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Development of a Musculoskeletal Load Measuring Device for Construction Workers Based on Accelerometers and Gyro Sensors

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Abstract

The characteristics of construction work cause excessive strain on specific body parts of the construction craft workers. However, there are few tools to mane an accurate measurement of the load on the musculoskeletal system, and the musculoskeletal disorders (MSDs) experienced by the workers have not been properly understood. So, there is an urgent need for development of a tool to measure the load on the musculoskeletal system. Therefore, this research aims to develop a musculoskeletal load measuring device for construction workers. In order to eliminate the noise and errors, an accelerometer, gyro sensors and the Kalman Filter are used in the device developed in this research.

Keywords : construction worker, musculoskeletal disorders, construction safety, work efficiency

1. Introduction

1.1 Research background and objective

Construction craft workers perform a variety of works in an unstructured work environment, like the outside of a building. Although they perform only one type of work, the working position and body motion continues to change in the course of work, and excessive strain is put on specific body parts of the workers. In addition, construction workers perform simple and repetitive work using heavy materials and tools in an unstable position, such as squatting on their hams to connect rebars[1]. The repetitiveness of such work leads to the high likelihood of adverse effects on the musculoskeletal system[2, 3]. In other words, construction craft workers are exposed to a high risk of musculoskeletal disorders (MSDs). For these reasons, researchers including Holmstom[4] and Peterson[5] have already studied MSDs of workers overseas; however, there have been few studies on this subject in Korea[6].

More than anything else, the actual conditions of MSDs should be understood in order to protect workers from MSDs. Insufficient attention to the safety of construction craft workers has led to speculation that many suffer from MSDs, without an accurate understanding of actual conditions. Furthermore, it has been pointed out that actual conditions are difficult to investigate, as there is no appropriate tool to measure the load placed on specific body parts while the workers are doing different types of work[7].

To address this problem, an attempt will be made to introduce cutting-edge IT to measure the load placed while performing construction work. For instance, such an information technology, the Man-Machine Interface, is being used to make a precise measurement of the load placed to the workers. It is more important to enhance resistance

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of individual workers to MSDs than to control the environmental factors necessary for the investment of a large sum of money and time[8]. In this regard, an accelerometer was used to measure the body movement of the workers[1, 7]. It is significant that it uses a simple device to measure the body movements of workers at an ever-changing construction site. However, the values output with this accelerometer-based device contain a certain amount of error and noise due to the limitations of the device, which continues to accumulate until the device is reset. For this reason, the values measured by the device can be utilized as the data of overall body movements, but unable to as precise body movements. Therefore, a new device that can address this problem must be developed.

Hence, the objective of this research is to develop a more accurate musculoskeletal load measuring device by improving the accelerometer-based measuring device. This research is ultimately expected to improve the working posture and working efficiency of the construction workers.

1.2 Research method and scope

The research trend in relation with the musculoskeletal load measurement is first discussed, and the limits to the conventional musculoskeletal load measuring system are analyzed. Next, the 3D coordinate transformation and the errors generated from the 3D linear coordinate system are studied, and a plan is sought to minimize such errors. Finally, the sensors are selected for building the device, and the validity of the system is verified.

2. The research trend of musculoskeletal load measurement for the construction craft workers

Research on MSDs of construction craft workers can be broadly divided into two categories: characteristics of exposure to risk factors and development of a load measuring device. In relation with the exposure-related research, the work of Lee Yun-geun[9] is considered representative, and identifies the problems of the process to prevent MSDs among such workers. Also, both the characteristics of exposure to risk factors in an actual working conditions and the characteristics of the development of MSDs by work type are analyzed. In addition, a risk factor evaluation table is included, in which the characteristics of each work type are reflected, along with guidelines for the prevention of MSDs[9].

