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A New Potentiometer-Based Goniometer Design in Joint Angle Measurement

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ABSTRACT

Accurate measurement of joint angles is critical in the diagnosis, monitoring, and treatment of musculoskeletal disorders. In this study, we focus on developing a reliable system for measuring the elbow joint angle in a clinical setting, utilizing an exoskeletal linkage-based approach. To achieve this, we design and implement a novel goniometer that combines mechanical simplicity with high measurement accuracy. The device is built around a modern AVR microcontroller platform, ensuring ease of manufacturing, low power consumption, and real-time performance. One of the key innovations of this work lies in the ergonomic and wearable physical design, which enhances user comfort and minimizes interference with natural joint movement. The proposed system is lightweight, compact, and can be worn for extended periods without discomfort, making it particularly suitable for patient use in both clinical and ambulatory environments. Furthermore, the goniometer supports real-time data acquisition and communication via a USB interface, allowing for seamless integration with external monitoring or data logging systems. This feature facilitates mobility during experimental procedures while maintaining continuous tracking of joint kinematics. Overall, the proposed solution presents a practical and efficient tool for clinicians and researchers seeking accurate and wearable joint monitoring systems.

1. INTRODUCTION

The joint angle measurement has been emerged as a key factor in clinical researches due to its simple and comparable output that leads clinicians to assess treatments and compare individual features with reference databases [1], [2]. Over past decades, several joint angle measurement techniques such as X-ray analysis [3], fiber optic sensors [4], exoskeletal linkage methods, stereo sonic techniques, frame by frame analysis [5], Inertial Measurement Unit (IMU) sensors [6], [7], and combination of accelerometers and gyroscopes [8]–[10] have been developed to satisfy the above challenges. Despite widespread usage of these methods, the techniques involve a complicated procedure in the angle measuring process, and each has its own disadvantages. Some of the advantages and disadvantages are

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stated in [3], [5]. Accelerometers, on the other hand, are widely utilized for the joint angle measurement and do not need any mechanical device to install on the human body. However, since accelerometers consider the acceleration of gravity as a basis of calculations, and the joint angles are obtained by an integration process, those typically are prone to inaccuracy [1], [8], [11]–[13]. The exoskeletal linkage method offers potentiometer-based and encoder-based goniometers in achieving the accurate measurement of joint angles. In another aspect, the exoskeletal linkage method could be divided into two major categories. The first one includes goniometers which model the structure of a joint using one axis of rotation, as in references [8] and [14]. Another group models the structure of a joint with more than one axis of rotation, as in [15]. Choosing between these two groups is a compromise between simplicity and accuracy. Salter in [16] claims that goniometers are so accurate and reliable, and any error is due to defective devices. Despite a high accuracy and simplicity in the implementation of potentiometers and encoders, these devices need mechanical equipment to install on body that causes inaccuracy and error. Broadly, goniometers are divided into three categories: 2-D (or planar) goniometers, 3-D goniometers and spatial goniometers. Planar goniometers are largely used due to the simple assessment of joint movements.

The International Standard Orthopedic Measurement (ISOM) [17] states that in clinical applications of the joint angle measurement, the angular rotation of joints in one plane is considered. The above challenges motivate us to propose a new goniometer that is simple enough to be implemented by state-of-the-art AVR microcontroller devices in reaching to a high precision in the joint angle measurement. To overcome the problems on installation methods, a unique physical design is used that results in a high degree of wearability and compatibility with the joint structure. In addition, the proposed technique achieves a high degree of accuracy due to the high compatibility with the joint structure. In addition, once the device is calibrated, it does not need any further setup before the experiments. Furthermore, the design offers the advantages of low weight and low cost in the implementation.

2. THEORY OF OPERATION

In this work, we aim to measure the angle of the elbow joint of a patient in a medical application using the exoskeletal linkage method. Toward this goal, we need to briefly describe the elbow joint internal structure. As shown in Fig. 1, the elbow joint and connected bones are covered with a thick layer of limb that is troublesome for installing and fixing an external device on this part. Earlier versions of goniometers were installed on the Humerus bone and the Extensor muscles that are the most unstable parts of the arm and produce noticeable errors in ambulatory experiments. To tackle this problem, we install our new designed instrument on the back of Humerus bone (point B in Fig. 1) and the bottom of Ulna bone (point A in Fig. 1). This type of installation benefits from a lower limb thickness and more stability than other parts of the arm during our experiments.

