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Development of a System Observing Worker's Physiological Responses and 3-Dimensional Biomechanical Loads in the Task of Twisting While Lifting

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Abstract

Purpose: The purpose of this study is to provide analysis of physiological, biomechanical responses occurring from the operation to lifting or twist lifting task appears frequently in agricultural work. **Methods:** This study investigated the changes of physiological factors such as heart rate, heart rate variability (HRV) and biomechanical factors such as physical activity and kinetic analysis in the task of twisting at the waist while lifting. **Results:** Heart rates changed significantly with the workload. The result indicated that the workload of 2 kg was light intensity work, and the workload of 12 kg was hard intensity work. Physical activity increased as the workload increased both on wrist and waist. Besides, stress index of the worker increased with the workload. Dynamic load to herniated discs was analyzed using inertial sensor, and the angular acceleration and torque increased with the workload. The proposed measurement system can measure the recipient's physiological and physical signals in real-time and analyzed 3-dimensionally according to the variety of work load. **Conclusions:** The system we propose will be a new method to measure agricultural workers' multi-dimensional signals and analyze various farming tasks.

Keywords: Acute stress index, Bio-information, Lumbar spine workload, Physical activity, Repeated lifting work

Introduction

Most agricultural works, especially for some crops have been done manually, because process of the agricultural works could not be mechanized due to the characteristics of the specific crops or working environment. Some research have reported that manual labor causes musculoskeletal symptoms which may lead to musculoskeletal diseases or body deformation due to the repetitive use of part of the body, uncomfortable posture, or excessive labor intensity. When farmers lift and load the harvested fruits and vegetables, they should bend and twist the waist, which is the main cause of musculoskeletal diseases. For these reasons, instrumentation system for comprehensive observation of health condition and stress of farmers should be developed. With this instrumentation system for biometric information, more research need be implemented to prevent musculoskeletal diseases of farmers and to improve agricultural work environment (Son et al., 2010; Kraus et al., 1997). According to the survey on the self-perceived musculoskeletal symptoms using Dutch Musculoskeletal Questionnaire (DMQ), the result showed that over 90% of farmers complained of multiple musculoskeletal symptoms. Overall they complained of symptom at the waist, shoulder, and knee, but the body part showing symptoms are different according

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to the work types and labor intensity. Therefore, analyses of work load and posture of farmers are very important in manual farm labor. Amongst, analysis of workload on the waist is the most important because musculoskeletal symptoms have mostly been prevalent in the waist because of the repetitive work load.

Previous studies were conducted on working method and evaluation in qualitative assessment method. Ovako Working-posture Analysis System (OWAS), Rapid Upper Limb Assessment (RULA), and Rapid Entire Body Assessment (REBA) were well-known qualitative mothod. However, these methods showed different results depending on the researchers due to the limitation of qualitative study. Thus, several researches on quantitative method to overcome the qualitative method have been recently reported (Son et al., 2010; Kim et al., 2010). Kim et al. (2010) analyzed the risk for musculoskeletal injuries in combined harvesting operation using a digital human model, and Rim et al. (2009) conducted a study on assessment of musculoskeletal injuries at lower extremities using 3-D musculoskeletal model. Moreover, Koo et al. (2004) investigated a worker's electromyography in box lifting work using Vicon and electromyographic system. Lim et al. (2011) measured a worker's workload in twisting work. However, these studies have limits to apply in actual agricultural working environment. Usually, human motion analysis systems used in previous study are vision-based optical capture system. Even though those equipment shows very high performance and accuracy, these are vulnerable to use outside. In addition, many researchers have been aware of the importance of measurement of biometric information such as heart rate for creating work environment. Brage et al. (2005) examined the relationship between physical activity and heart rate and developed an instrumentation system. But still more thorough study on measurement and analysis of biometric information of worker in agricultural work is needed.