The research on the load measuring device for construction workers includes a pattern analysis of construction work type for the design of a load measuring device, deduction of plans to measure the load, the design of a motion measuring system, and the development of an accelerometer-based motion measuring system. The previous research is summarized in Figure 1. As shown in Figure 1, the body parts at which the load was measured are specified as wrist, elbow and shoulder. The concept of a load measuring system was derived to measure the quantity of motion at torso, upper arm, ulnar/radius and dorsum of hand with devices attached to the body parts. An accelerometer-based measuring system was developed, and its applicability was also tested[1, 7, 10].

When using only an accelerometer along with a motion measuring system, the output includes a significant amount of noise and error. Repetitive experiments have also shown that such errors continuously accumulate. Therefore, it is believed that while the values from the accelerometer can be utilized to grasp an overall movement, they cannot accurately measure the quantity of motion. In particular, the error continues to accumulate until the system is reset, which can, as a result, cause a situation in which one cannot accurately obtain an objective function. For this reason, the need arose for an algorithm that can both minimize and initialize the error function from time to time[10].

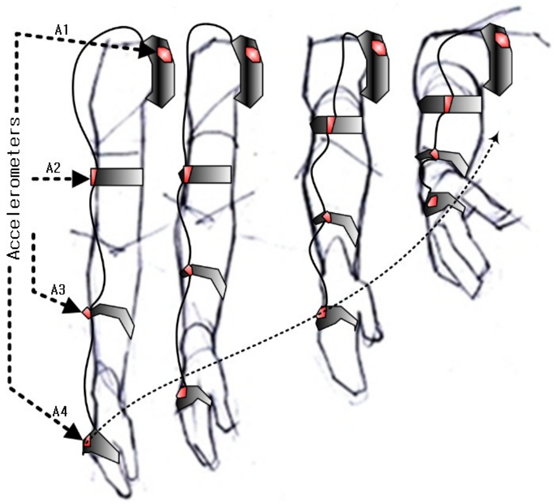
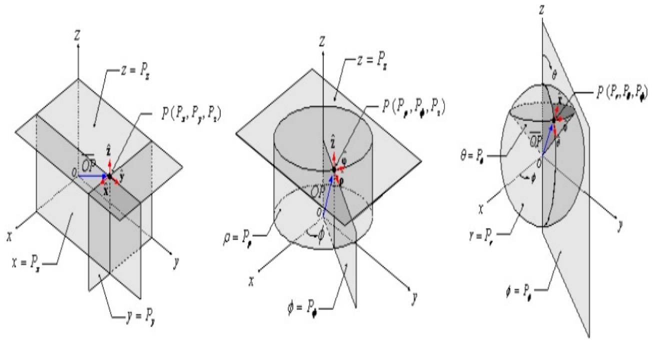


Figure 1. Concept of motion measurement using 4 accelerometers(A1~A4)[1]

3. Design of algorithm

3.1 Basic theories

For this research, it is necessary to measure the motion from torso to shoulder and to wrist. A sensor is attached to each of torso, upper arm, radius/ulnar and dorsum of hand. When the joints move, the quantity of motion at each joint is calculated using the values output from the sensors. The output values are the tangent vectors of the spherical coordinate system on the rectangular coordinate system. Therefore, the tangent vectors on the rectangular coordinate system should be converted into the values of the spherical coordinate system suitable for a circular motion by which one can calculate a relative quantity of motion at each joint. Figure 2 shows the diagrams of rectangular, cylindrical and spherical coordinate system[10]. Eq. (1) through Eq. (4) show how to convert the quantity of motion from one coordinate to another.