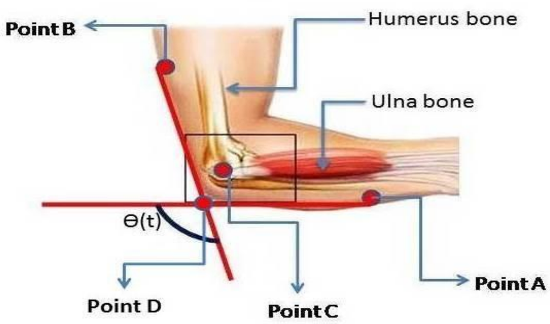

Fig. 1. Schematic of the elbow joint

Another challenge in previous works on the joint angle measurement is the position of the transducer on the goniometer. Most of commercial and prototypes of goniometers tend to place the transducer on point D in Fig. 1. This tendency makes the structure of the goniometer so simple; however, point D is not coincided with the center of rotation, i.e., point C in Fig. 1 which leads to the inaccuracy. In this work, a mechanical shift is applied to the transducer to align the transducer with the center of rotation and makes the new design more compatible with the joint structure (see Fig. 2).

3. STRUCTURE OF INSTRUMENT

This section aims to introduce the architecture of the instrument and in particular the significant elements of device. The designed goniometer consists of two major parts:

1. The electronic/programming section that comprises the electronic circuit and the code programmed on the microcontroller. In this part, the logical procedure for measuring the joint angle is covered.
2. The mechanic part that deals with the design of instrument and deployment of materials and components.

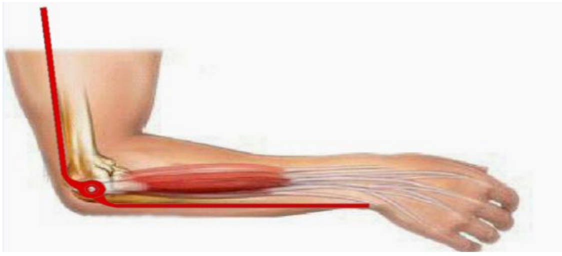

Fig. 2. Mechanical design of the new goniometer

3.1. Electronic/Programming Part

The electronic part of the designed joint angle measurement instrument is referred to the circuit board and the components including the AVR-ATmega8 IC, the FT232RL IC and a 10 KΩ potentiometer (see Fig. 3). The circuit board and the PCB are designed by the Proteus ver. 8 software. One advantage of the proposed device is its nominal voltage. Our instrument is designed to work with a single USB port (5 volts) and deploys a state-of-the-art microcontroller AVR-ATmega8 IC that is widely utilized in robotics and industry because of its high-performance, low-power consumption and advanced RISC architecture. The AVR-ATmega8 IC processes the following procedures:

The code which is considered as the functioning algorithm of the instrument is programmed on the AVR-ATmega8 IC. The Analog to Digital Convertor (ADC), converts the analog output of the potentiometer, $\theta(t)$, to digital data Dn. The program is written in C language using the CodeVision AVR software ver. 2.05. Since, our device uses the 10 bits ADC, the output of the ADC unit, denoted by Dn, has 1024 discrete values. In addition, the input voltage of the goniometer is 5 volts and the output voltage of the potentiometer varies from 0 to 5 volts, thus, the resolution of the ADC unit would be 5/1024 = 0.00488 volts.

The goniometer computes the angle using the digital data Dn. In the case of ideal performance, the ROM in the potentiometer is about 300 degrees and the output of the ADC unit is quantized into 1024 values. Thus, the angle resolution of the goniometer is 300/1024 = 0.293 degrees.

The AVR-ATmega8 IC communicates with the computer using the Serial Peripheral Interface (SPI) and the FT232RL IC to monitor and analyze the measured angles. More precisely, the FT232RL IC is an asynchronous serial data transfer interface between the AVR-ATmega8 IC and the computer. Since, the FT232RL IC supports the USB communication; the output of our designed instrument is accessible through PCs, laptops and Android-based smart phones. The PWM wave generator yields a Pulse Width Modulation (PWM) wave based on the measured angle to control the servo motor to drive a robotic arm.

In addition, we deploy a LC low pass filter (L=10uH, C=100 µF) in our instrument to decrease the sensitivity of the device to the noise which results in a better performance. Another source of noise is the electromagnetic inducements on the connecting wires of the potentiometer.