To overcome those problems, our research group developed the systems that not only measure worker's work load in outside but also observe physiological and physical signals simultaneously. Through this study, Son et al. (2010) confirmed that biometric body signals affecting to body part in workload assessment are important. Recently, these systems successfully measured and analyzed biometric information of worker in harvesting cherry tomatoes (Seonwoo et al., 2011). Yet, these systems still have a limitation: only workers' 1-dimensioanl (1D) physical signals were measured. Because farm workers always receive 3-dimensional (3D) work load, measurement should be conducted 3-dimensionally. Yet, the researches related with those are insufficient. Consequently, biometric information measurement and 3D dynamics analysis in the task of twisting at the waist while lifting are required so that work load that the worker should endure can be well known.

In this study, a new system that measure and analyze 3D physical signals as well as physiological signals, e.g. heart rate, physical activity and stress index, was developed as a basic research. Using measurement system of biometric information developed in the previous study (Son et al., 2010), the system intended to measure and analyze heart rate, physical activity, stress index, and workload to the waist in the process of repetitive twisting and lifting task. Especially this study examined the changes of worker's 3D physiological and kinematic workload according to the weight by analyzing worker's biometric signal according to different loads. Given the thorough inspection, the system discussed in depth to valid the appropriacy of the system, expecting improvement of working environment and preventing musculoskeletal injuries and stress.

Materials and Methods

Measurement of biometric signal in the task of twisting at the waist while lifting

Devices for measuring heart rate, physical activity, and

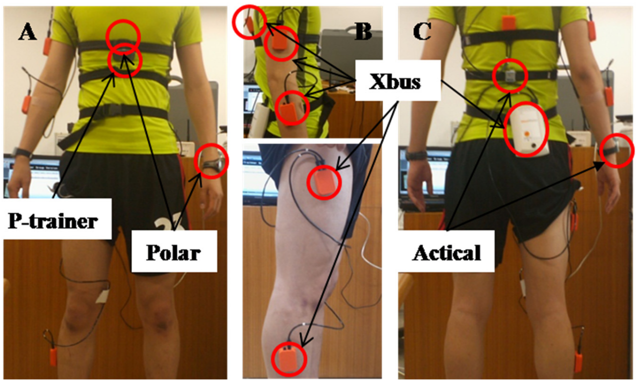

Figure 1. Photo of measurement system: (A); a heart rate ECG sensor: Polar^{TM} and a HRV (heart rate variability) ECG sensor: P-trainer^{TM} (B); 5 multi-axis motion sensor device (Xbus) (C); two physical activity measurement sensors (wrist, waist), a wireless data communication unit for motion sensor during asymmetrical lifting work(A: view of frontal plane(anterior), B: view of frontal plane, C: view of frontal plane(posterior).

Table 1. Specification of P-trainer™forstressindex

Item	Specification
Power	Lithium polymer battery : internal protect circuit :160 mAh, +3.7 V
ECG circuit	Lead-(RA-LA) signal and potential difference measure, 200 samples/(sec*ch)
Zigbee	Zigbee module : Jennic 5139 chip antenna, 10 m boundary response
Battery adaptor	24 pin standard mobilephone adaptor
Size, Weight	W69.8 * L37.1 * H15.1 mm, 21 g

Table 2. Specification of Xbus™motionsensorkit

Item	Specification
Type	RS-485
Speed	460k8 bits/sec
Number of Xbus connectors	2 (enables 2Xbus strings of max 2*5 MTx)
Sample frequency	Adjustable from 10-512 Hz
Maximum number of Motion Trackers	10* MTx (at 100 Hz sampling frequency)
Size, Weight	W10*L15*H4 cm, 330 g (200 g excl batteries)

Table 3. Specification of MTx™motionsensor

Item	Specification			
	Dimensions	Full scale	A/D resolution[bits]	Bandwidth [Hz]
Accelerometer	3 axes	±50 m/s^2	16	40
Rate gyroscope	3 axes	±1200 deg/s	16	30
Magnetic Field	3 axes	±750 mGauss	16	10
Temperature	-	-55,+125°C	12	-
Size, Weight(total)	W38*L53*H21 mm, 30 g			

acute stress index are used to measure the biometric signals in the task of twisting at the waist while lifting. Heart rate is measured with portable heart rate monitor (Polar RS400, Polar Electro INC, USA) as in Figure 1A. Physical activity is measured by the three-axis motion sensor (Actical, Minimeter®, USA) attached on the wrist and waist as in Figure 1C. Stress index - measuring device (P-trainer, ManTech Inc. Korea) is used to measure the acute stress index as in Figure 1A. Its specification is listed in Table 1. Acute stress index is calculated with heart rate and balanced automatic nervous system value (Choi et al., 2007).

