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DEVELOPMENT OF A BODY JOINT ANGLE MEASUREMENT SYSTEM USING IMU SENSORS

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***Abstract*—This paper presents an approach for measuring and monitoring human body joint angles using inertial measurement unit (IMU) sensors. This type of monitoring is beneficial for therapists and physicians because it facilitates remote assessment of patient activities. In our approach, two IMUs are mounted on the upper leg and the lower leg to measure the Euler angles of each segment. The Euler angles are sent via Bluetooth protocols to a pc for calculating the knee joint angle. In our experiments, we utilized a motion capture system to accurately measure the knee joint angle and used this as the ground truth to assess the accuracy of the IMU system. The range of average error of the system across a variety of motion trials was 0.08 to 3.06 degrees. In summary, the accuracy of the IMU measurement system currently outperforms existing wearable systems such as conductive fiber optic sensors and flex-sensors.**

I. INTRODUCTION

CONTINUOUS monitoring of patients' activities has become one of the active research areas in the field of Body Sensor Network (BSN). This includes human activity recognition using attached sensors, joint angle monitoring using light-weight wearable sensors, and smart cloth [1]. For many medical and rehabilitation applications, it is desirable to continuously monitor patients' daily activities. For instance, remote monitoring of body joints without visiting the hospital can be beneficial for the therapists and physicians. Traditionally, measuring the joints range of motion (ROM) has been performed by utilizing standard tools such as goniometer. This method must be completed by a physiotherapist in the hospital and requires a great deal of overhead. In addition, the ROM is only measured during standard postures and a continuous measurement of joint angles cannot be captured for advanced assessment. Thus, an affordable remote sensing system for monitoring the progress of body joint flexion during regular daily life activities is valuable. Particularly, the measurements and acquired data can then be reviewed by a clinician and in the case of unsatisfactory results, the patients would be asked for hospital visit for further evaluations.

Wearable sensors for measuring movement of joints have been studied for several applications [2, 3, 4, 5, 6]. In most studies, sensors are sewn to a piece of fabric and then mounted on person's cloth [2, 8]. For instance, Bakhshi and Mahoor [8] developed a novel sensing mechanism to measure joint flexion based on resistive flex-sensors. Their method utilized data-fused flex-sensors along with an extended Kalman filter to reduce uncertainty and improve both accuracy and precision of estimated joint angles. They reported an error rate of 6.92° for knee angle measurement.

Gibbs and Harry [3] monitored long term body movement by using a wearable and comfortable garment that contains conductive fiber. However, several uncertainties and drawbacks such as inconsistence sensor outputs due to the fiber tensions and resistance alterations were reported. Other researchers used 20 Hall Effect sensors on a glove for measuring joint angle such as hand joints [4]. The overall error in measuring angle using this method was 6.17°.

Some researchers used accelerometer and gyroscope to calculate the ROM [5, 6]. Luinge *et al.* [5] focused on the ambulatory measurement of human body and the orientation of joints using accelerometer and gyroscope. Kobashi *et al.* [6] proposed a way to monitor knee joint angle using a sensor called MARG (Magnetic, Angular Rate, Gravity) which is a combination of magnetometer, gyroscope, and accelerometer from XSENS technology. Although the accuracy of their system is very high, the MARG sensors are expensive and may not be appropriate for home applications and large scale use in the medical field.

This paper presents an affordable sensing system using Inertial Measurement Units (IMUs). These tiny electronic sensors are fabricated by Micro Electro Mechanical System (MEMS) technologies to compute motions of an object in free space relative to an inertial frame with relatively low power consumption [7]. Accelerometers and gyroscopes are two primary types of IMU sensors for inertial measurement. This study proposes a method to measure the range of motion of the knee joint using two IMU sensors mounted on the body shank and thigh. The measurements are transmitted to a computer via Bluetooth protocol for further data analysis and evaluation.