Fig. 3. The goniometer installed on the arm of a volunteer

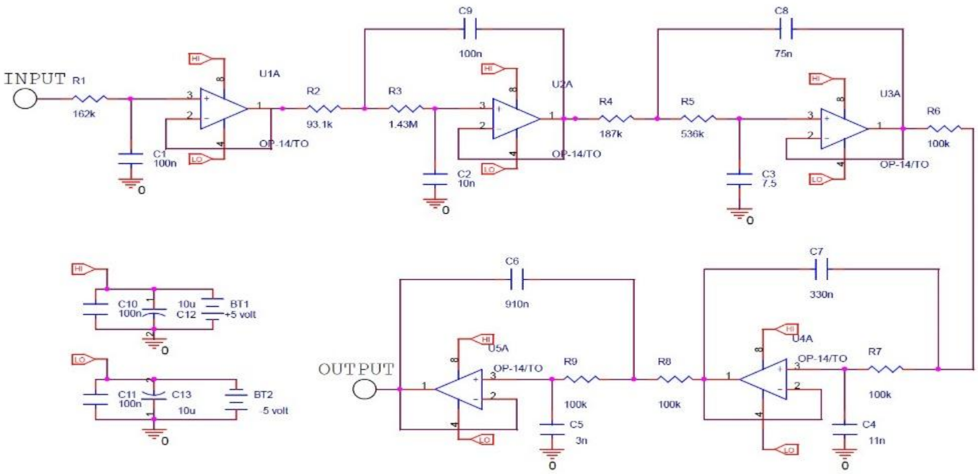

Fig. 4. The designed circuit board for the Chebyshev type 1 low pass filter on the order of 9.

The 50 Hz noise induced by the power-line is the main source of the electromagnetic interference. To overcome this problem, twisting the connecting wires as a simple solution is deployed. In addition, a Chebyshev type 1 low pass filter on the order of 9 is used to reject the above 10 Hz contents of the signal. We deploy the Filter Design and Analysis (FDA) toolbox of the MATLAB software to design the desired filter and to extract the coefficients. Through utilizing Active Filter synthesis techniques, the circuit board of the desired filter is designed in Fig. 4. It is worth mentioning that according to some precise computations, it is understood that the sampling rate of the proposed goniometer is 160 Hz.

3.2. Mechanic Part

The main part of the mechanical design is the part of the instrument installed on the arm that holds the transducer (see Fig. 3). Since the designed goniometer is used as a in clinical experiments, exactitude dimensions is the key factor in the mechanical design to match the mechanical parts together and to match the goniometer with the joint structure. Toward this goal, we deploy the AutoCAD software ver. 2007 which is fully compatible with the Computer Numeric Control (CNC) machines. The components are cut with a precise laser cut CNC. The material used for the mechanical parts is Plexi Glass that benefits from low weight, good looking surface and strong structure.Toward this goal, we deploy the AutoCAD software ver. 2007 which is fully compatible with the Computer Numeric Control

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Table 1. The results of the final test performed on N=10 participants

Marked angle degrees ϕ	Minimum measured angle	Maximum measured angle	Average $\bar{\phi}$	Standard deviation $\sigma_N = \sqrt{\frac{\sum_{i=1}^{N}(\phi_i - \bar{\phi})^2}{N}}$	Relative error $e_r = \lvert \frac{\bar{\phi}-\phi}{\phi} \rvert * 100\%$
$30°$	$30.2779°$	$30.8542°$	$30.59°$	$0.6197°$	1.967%
$60°$	$57.9357°$	$60.8364°$	$59.4379°$	$0.5668°$	0.9369%
$90°$	$86.679°$	$91.6893°$	$88.7345°$	$1.2702°$	1.4061%

4. EXPERIMENTAL SETUP

To examine the designed goniometer and to check its performance such as error, wearability and compatibility with the joint structure, we conducted a test with the following conditions. Ten people including five males and five females aging from 18 to 60 were volunteered to participate in our test. They were among the students and the staffs of the ECE department of Yazd University. In this test, the goniometer is installed on their arms as depicted in Fig. 3 and the participants were asked to move their hands to a specific angle. For this case, the output of the goniometer (ϕn) is recorded for ten times and this routine is performed on three different angles $\theta(t)$ = 30, 60 and 90 degrees. The procedure under test is performed through the following sequence of operations:

- The 30, 60 and 90 degree angles are marked on a wall precisely using a goniometer.
- The zero of the potentiometer and the zero of the goniometer are matched together.
- One leg of the goniometer is fixed to the Humerus bone and is aligned with $\theta(t) = 0$ and the other leg is fasten to the Ulna bone where this bone can be moved from $\theta(t) = 0$ to other marked angles.
- The output of the instrument is recorded.
- The participant is asked to move his/her arm toward $\theta(t) = 0$.