(a)rectangular (b) cylindrical polar (c)spherical polar

Figure 2. Coordinate systems of 3 dimensions[10]

rectangular →cylindrical:

$$\begin{bmatrix} \overrightarrow{A_\rho} \\ \overrightarrow{A_\phi} \\ \overrightarrow{A_z} \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \overrightarrow{A_x} \\ \overrightarrow{A_y} \\ \overrightarrow{A_z} \end{bmatrix} \text{......} \ (1)$$

cylindrical →rectangular:

$$\begin{bmatrix} \overrightarrow{A_\rho} \\ \overrightarrow{A_\phi} \\ \overrightarrow{A_z} \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \overrightarrow{A_x} \\ \overrightarrow{A_y} \\ \overrightarrow{A_z} \end{bmatrix} \text{......} \ (2)$$

rectangular →spherical :

$$\begin{bmatrix} \overrightarrow{A_r} \\ \overrightarrow{A_\phi} \\ \overrightarrow{A_\theta} \end{bmatrix} = \begin{bmatrix} \sin\theta\cos\phi & \sin\theta\sin\phi & \cos\theta \\ \cos\theta\cos\phi & \cos\theta\sin\phi & -\sin\theta \\ -\sin\phi & \cos\phi & 0 \end{bmatrix} \begin{bmatrix} \overrightarrow{A_x} \\ \overrightarrow{A_y} \\ \overrightarrow{A_z} \end{bmatrix} \text{...} \ (3)$$

spherical →rectangular:

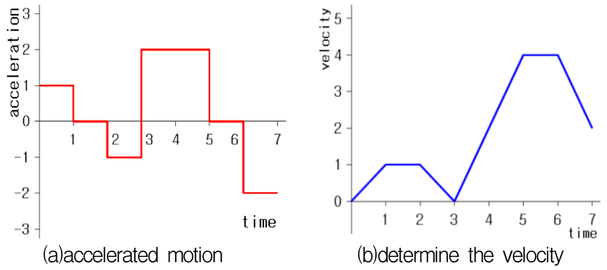
$$\begin{bmatrix} \overrightarrow{A_x} \\ \overrightarrow{A_y} \\ \overrightarrow{A_z} \end{bmatrix} = \begin{bmatrix} \sin\theta\cos\phi & \cos\theta\sin\phi & -\sin\phi \\ \sin\theta\sin\phi & \cos\theta\sin\phi & -\cos\phi \\ \cos\theta & -\sin\theta & 0 \end{bmatrix} \begin{bmatrix} \overrightarrow{A_r} \\ \overrightarrow{A_\phi} \\ \overrightarrow{A_\theta} \end{bmatrix} \text{...} \ (4)$$

At this time, acceleration refers to a change in velocity, which can be expressed as shown in Eq.(5). The method of calculating the velocity from the measured acceleration data is shown as Eq.(6). Eq.(6) can be obtained by integrating both sides of Eq.(5). Here, C_0 means the initial velocity.

$$\vec{a} = \frac{\Delta\vec{v}}{\Delta t} = \frac{\overrightarrow{v_2} - \overrightarrow{v_1}}{t_2 - t_1} \quad ------ \ (5)$$

$$\vec{v} = \int \vec{a}\,dt + c_0 \quad ------ \ (6)$$

Figure 3(a) is an example of the measured data of a change in acceleration of an object that is moving along the one dimension. Figure 3(b) shows the velocity obtained by using Eq.(6) of an object that moves with accelerated speeds.



(a)accelerated motion (b)determine the velocity

Figure 3. Accelerated motion and determine the velocity(C_0=0)

3.2 A transfer function considering the error in the linear system

According to KIM[10], although the values output from a device developed to measure with only an accelerometer are similar those of A/B output from the encoder, they include a significant amount of noise and error. In other words, it is hard to accurately calculate how much a joint is used due to the significant error level in values output from the acceleration sensor. Moreover, as noise and error become greater as time proceeds without it being reset, it becomes harder to accurately calculate the quantity of joint motion [10]. For this reason, it is suggested that something be done to improve the algorithm and complement the sensors to eliminate the noise and error.