Evaluating worker's biomechanical workload in the task of twisting at the waist while lifting

Three-axis motion sensor, Xbus-Kit (Co. Xsens, Netherland) which was developed to measure joint movement, is attached around celiac plexus for 3D analysis. Multiple axis motion sensors with five inertial sensors (MTx, Co. Xsens, Northerland) are attached to each joint, and Xbus-kit gives data about three axis accelerometer, rate gyroscope, magnetic field, and temperature of atmosphere (Table 2). Table 3 shows the specification of MTx motion sensor. Motion sensors can evaluate the dynamic and static load of each joint in the greenhouse work which has simple repetitive lifting, twisting at the waist while lifting, and complicated working posture.

Static and dynamic workloads of herniated discs are calculated in the same ways with the previous studies (Son et al., 2010; Nordan and Frankel, 2001). Considering the dynamic factors, tilted angle of trunk, θ, is set from the perpendicular at the point of maximum angular acceleration during flexion or extension.

Angular velocity sensor is attached on the back to measure the dynamic motion of waist (Fig. 1). Angular velocity measured by the angular velocity sensor is differentiated to produce angular acceleration, and torque

Table 4. Principal moment of inertia of a subject (kg · m^2)

Subject	1	2	3	4	5	6
I_{xx}	0.2643	0.5008	**0.6194**	0.2302	0.3022	0.3541
I_{yy}	0.9315	1.4320	**1.8063**	0.9022	0.6635	0.7902
I_{zz}	1.4436	2.0449	**2.3142**	1.3555	1.2464	1.3116

of each direction is obtained using inertia moment of each joint, i.e. trunk, in the task of twisting at the waist while lifting (Chandler et al., 1975). Inertia moment in the Table 4 is the x-axis, y-axis, and z-axis values produced from the inertia moment of the subjects' body measurements from the previous study (Chandler et al., 1975). Height and weight of the subject participated in this study is similar with the third subject in the Table 4, and torque applied to the disc for each axis is calculated using inertia moment I (1).

$$T = I \cdot \alpha \qquad (1)$$

T = Torque (N·m)
I = Inertia moment (N·m · sec^2)
α = Angular acceleration (rad/sec^2)

Description of task of twisting at the waist while lifting

Biometric information of a subject in the task of twisting at the waist while lifting, which occurred frequently in agricultural work, is measured using biometric information measurement system as shown in Figure 1. Multi- axis gyrosensor is used to trace the trunk motion in the task of twisting at the waist while lifting, which gives a heavy burden on lower back disc (Fig. 2). The task of twisting at the waist while lifting which is a typical type of work in box loading process, and this study measured the trunk motion from the three axis at the process. The subject stands on feet with 40 cm apart, and he lift the box. The distance between the feet and the lifted box is 40 cm. The subject performs box lifting with twisting torso (Fig. 3). The box used in this study is a yellow plastic box (W52* H37* D32 cm) which is used in fruit picking. The weight of the box is 12 kg, because it comes from the weight of empty box 2 kg and fruit 10 kg. The experiment performs lifting the box while twisting at the waist for 15 minutes repeatedly. Since the study observes the main load at the waist, the subject performs the lifting with minimal movement of other body parts. He lifted the box not bending the knees, instead bending the waist (Fig. 3).