The remainder of this paper is organized as follows. We present the details of our system for joint angle measurement using IMU sensors and data transmission via Bluetooth protocol in Section 2. Comparison with motion capture data are illustrated in Section 3. Finally, conclusions and future work are given in Section 4.

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II. BODY JOINT MEASUREMENT USING IMU

Two IMUs (SparkFun Electronics, Boulder, CO), each with dimensions 49.53 × 27.94 × 1.5 mm were used in this study. Each sensor consists of triple axis accelerometer with 13-bit resolution and three degrees of freedom gyroscope and magnetometer. The outputs of all sensors are processed using an on-board ATmega328 microcontroller. The two sensors were mounted on simple straps and located on the shank and thigh (Fig. 1). Attached to each IMU is a Bluetooth radio that wirelessly transmits data to a PC. The IMUs and Bluetooth radios are powered with 3.6 Volt batteries.

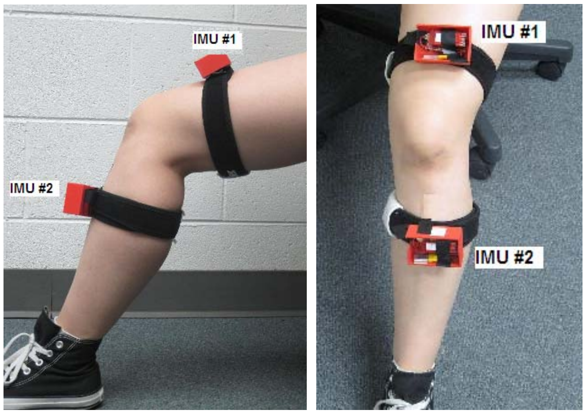


Fig. 1. Two IMUs mounted on the shank and thigh using Velcro straps (side and front view).

Before powering and wearing the sensors, the IMUs were calibrated on a flat surface that was parallel to the ground. In this case, both sensors have the same zero reference coordinator. The assumption that thigh and shank segments are in the same plane was considered.

We used the accelerometer for finding flexion angles, and gyroscope to eliminate the effect of vibrations on the accelerometer. As Fig. 2 shows, γ is the absolute tight angle measured by IMU #1 and is the angle between the gravity vector and a perpendicular vector to the femur. This vector is exactly equal to the sense of gravity by accelerometer. Also λ is absolute shank angle measured by IMU #2 and is the angle between the gravity vector and a perpendicular vector to the tibia. The flexion angle, θ, is calculated by: $\theta = \gamma - \lambda$. The following equations show how β (Roll of thigh segment) and γ are calculated based on Fig. 2.

$$\beta = \gamma \tag{1}$$

$$Acc = \cos(\gamma) * g \tag{2}$$

where Acc and g indicate accelerometer and gravity, respectively.

$$\gamma = \arccos(\frac{Acc}{g}) \tag{3}$$

By substituting γ in (2), we obtain:

$$\beta = \arccos(\frac{Acc}{g}) \tag{4}$$

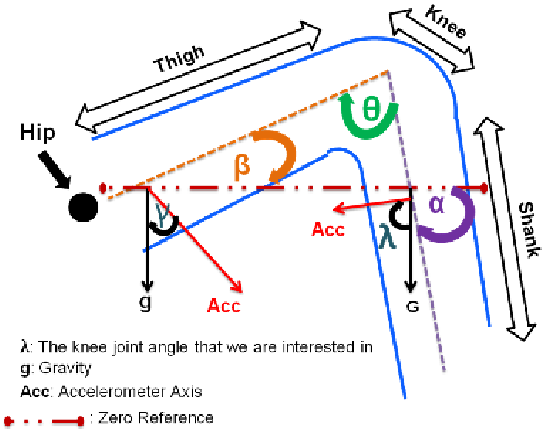


Fig. 2. Schematic of the knee shows the angle configuration with respect to the reference point.

α (roll of shank segment) and λ are calculated the same way as β and γ. These calculations are performed by implementing python programming language in the microcontroller of the IMUs. Therefore, we have the corresponding roll angle of each segment, α and β relative to the calibrated orientation.