To explain this in a mathematical fashion, the transfer function considering the error in the linear system can be expressed as Eq. (7), whereF_{obj} is the objective function; A is the transformation matrix; X is the input variable; and E is the error function. The error function can be defined as the error of the acceleration sensor itself and the error generated in the course of the program calculation.

$$F = AX + E \text{ ------ } (7)$$

To calculate the motion of a joint based on the data measured by the sensor, Eq. (8) is applied to Eq. (7). Here, θ and ϕ can be obtained using X.

$$F = \begin{bmatrix} \overrightarrow{A_r} \\ \overrightarrow{A_\phi} \\ \overrightarrow{A_\theta} \end{bmatrix}$$

$$A = \begin{bmatrix} \sin\theta\cos\phi & \sin\theta\sin\phi & \cos\theta \\ \cos\theta\cos\phi & \cos\theta\sin\phi & -\sin\theta \\ -\sin\phi & \cos\phi & 0 \end{bmatrix} \text{ ------ } (8)$$

$$X = \begin{bmatrix} \overrightarrow{A_x} \\ \overrightarrow{A_y} \\ \overrightarrow{A_z} \end{bmatrix}$$

Like the systems used in previous research, when only the data from an accelerometer is used, the error function, E, continues to accumulate, preventing one from obtaining an accurate objective function. Therefore, an algorithm is needed in order to minimize the error function, E and initialize the process in the middle of calculation. The Kalman filter is the algorithm known to provide such a function.

3.3 Application of Kalman Filter

Invented by Rudolf E. Kalman, the Kalman Filter is a recursive computational solution that effectively traces the time-dependent state vector that has a real-time noise movement equation by using the least squares method. The Kalman Filter is used to trace signals from noise, which enables a system to perform an appropriate prediction of a change in the course of the passage of time [11]. For instance, when radar is used to trace signals, although it can calculate the position, velocity, and acceleration of a specific object, there might be some error included in the calculated values. The Kalman Filter eliminates the error of the consecutively calculated values, and helps estimate the position of the object more accurately. In other words, the Kalman Filter is a filter for linear systems that is applicable only in the cases in which the state of an object at a given time must have a linear relation with the previous point of time, and when there is some error in the values obtained from the object. Here, a linear system denotes a system whose modeling equation can be expressed with linear operators.

Figure 4 indicates the Kalman filter model in which a square is the matrix and an oval is the standard distribution of variables, including an average within the covariance matrix. Here, internal variables are vectors. The Kalman filter is operated based on a discrete-time dynamic system.

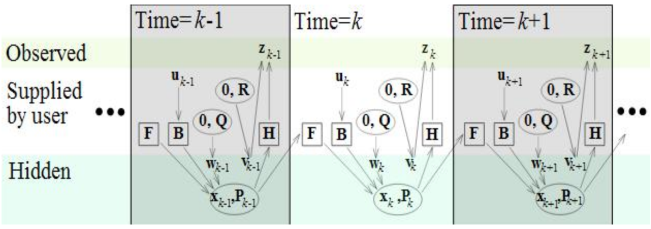


Figure 4. Kalman filter model

In the model, a state vector and the user input at a given time are defined as x_k, and u_k, respectively, Eq.(9) is assumed in the Kalman filter model.

$$x_k = F_k x_{k-1} + B_k u_k + w_k \text{-----}\ 9)$$

F_k is the transition matrix based on the previous state at a given time, B_k is the state transition matrix by the user input, and w_k is the noise variance with, of the multivariate normal distribution, $w_k \sim N(0, Q_k)$ the covariance matrix, Q_k. In addition, the actually calculated vector z_k can be expresses as Eq.(10) x_k is the state vector ,

$$z_k = H_k x_k + v_k \text{------}\ (10)$$

where, H_k is the matrix related to the measurement at a given time, v_k is the noise variance of the multivariate normal distribution $v_k \sim N(0, Q_k)$ with the covariance matrix, R_k. In addition, the initial state and each noise vector at each step $\{x_0, w_1, \cdots, w_k, v_1, \cdots, v_k\}$ are assumed to be mutually independent.