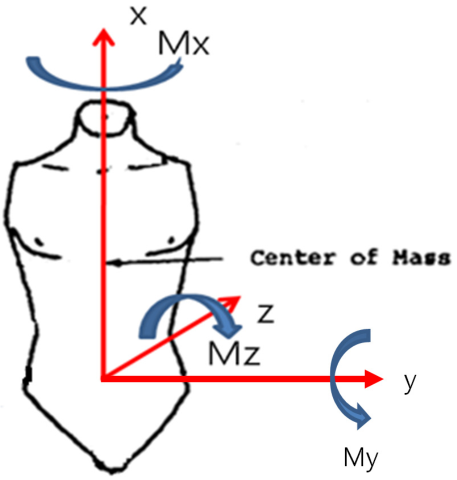

Figure 2. Determination of axes. Axes followed the axes of X-bus attached to waist.

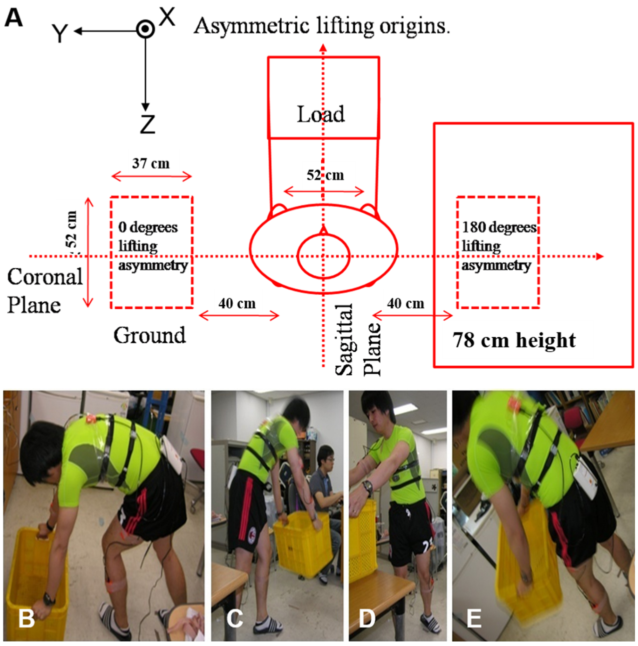

Figure 3. (A) Layout of the asymmetric lifting work with twisting at the waist. (B-E) Illustration of the postures during the asymmetric lifting work with twisting at the waist: one cycle.

The weights of the boxes are 2 kg and 12 kg each, and the places of the boxes are the same for the kinematic analysis of the waist. One cycle of the action is that the subject lifts the box on the floor to the 78 cm height of the desk top, and returns it to the original position. Figure 3 shows a scope of work sets. MATLAB (MathWorks, USA) is used to remove the noise of trunk because angular velocity sensors are attached at the trunk. It is filtered by 3 Hz cutoff frequency with the fourth butterworth Low-Pass Filter.

Results and Discussion

Analysis of physiological responses and workload at the task of twisting at the waist while lifting

This study analyzed the physiological signals, physical activity, and acute stress index of the subject in the task of lifting with twisting at the waist.

Heart rate

The heart rate of the subject was increased up to 108 beat/min. in task of lifting the 2 kg-box by twisting the waist, and 155 beat/min in 12 kg-box lifting (Fig. 4A). The average values of 2 kg- and 12 kg-box lifting are 98.2 ± 24.1 beat/min and 149.8 ± 20.7 beat/min respectively. The heart rate of 2 kg-box loading showed minor difference with initial heart rate, but that of 12 kg-box loading showed a significant change (Fig. 4B). It indicates that 2 kg-box loading is not hard task whereas 12 kg-box loading is hard work. Polar™ categorized the work causing heart rate of 130-150 beat/min as hard intensity work, so 12 kg-box loading task can be considered as hard intensity work.