As shown in Fig. 2, we are interested in finding λ, i.e. the knee flexion angle where full extension is equal to zero degrees. Because, knee flexion occurs in one plane, the roll data from IMU #1 (β angle) and roll data from IMU # 2 (α angle) can be combined to provide a knee flexion angle, $\theta = 180 - (\alpha + \beta)$.

Calculation of θ is performed using a custom program written using Labview 2010. Data from each IMU is received by the program through the serial port in the same time.

III. EXPERIMENTAL RESULTS

We tested the accuracy of the IMU measurement system by comparing the concurrent recorded knee flexion angle with the calculations from a passive infrared motion capture system (Vicon Motion Systems, Centennial, CO). This comparison was performed on a subject 26 year-old male. We mounted the IMU sensors onto the thigh and shank along with series of reflective spheres placed in a modified Helen-Hayes configuration, a standard set for accurate lower body motion capture[9] (Fig. 3). The subject performed four tasks involving knee movement: 1) swinging the lower leg while in a seated position, 2) unilateral hip and knee flexion in a standing position, 3) sitting down and standing up, and 4) combined movement patterns of gait and squatting.

Using the motion capture and anthropometrics collected from the subject, lower limb kinematics was calculated using the Newington Model through Plug-In Gait [10]. Location of the hip, knee, and ankle joint centers were estimated using marker and anthropometric data. Orientation of the thigh and shank segments were modeled by orthonormal coordinate systems attached to planes passing through the joint centers.

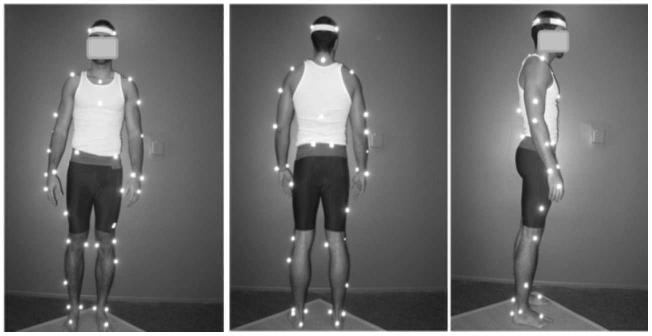
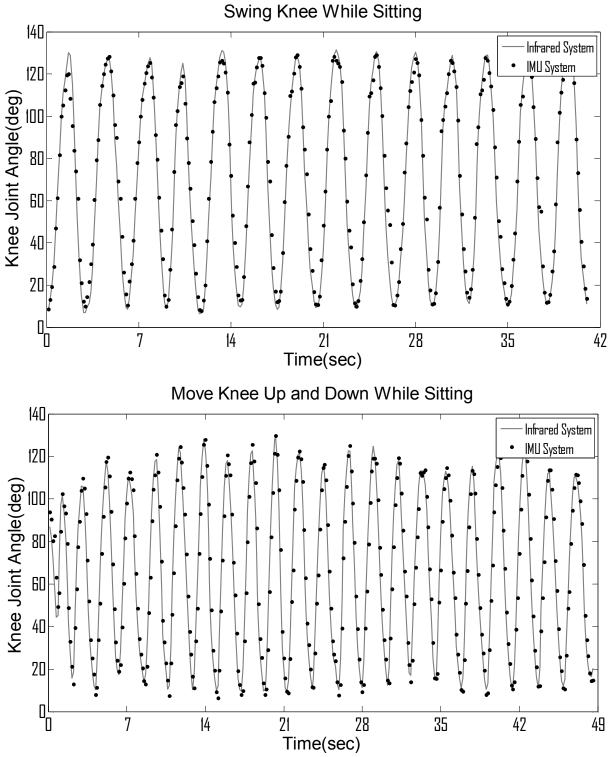


Fig. 3. Markers attached to one the subjects under test to measure the body joint angles.