Since the Kalman filter is a recursive estimator, the current state is estimated based only on the previous time step, which means that the current state is independent of all other states except for the previous time step. The Kalman filter can be thought of as operating in two distinct phases: prediction and update. In the prediction phase, the estimate state will be modified by the user input. In the update phase, the state is accurately estimated based on the estimated state and the actually measured state.

Each estimated state at a given time can be expressed using two variables of average and variance, as follows. Here, the lower index, $n|m$, denotes the state estimate at the given time, n. Based on the me asurement at m.

- $\hat{x}_{n|m}$: estimate at the given time, n, based on the measurement at m
- $P_{n|m}$: state covariance matrix at the given time, n, based on the measurement at m

3.3.1 Prediction phase

The computation done by the Kalman filter in the prediction phase takes the deductive approach. The deductive approach to state estimate and to covariance are shown in Eq. (11) and Eq.(12), respectively.

$$\hat{x}_{k|k-1} = F\hat{x}_{k-1|k-1} + B_k u_k \text{----}\ (11)$$
$$P_{k|k-1} = F_k P_{k-1|k-1} F_k^T + Q_{k-1} \text{----}\ (12)$$

3.3.2 Updata phase

The computation done by the Kalman filter in the update phase takes the inductive approach to correct the previously computed value based on the discrepancy between the previously computed estimate and actual measurement. Eq.(13) is for the discrepancy between previous estimate and actual measurement. Eq.(14) is for Kalman gain. Eq.(15) is for the inductive state update. Eq.(16) is for the inductive covariance update.

$$\tilde{y}_k = z_k - H_k \hat{x}_{k|k-1} ------ (13)$$

$$K_k = P_{k|k-1} H_k^T S_k^{-1} ------ (14)$$

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k \tilde{y}_k ------ (15)$$

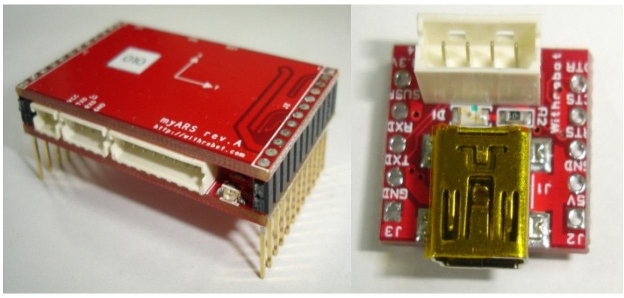
$$P_{k|k} = (I - K_k H_k) P_{k|k-1} ------ (16)$$

When the trajectory of an object that moves in a 3D space, like joint movement, is measured using only an accelerometer, it is unreasonable to apply the Kalman filter to the measurements. To make it possible to apply the Kalman filter, gyroscope sensors are used with the accelerometer. In this research, we also equipped gyroscope sensors in the device developed.

4. System building and evaluation

4.1 Selection of sensors

To develop the sensor-based measuring device for this research, several steps were required, including circuit design and safety verification. For this reason, with the aim of reducing the development cost, securing the safety of the circuit, easing the verification of the measured values and reducing the development period, we decided to select a domestic company that produces sensor modules equipped with an accelerometer and a gyroscope sensor. Our final selection of the sensor module and tool-kit are myARS(Attitude Reference System) shown in Figure 5(a) and myUSB2UART shown in Figure 5(b), which are both manufactured by W company in Korea.