Physical activity (Metabolic Equivalent Task, MET)

Result of the physical activity in the task of lifting while twisting the waist (Fig. 5) was that the physical activity was increased with the weight of box. Activities of waist with 2 kg-box was 118.6 ± 11.5 activity count (AC)/min and 12 kg was 210.6 ± 46.8 AC/min. Activities of wrist with 2 kg was 396.9 ± 60.1 AC/min and 12 kg was 894.9 ± 225.9 AC/min ($p<0.01$). Physical activity measured at the wrist was 1.83 kcal/hr-kg with 2 kg and 2.79 kcal/hr-kg with 12 kg, while physical activity at the waist was 1.85 kcal/hr-kg with 2 kg and 2.79 kcal/hr-kg with 12 kg. Wrist had a wider turning radius than waist, so it also had

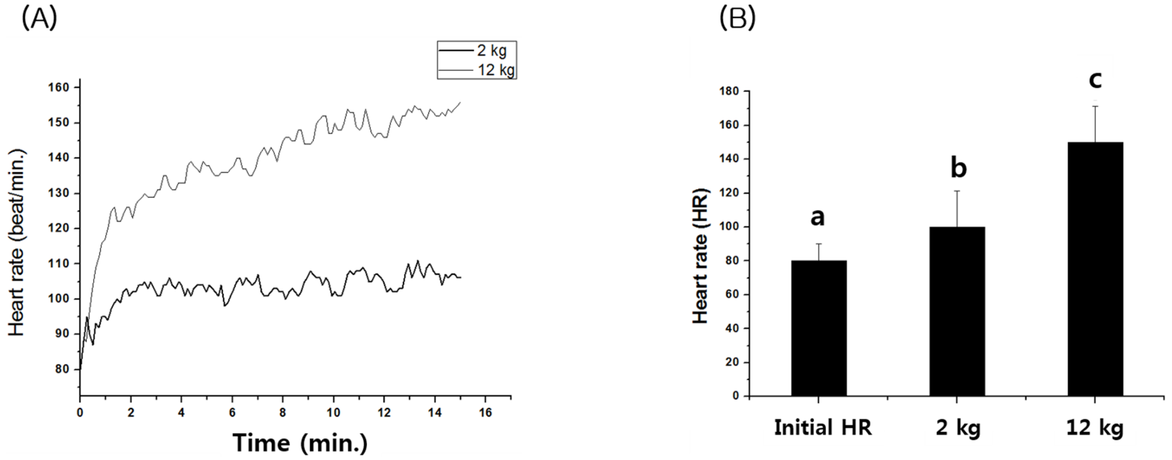

Figure 4. (A) Change of representative heart rate during the asymmetric lifting works for 15 min. (B) Mean value of the heart rate (* : $p < 0.05$, ** : $p < 0.01$).

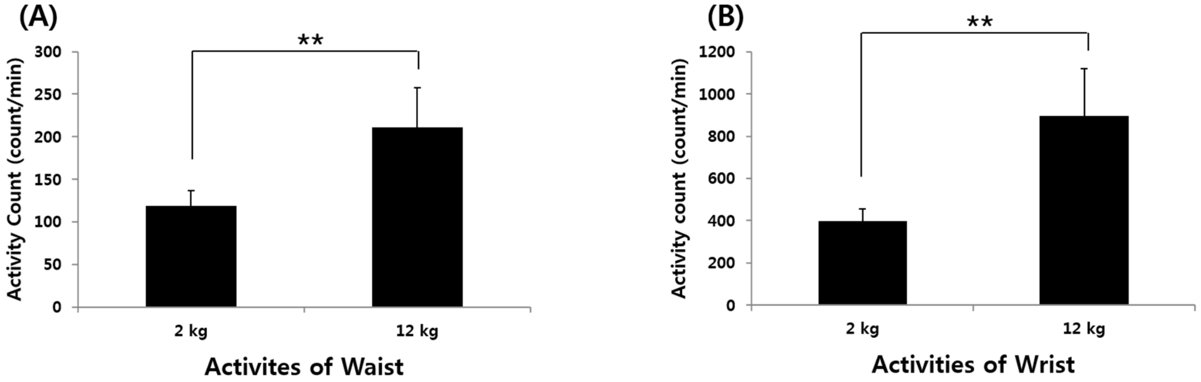

Figure 5. Change of activity count between 2 kg and 12 kg in asymmetric lifting works (A) activity change on waist, (B) activity change on wrist (** : $p < 0.01$).

high acceleration. As a result, AC of wrist was higher than that of waist. Physical activity was higher with 12 kg-box than that with 2 kg-box.