Standard Euler angles were [11] used to define the knee angle in relation to the thigh coordinate system with the following rotation order: flexion, adduction, rotation. Knee flexion angle comparisons to the IMU system were performed with the first rotation (flexion). Fig. 4 shows a graphical comparison of knee joint angle measurements using the two systems for the subject under test.

The sampling rates of infrared system and the IMU system were 100 Hz and 5 Hz, respectively. Therefore, the data from the infrared system was down sampled to 5Hz for comparison. To synchronize the IMU system with the infrared motion capture system, the subject remained still at the beginning and the end of the trials. Data was then synchronized at the start and end of the motion. The results demonstrate that the knee flexion angle calculated with the IMU system approximates the angle calculated using the infrared motion capture system.



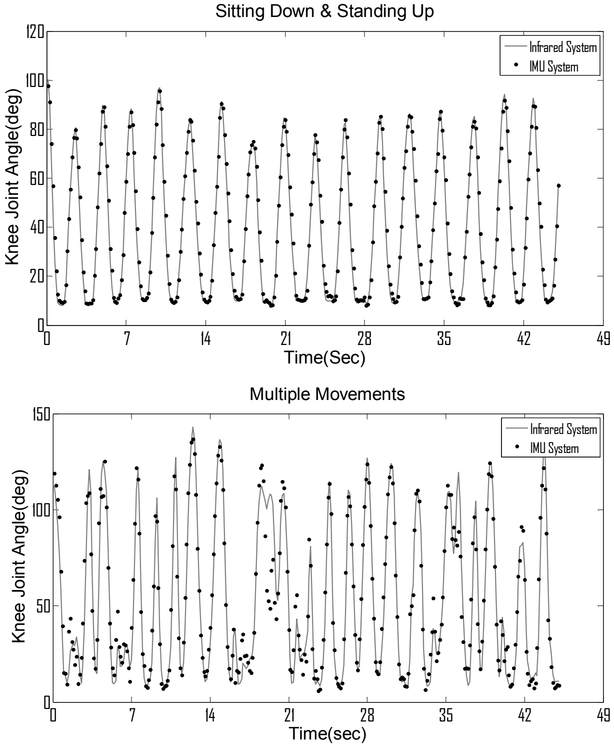


Fig. 4. Results of two IMUs attached to the subjects leg during an experiment.

Table I. demonstrates the results for the subject for four tasks which are mentioned in the first paragraph of this section. For each task the average error, standard deviation, and correlation coefficient were calculated. The error is almost zero in the primary range of knee flexion during these motions. However, when a change in direction occurs, the deviation between the modes of measurement is larger. In addition, the speeds of activities in different tasks are not equivalent. Therefore mean errors and standard deviations in tasks 2 and 4 are larger because body motion is faster.

TABLE I. EXPERIMENTAL RESULTS

Task	**Average Error (degrees)**	**Standard Deviation**	**Correlation Coefficient**
1	0.08	6.55	0.99
2	3.06	7.24	0.97
3	1.68	4.67	0.98
4	2.40	13.30	0.94

Bland-Altman plots (Fig. 5) demonstrated good agreement between the two systems with slightly larger variation toward the middle of the range of motion. These residuals correspond to larger angular velocities that occur the middle of the range of motion, and are likely related to a small time lag between the devices. Tasks 1, 2, 3 and 4 demonstrated approximate biases of 0.38, 2.88, 2.28 and 1.05 deg, respectively, which are clinically insignificant.

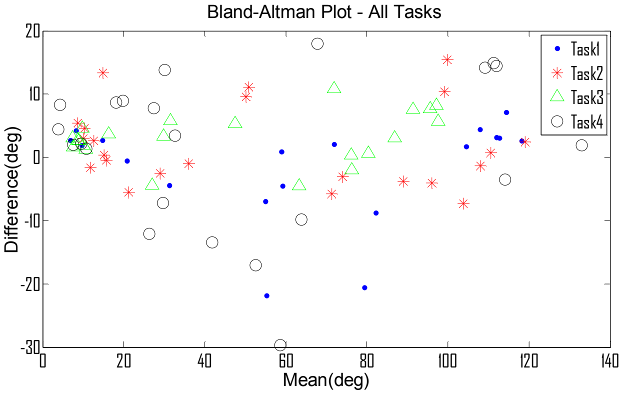


Fig. 5. Bland-Altman Plot for all tasks.