The results of the above tests are shown in Table I. As seen from Table I, the standard deviation factor is low enough to make the results of the designed goniometer reliable. The average $\bar{\phi}$, standard deviation σ_N, and relative error e_r factors show a high degree of repeatability. These features let the scientists to compare their results from different laboratories without being worried about the correctness of the results. It should be noted that the results of Table I could be compared with the similar works in [8] and [18].

5. CONCLUSION

In this paper, we designed and implemented a new goniometer for the joint angle measurement with focus on achieving a high degree of wearability and low error rate. By comparing the existing models of goniometers, we came to this conclusion that if we shift the position of the transducer to the center of rotation, our goals would be satisfied. Numerical results have shown a high degree of accuracy and repeatability; besides, attendees were completely pleased by the wearability and comfortability of the goniometer.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Cheng, P., & Oelmann, B. (2010). Joint-angle measurement using accelerometers and gyroscopes—A survey. IEEE Transactions on instrumentation and measurement, 59(2), 404-414.
[2] Hirose, K., Doki, H., & Kondo, A. (2012, August). A measurement method of the 2dof joint angles and angular velocities using inertial sensors. In SICE Annual Conference (SICE), 2012 Proceedings of (pp. 366-371). IEEE.
[3] Chao, E. Y. (1980). Justification of triaxial goniometer for the measurement of joint rotation. Journal of Biomechanics, 13(12), 989-1006.
[4] Patil, M. M., & Prohaska, O. (1988, November). Fiber optic sensor for joint angle measurement. In Engineering

in Medicine and Biology Society, 1988. Proceedings of the Annual International Conference of the IEEE (pp. 803-804). IEEE.
[5] Buchholz, B., & Wellman, H. (1997). Practical operation of a biaxial goniometer at the wrist joint. Human Factors, 39(1), 119-129.
[6] Bakhshi, S., Mahoor, M. H., & Davidson, B. S. (2011, August). Development of a body joint angle measurement system using IMU sensors. In Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE (pp. 6923-6926). IEEE.
[7] Tomaru, A., Kobashi, S., Tsumori, Y., Yoshiya, S., Kuramoto, K., Imawaki, S., & Hata, Y. (2010, October). A 3-DOF knee joint angle measurement system with inertial and magnetic sensors. In Systems Man and Cybernetics (SMC), 2010 IEEE International Conference on (pp. 1261-1266). IEEE.
[8] Dejnabadi, H., Jolles, B. M., & Aminian, K. (2005). A new approach to accurate measurement of uniaxial joint angles based on a combination of accelerometers and gyroscopes. IEEE Transactions on Biomedical Engineering, 52(8), 1478-1484.
[9] Watanabe, T., Saito, H., Koike, E., & Nitta, K. (2011). A preliminary test of measurement of joint angles and stride length with wireless inertial sensors for wearable gait evaluation system. Computational intelligence and neuroscience, 2011, 6.
[10] Sudin, S. (2012). Wireless knee joint angle measurement system using gyroscope (Doctoral dissertation, Universiti Tun Hussein Onn Malaysia).
[11] Bo, A., Hayashibe, M., & Poignet, P. (2011, August). Joint angle estimation in rehabilitation with inertial sensors and its integration with Kinect. In EMBC: Engineering in Medicine and Biology Conference (pp. 3479-3483).
[12] Djurić-Jovičić, M. D., Jovičić, N. S., & Popović, D. B. (2011). Kinematics of gait: new method for angle estimation based on accelerometers. Sensors, 11(11), 10571-10585.
[13] Cheng, P., Linnarsson, F., & Oelmann, B. (2007, November). Joint angular sensor based on distributed biaxial mems accelerometers. In IECON 2007-33rd Annual Conference of the IEEE Industrial Electronics Society (pp. 2242-2247). IEEE.
[14] London, J. T. (1981). Kinematics of the elbow. The Journal of bone and joint surgery. American volume, 63(4), 529-535.
[15] Cai, V. A. D., Bru, B., Bidaud, P., Hayward, V., Pasqui, V., & Gosselin, F. (2010). Experimental evaluation of a goniometer for the identification of anatomical joint motions. In Emerging Trends In Mobile Robotics (pp. 1255-1262).
[16] Salter, N. (1955). Methods of measurement of muscle and joint function. The Journal of bone and joint surgery. British volume, 37(3), 474-491.
[17] Russe, O. A. (1975). International SFTR method of measuring and recording joint motion. Bern: H. Huber;[Chicago].
[18] Williamson, R., & Andrews, B. J. (2001). Detecting absolute human knee angle and angular velocity using accelerometers and rate gyroscopes. Medical and Biological Engineering and Computing, 39(3), 294-302.