Acute stress index

Acute stress index of hart rate variability (HRV) was measured using p-trainer™ (Fig. 6), it was 61.9 ± 20.5 with 2 kg-box loading and 73.1 ± 15.0 with 12 kg ($p < 0.0$). According to guideline suggested by p-trainer™ worker is under stress, when the acute stress index is over 70. Therefore, worker who lifted 2 kg-box was not stressed, while worker who lift 12 kg-box was stressed.

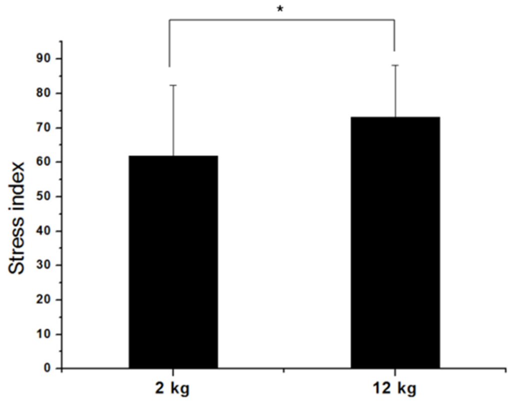

Figure 6. Change of stress index between 2 kg- and 12 kg-box loading. (* : $p < 0.05$).

Static and dynamic load to the waist while lifting with twisting

Angular acceleration of x-axis, y-axis, and z-axis in the gyrosensor was calculated when 2 kg and 12 kg-box were lifted. Angular acceleration of x-axis was greater with the heavy box, and z-axis (flank direction) showed the least changes (Fig. 7). At the previous section it was observed that physical activity of 12 kg-box lifting was higher than that of 2 kg-box. The reason was that the change of angular acceleration of x-axis gave a significant impact on physical activity. Lifting a heavy object influenced significantly on the musculoskeletal system, so more physical activities were needed to minimize the impact on the musculoskeletal system.

Figure 8 shows the torque calculated using angular acceleration from Figure 7 (C, F). When Figure 8 (A, C) was compared with Figure 7 (C, F), the property of x-axis was decreased while z-axis was increased. It is because that I_x was relatively smaller than I_y, and I_z was relatively greater. The maximum value of t_y was found in Figure 8 (A, C), and t had the maximum value when t_y had maximum value in the scalar sum of the torque (Figs 8B, D). The reason is that angular motion of y-axis gave the biggest load to the waist. When it compared in terms of weight, the t_x, and t_y of 12 kg-box lifting was increased more than those of 2 kg. Dynamic load was increased toward x-axis and y-axis as the object got heavier.