(a) myARS (b) myUSB2UART

Figure 5. myARS and myUSB2UART

The basic performance of myARS is as follows:

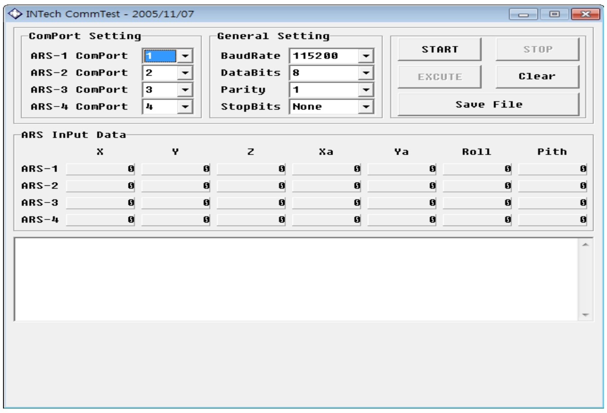
- Equipped with 3-axis accelerometer, and 2-axis gyroscope sensor, 32-bit ARM Cortex-M3 microprocessor
- 3D information of 6 motions types (x, y, z, roll, pitch, yaw), output of raw data of 5 motions (x, y, z, roll, pitch)
- 5-axis IMU sensor fusion using the Kalman filter
- 100Hz data bandwidth (output of the data message every 10ms)

To connect myARS with PC in parallel, a USB-to-UART adapter is required. The tool-kit named my USB2UART has the following specifications:

- Micro USB to UART
- Directly connecting the UART of the embedded system to USB port of a PC without the MAX232 chip
- USB bus power (5V, 500mA) and power protection
- Virtual COM port(VCP) driver

4.2 System development

For communication between the tool-kit named myUSB2UART and the PC, 4 Comport software is required. Therefore, the 4 Comport communication program was developed for this research. With the selected sensors, hardware to measure worker motions is developed. Figure7(a) shows the sensor module developed for this research, and Figure7(b) shows the module attached to the arm of a subject.


INTech CommTest - 2005/11/07

ComPort Setting

ARS-1 ComPort 1

ARS-2 ComPort 2

ARS-3 ComPort 3

ARS-4 ComPort 4

General Setting

BaudRate 115200

DataBits 8

Parity 1

StopBits None

ARS InPut Data

	X	Y	Z	Xa	Ya	Roll	Pith
ARS-1	0	0	0	0	0	0	0
ARS-2	0	0	0	0	0	0	0
ARS-3	0	0	0	0	0	0	0
ARS-4	0	0	0	0	0	0	0

Figure 6. PC to tool kit communication program

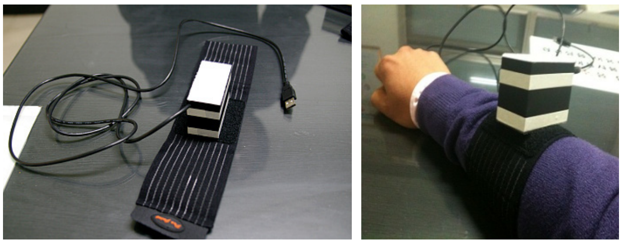

(a)sensor module (b)attachment of the sensor module

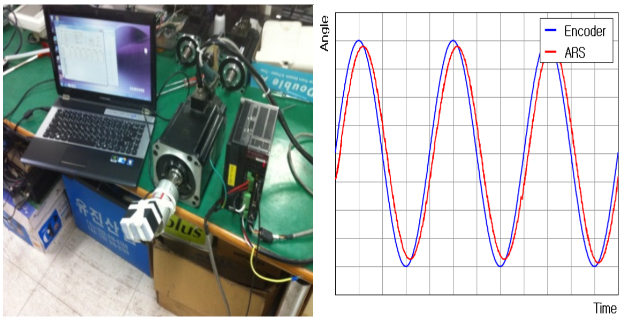
Figure 7. Example of developed sensor module and its attachment

4.3 System verification

To verify the developed system, experiments are performed separately for both the servo-motor and the basic motion. In the experiment for the servo-motor, as with the experiment conducted to verify the system in Kim[10], a reciprocating and rotary motion is performed using a servo-motor, similar to a motor pendulum motion. The A/B values generated from the motor encoder are compared with those from the newly developed system. In the basic motion experiment, the sensor module is attached to the subject to verify whether or not each part of the system works properly while doing a basic motion.

