raw data can be accessed.

However, the larger size of OPAL sensors limits the motions of a patient. This causes the patient feeling uncomfortable wearing the sensor during the rehabilitation exercises. OPAL sensors as a combination of electronic sensors, such as accelerometer, gyroscope and magnetometer, which weighted 22 grams in each sensor, and they become a burden to a post-stroke patient compared to Conductive Elastomer sensor, which consists of only strain sensor that directly printed on upper-limb kinesthetic garment [25][28].

By comparing the two sensors, a CE sensor is more suitable for rehabilitation of a post-stroke patient. The OPAL sensor can also be used in another field such as robotic movement monitoring.

V. Conclusion

To enable the physician and post-stroke patients to manage the rehabilitation process, we have identified the two types of body-worn sensors which are Conductive elastomer (CE) sensor and OPAL sensor. Upper limb kinesthetic garment (ULKG) and sensing glove are developed with the stretchability of the CE sensor. The concept of the wearable sensor to help the post-stroke patients is to record the motion of patients and analyse the data. In this case, OPAL sensor used the accelerometer and gyroscope, while the ULKG used the textile strain sensors. The textile strain sensor in CE is more accurate results in detecting the motion of patients because accelerometer and gyroscope cannot be attached tightly to the joint of the patients. Furthermore, OPAL sensor is often unable to satisfy the safety requirements for the presence of mechanical part in the movement.

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REFERENCES

[1] Rohrer, Brandon, Susan Fasoli, Hermano Igo Krebs, Richard Hughes, Bruce Volpe, Walter R. Frontera, Joel Stein, and Neville Hogan. "Movement smoothness changes during stroke recovery." *Journal of Neuroscience,* 22(18), 2002, pp. 8297-8304.

[2] Tognetti, Alessandro, Federico Lorussi, Raphael Bartalesi, Silvana Quaglini, Mario Tesconi, Giuseppe Zupone, and Danilo De Rossi. "Wearable kinesthetic system for capturing and classifying upper limb gesture in post-stroke rehabilitation." *Journal of NeuroEngineering and Rehabilitation,* 2(1), 2005, pp. 8.

[3] Kun-Hui Chen, Po-Chao Chen, Kai-Chun Liu and Chia-Tai Chan, Wearable Sensor-Based Rehabilitation Exercise Assessment for Knee Osteoarthritis, *Sensors*, 15(2), 2015, pp. 4193-4211

[4] APDM Wearable Sensors, [Online]. Available: http://www.apdm.com/wearable-sensors/ [Accessed: 21- Apr- 2017].

[5] National Instrument Corporation, [Online]. Available: http://www.ni.com [Accessed: 21- Apr- 2017].

[6] Simoes, Mario A. *Feasibility of wearable sensors to determine Gait parameters.* University of South Florida, 2011.

[7] El-Gohary, Mahmoud, Lars Holmstrom, Jessie Huisinga, Edward King, James McNames, and Fay Horak. "Upper limb joint angle tracking with inertial sensors." In *Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE*, pp. 5629-5632, 2011.

[8] Ermes, Miikka, Juha Pärkkä, Jani Mäntyjärvi, and Ilkka Korhonen. "Detection of daily activities and sports with wearable sensors in controlled and uncontrolled conditions." *IEEE Transactions on Information Technology in Biomedicine,* 12(1), 2008, pp. 20-26.

[9] Murthy, Sreerama K. "Automatic construction of decision trees from data: A multi-disciplinary survey." *Data Mining and Knowledge Discovery*, 2(4), 1998, pp. 345-389.

[10] Noh, Jin-Seo. "Conductive elastomers for stretchable electronics, sensors and energy harvesters." *Polymers,* 8(4), 2016, pp. 123.

[11] Tognetti, Alessandro, Federico Lorussi, Mario Tesconi, Raphael Bartalesi, Giuseppe Zupone, and Danilo De Rossi. "Wearable kinesthetic systems for capturing and classifying body posture and gesture." In *Engineering in Medicine and Biology Society, 2005. IEEE-EMBS 2005. 27th Annual International Conference of the*, pp. 1012-1015, 2006.

[12] Werner, Douglas H., and Zhi Hao Jiang, eds. *Electromagnetics of Body Area Networks: Antennas, Propagation, and RF Systems*. John Wiley & Sons, 2016.