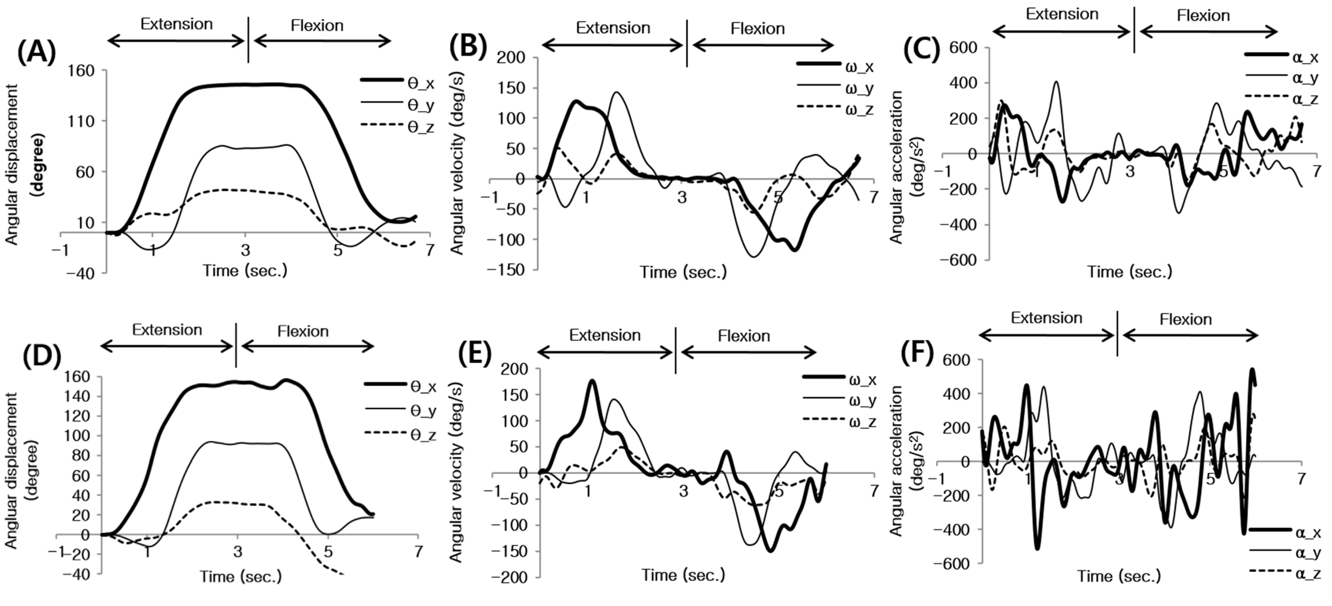

Figure 7. Changes of the various angular properties with 3-axis motion sensor, calculated by angular acceleration during one cycle of 2 kg-box lifting (A, B, C) and 12 kg-box lifting (D, E, F). (A, D) Angular displacement, (B, E) Angluar velocity, and (C, F) Angular acceleration. (— : X-axis, — : Y-axis, --- : Z-axis).

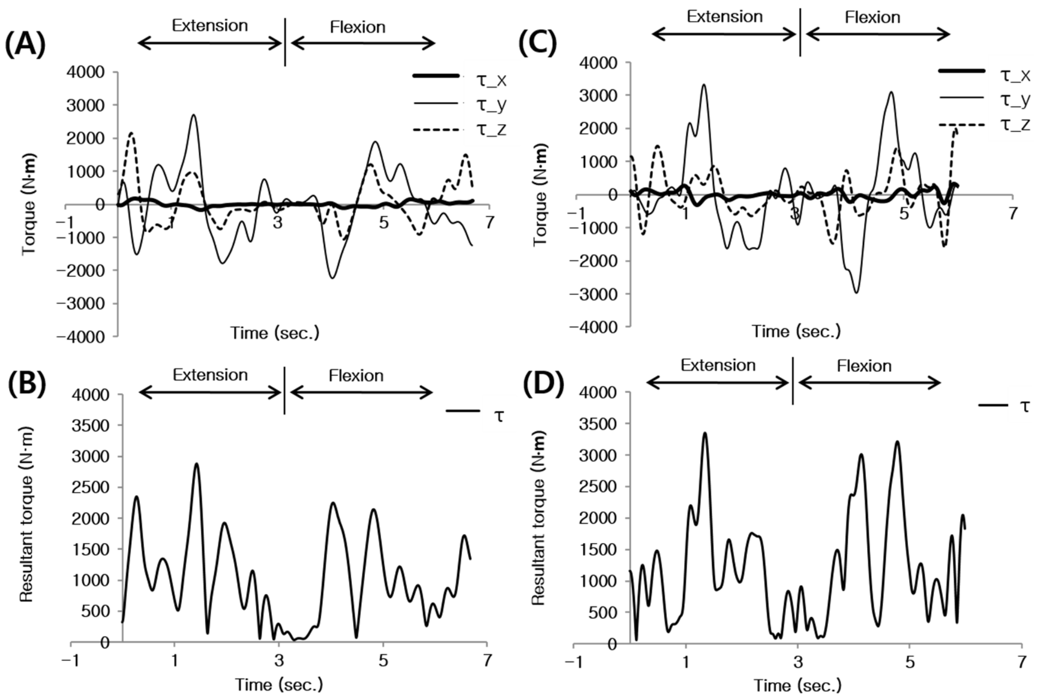

Figure 8. Changes of the various angular properties with 3-axis motion sensor, calculated by angular acceleration during one cycle of 2 kg-box lifting (A, B) and 12 kg-box lifting (C, D). (A, C) Torque generated by asymmetric lifting works on the L5/S1 disk in each axis (— : X-axis, — : Y-axis, --- : Z-axis), (B, D) Resultant torque on the L5/S1 disk.