IV. CONCLUSIONS AND FUTURE WORK

We developed a system to measure the knee joint angle using IMU sensors. This system is convenient, inexpensive (approximately $400), light, and portable. It also communicates with a computer via Bluetooth radios. The calculations were performed on Labview on a PC. Alternatively, the Bluetooth devices can potentially communicate with a smart phone in order to analyze, store, and process the data. We compared the accuracy of the knee flexion angles using the IMU system with widely accepted methods using infrared motion capture system. The comparison indicates that the IMU and motion capture systems deviated by an average range of 0.08 to 3.06 degrees from each other, a level of precision that is well below normal measurements performed in a clinical setting. In the future, we plan to extend this approach and use multiple IMUs to measure multiple body joint angles/flexions. We will use a smart phone-based system that can conveniently store the measurements, calculate important body kinematics, and send this information to a server over the internet for further monitoring or processing by clinicians.

V. ACKNOWLEDGMENTS

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VI. REFERENCES

[1] Vehkaoja, Zakrzewski, J. Lekkala, S. Iyengar, R. Bajcsy, S. Glaser, S. Sastry, and R. Jafari, "A resource optimized physical movement monitoring scheme for environmental and on-body sensor networks," in Proceedings of the 1st ACM SIGMOBILE international workshop on Systems and networking support for healthcare and assisted living environments San Juan, Puerto Rico, pp. 64-66, 2007.

[2] R. Jafari, F. Dabiri, P. Brisk, and M. Sarrafzadeh, "Adaptive and fault tolerant medical vest for life-critical medical monitoring," in Proceedings of the 2005 ACM symposium on Applied computing Santa Fe, New Mexico: ACM, 2005.

[3] P. T. Gibbs, H. Harry. Wearable conductive fiber sensor for multi-axis human joint angle measurement. Journal of Neuroengineering. Massachusetts Institute of Technology, 2004.

[4] L. Dipietro, A. M. Sabatini and P. Dario.2003. Evaluation of an instrumented glove for hand-movement acquisition. Journal of Rehabilitation. Advanced Robotics Technology and Systems (ARTS) Laboratory

[5] H. J. Luinge , P. H. Veltinkb and C. T. M. Baten. Ambulatory measurement of arm orientation. Journal of Biomechanics. University of Twente, 2005.

[6] S. Kobashi, Y. Tsumori, S. Imawaki. S. Yoshiya, and Y. Hata. 2008. Wearable Knee Kinematics Monitoring System of MARG Sensor and Pressure Sensor Systems. Graduate School of Engineering, University of Hyogo, JAPAN- WPI Immunology Frontier Research Center, Osaka University, JAPAN- Department of Orthopaedic Surgery, Hyogo College of Medicine, JAPAN and Ishikawa Hospital, JAPAN

[7] W.H. Ko, Solid-state physical transducers for biomedical research. IEEE Trans. Biomed. Eng. 33 2 (1986), pp. 153–162

[8] S.Bakhshi and M.H.Mahoor, “Development of a Wearable Sensor System for Measuring Body Joint Flexion”, Proceedings, International Conference on Body Sensor Networks (BSN), 2011.

[9] MP. Kadaba, HK. Ramakrishnan, ME. Wooten. Measurement of lower extremity kinematics during level walking. J Orthop Res 1990;8(3):383–92.

[10] RB. Davis, S. Õunpuu, D. Tyburski, and JR. Cage, “A gait analysis data collection and reduction technique” Human Movement Science 10, pp. 575-587, 1991.

[11] DT. Greenwood, “Principles of dynamics”. Englewood Cliffs, NJ: Prentice-Hall, 1965.