[13] Tognetti, Alessandro, Federico Lorussi, Raphael Bartalesi, Mario Tesconi, Giuseppe Zupone, and Danilo De Rossi. "Analysis and synthesis of human movements: wearable kinesthetic interfaces." In *Rehabilitation Robotics, 2005. ICORR 2005. 9th International Conference on*, pp. 488-491, 2005.

[14] da Silva, Alexandre Ferreira, Anselmo Filipe Gonçalves, Paulo Mateus Mendes, and José Higino Correia. "FBG sensing glove for monitoring hand posture." *IEEE Sensors Journal,* 11(10), 2011, pp. 2442-2448.

[15] Pacelli, M., G. Loriga, N. Taccini, and R. Paradiso. "Sensing fabrics for monitoring physiological and biomechanical variables: E-textile solutions." In *Medical Devices and Biosensors, 2006. 3rd IEEE/EMBS International Summer School on*, pp. 1-4, 2006.

[16] Lorussi, Federico, Alessandro Tognetti, Mario Tesconi, Giuseppe Zupone, Raphael Bartalesi, and D. Rossi De. "Electroactive fabrics for distributed, comfortable and interactive systems." *Studies in Health Technology and Informatics,* 117, 2005, pp. 17-24.

[17] Jiyong, Hu, Zhang Xiaofeng, Li Guohao, Yang Xudong, and Ding Xin. "Electrical properties of PPy-coated conductive fabrics for human joint motion monitoring." *Autex Research Journal,* 16(1), 2016, pp. 7-12.

[18] Amjadi, Morteza, Aekachan Pichitpajongkit, Sangjun Lee, Seunghwa Ryu, and Inkyu Park. "Highly stretchable and sensitive strain sensor based on silver nanowire–elastomer nanocomposite." *ACS Nano,* 8(5), 2014, pp. 5154-5163.

[19] Mattmann, Corinne, Oliver Amft, Holger Harms, Gerhard Troster, and Frank Clemens. "Recognizing upper body postures using textile strain sensors." In *Wearable Computers, 2007 11th IEEE International Symposium on*, pp. 29-36, 2007.

[20] Giorgino, Tormene, P. Tormene, G. Maggioni, D. Capozzi, S. Quaglini, and C. Pistarini. "Assessment of sensorized garments as a flexible support to self-administered post-stroke physical rehabilitation." *European Journal of Physical and Rehabilitation medicine,* 45, no. 1, 2009, pp. 75-84.

[21] J. Nurse, "Smart Fabric Inks: Printing technology onto future fashions - Future Worlds", *Future Worlds*, 2015. [Online]. Available: https://futureworlds.com/smart-fabric-inks-printing-technology-onto-future-fashions/. [Accessed: 21- Apr- 2018].

[22] Yu, Lei, Daxi Xiong, Liquan Guo, and Jiping Wang. "A remote quantitative Fugl-Meyer assessment framework for stroke patients based on wearable sensor networks." *Computer methods and programs in biomedicine,* 128, 2016, pp. 100-110.

[23] Aubrey Bailey. Codman Shoulder Exercises. 2015

[24] Raso, I., Hervás, R. and Bravo, J., "m-Physio: personalized accelerometer-based physical rehabilitation platform". In *Proceedings of the Fourth International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies, 2010,* pp. 416-421.

[25] John J. Rychcik, Jan E. Vandemeer, and Mark L. Shaw, "Characterizing Input Saturation in Low-g Accelerometers", Archives.sensorsmag.com, 2002. [Online]. Available: http://archives.sensorsmag.com/articles/0502/68/main.shtml. [Accessed: 21- Apr- 2017].

[26] Arlt, G. "The sensitivity of strain gauges." *Journal of Applied Physics,* 49(7), 1978, pp. 4273-4274.

[27] J. Johnston and K. Coffey, "Getting the Most out of Strain Gauge Load Cells", Archives.sensorsmag.com, 2000. [Online]. Available: http://archives.sensorsmag.com/articles/0500/52/. [Accessed: 21- Apr- 2017].

[28] A. Kostiainen and R. Bhaumik, "Magnetometer", *W3.org*, 2016. [Online]. Available: https://www.w3.org/TR/magnetometer/. [Accessed: 21- Apr- 2017].

[29] Peter Van Vessem and Don Williams. "Rediscovering the Strain Gauge Pressure Sensor", Sensors-Peterborough, 16, pp. 36-4.