4.3.1 Servo motor experiment

Figure 8 shows the verification process and the result graph. It is noted that the performance of noise filtering and the phase difference detection are greatly improved when the servo-motor experiment results are compared with those in Figure 9, notwithstanding the fact that the limitations of the sensor system caused a slight delay in sensor and encoder values. However, the objective of this research was to measure the working motion of the construction craft workers, so it is considered that the delay time is not an important variable.



(a)verification scene (b)verification result

Figure 8. Verification of the developed system by servo motor

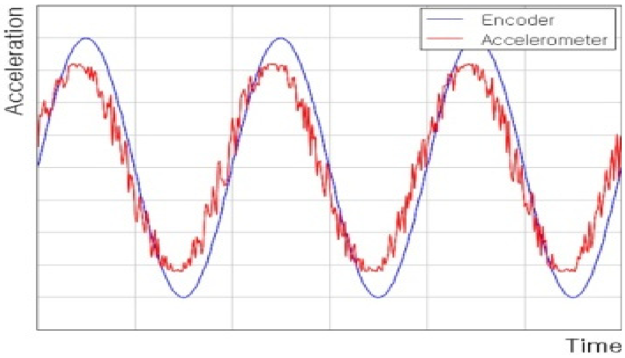


Figure 9. Verification result of the Kim's system[10]

4.3.2 Basic motion experiment

The purpose of the basic motion experiment is to verify whether the values are correctly input to the linked sensors when each sensor is connected. As shown in Figure 10, with the sensors attached to the arm and shoulder, the subject moves the arm in every direction with the arm spread to verify that the data values are being correctly delivered by the sensors.

As you can see in Table 1, the sensors attached to the wrist and the shoulder output the measurement of the 2-axis rotary motion, and the sensor attached to the arm generates the measurement of 1-axis rotary motion without a hitch. Therefore, the developed system is expected to bring a significant outcome.


(a)set the system to zero (b)perform the experiment

Figure 10. Experimental test

Table 1. Result of experimental test

Time [sec]	Shoulder1 [°]	Shoulder2 [°]	Elbow [°]	Wrist1 [°]	Wrist2 [°]
0	75	20	62	64	12
0.109	70	20	57	59	12
0.219	64	18	50	53	11
0.328	60	18	46	47	10
0.437	55	17	41	43	9
0.546	51	16	37	38	8
0.655	47	16	33	27	6
0.765	43	15	29	24	6
0.874	40	14	26	21	5
0.983	36	14	22	19	5
1.092	34	13	20	17	5
1.201	31	13	17	15	4

5. Conclusion

Construction craft workers are prone to being exposed to the risk of MSDs. However, thus far there has not been a thorough understanding of their actual condition. One of the reasons for this lack of understanding is the fact that there is no measuring tool appropriate for the construction site and work types. Therefore, a musculoskeletal load measuring system for workers by applying an accelerometer, a gyroscope sensor and the Kalman filter is developed in this study.

Comparing the developed system with previous systems, it was found that noise and error were removed, and the phase difference detection and noise filtering performance has been greatly improved. However, the newly developed device is very limited in terms of its capacity to accurately measure all of a worker’ s motions due to the limited of accuracy of the sensor and limitations of the motion-tracing algorithm. It also cannot measure other factors like muscle strain that can affect the musculoskeletal system. In addition, the system is only for the body parts from the shoulder to the wrist. Further study is needed to expand the applicability of the system to other body parts.

If the system is improved through further research and a more finite verification of the system, it is expected that the improved system can be applied to future research and evaluation for construction workers of postures and positions with an increased risk of MSDs. In this way, it will contribute to the preparation of a plan to correct the workers’ position and reduce the incidence of industrial accidents.

Acknowledgement

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