Discussion

Due to necessity of manual work, agricultural workers are always exposed in danger. Yet, correlation between agricultural worker's disease and their working posture had not been investigated sufficiently. Recently, several studies assessing agricultural workers' working posture and their disease was conducted (Koo et al., 2004; Lim et al., 2011). However, the systems used in these research were valid only indoor circumstances because these systems are so vulnerable to light that it can easily lose its sensitivity outside. Hence, development of device detecting working posture wherever it was set is very important especially for earning data of real agricultural work. Furthermore, investigators have been aware of the importance of biometric information, for instance, heart rate, physical activity, and stress index. Detecting and analyzing these values is also an important part for investigation of agricultural worker's work load. But, the research observing more than two biometric signals at the same time was not enough. To solve the problem, our group developed multiple index-detecting system in previous study. (Son et al., 2010). The system also had a potential to be able to use outside, because the system used gyro sensor to get worker's physical signals instead of visual-based sensor. As expected, it successfully measure agricultural worker's biometric and physical information during cherry tomato harvesting (Seonwoo et al., 2011).

Although the system resolved the problem and opened the gate to investigate actual agricultural work, the system still had a limitation: the system was capable to observe only 1D physical signals. It is due to the 1-axis gyro sensor used in the system. Though same equipment with this research, 3-axis gyro sensor, was used when the system detected worker's signal harvesting cherry tomato, only 1-axis data was used and analyzed in the previous research. New system was required to detect workers' 3D physical signals and analyze work load more accurately. Thus, in this research 1-axis gyro sensor was replaced by MT_X, the device composed of 3-axis gyro sensors. For evaluating the system, task of waist was chosen because the movement consist of 3D bending and twisting. As expected, the system is capable of measuring 3D angular velocity. Then the system analyzed the signal and derived 3D angular displacement and acceleration. In this system, 3D torque and resultant torque sequently derived, too.

The greatest merit of the system is it is able to measure actual 3D-work load. Its measurements and analyses were not hampered by outdoor environment whereas video capture system and vision-based measurement system analyzing work load by modeling equation can be hampered by circumstances, e.g. temperature, moisture, and illuminance (Waters et al., 2011). Owing to accurately measured physical signals derived by this system, more accurate work load can be derived. Derived work load can be utilized in modeling using finite element method, resulting in new model that can prevent occupational disorder (Arif et al., 2013). Together, simultaneous measurement is still available in the system. All heart rate, physical activity, stress index, static load, and dynamic load changed along the increase of burden. In the next study, it is planned to derive correlation between these values and making a model. The system will measure and analyze various agricultural workers' bioinformation and suggest the best motion of each agricultural work.

Conclusion

This study analyzed the worker's physiological signals and 3D physical activity in the task of twisting at the waist while lifting using newly developed system. Developed biometric information measuring system measures the heart rate, physical activity, 3D movement in real time. It was confirmed that average heart rate, physical activity, stress index increased in case of 12 kg-box lifting compared to 2 kg-box lifting, indicating 12 kg-box lifting is harder work than 2 kg-box lifting. Dynamic load to herniated discs was analyzed using inertial sensor. As the load weight increased, the angular acceleration and torque increased. As a result, load to body also increased. This system have a capability to derive actual agricultural work load more accurately. It is also expected to give a benefit to make a modeling equation, in which heart rate, stress index, work load, etc. are included.

Conflict of Interest

The authors have no conflicting financial or other interests.

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