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Dynamic Electromyography Analysis of Shoulder Muscles for One-handed Manual Material Handling

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Objective: The objective of this research is to quantitatively analyze muscle activities of arm and shoulder, according to direction in various types of one-handed manual material handling, based on surface electromyography.

Background: Workers in industrial sites frequently carry out one-handed manual material handling using arm and shoulder muscles. Therefore, chronic load and accumulated fatigue occur to arm and shoulder muscles, which becomes a main cause of upper arm and shoulder musculoskeletal disorders. The shoulder muscles have widely range of motion, and complex interactions take place among various muscles including rotator cuff muscles. In this regard, research on interactions among should muscles, according to such various dynamic motions, is required.

Method: Ten male subjects in their 20s participated in this research. This research considered upward, downward, leftward, rightward, forward and backward directions and fourteen muscles around arm and shoulder (biceps brachii and trapezius, etc.) as independent variables. The mean muscle activity was set as the dependent variable. This research extracted 4^{th}~7^{th} repetition signals according to ten times of repetitive muscle contraction, and analyzed the muscle activity concerned using the envelope detection technique.

Results: The mean muscle activity of upward direction was analyzed highly statistically significant. The reason is that the effect of gravity works to arm and shoulder muscles. Also, it is conjectured that deformation of coracoacromial ligament was caused, and its contact pressure increased, due mainly to the shoulder flexion, and therefore load was analyzed high. Muscle activity was analyzed significantly low, according to concentric ballistic motion used in the concentric contraction phase by storing elastic energy in the eccentric contraction phase with a motion to bring the weight to the front of subject's body as to downward, leftward and backward directions. Because, elbow joint's flexion-extension motions mainly occurred, biceps brachii was analyzed high muscle activity as the prime mover.

Conclusion: The information on the quantitative load of muscles can be applied to ergonomic work design for one-handed manual material handling to minimize muscle load.

Application: This research has effectively identified muscle activity according to dynamic contraction by applying an envelope detection technique. The results can be used for ergonomic work design to minimize muscle load during the one-handed manual material handling, according to each direction. The research results are expected to be used for musculoskeletal disorder prevention and physiotherapy in the rehabilitation medical field, based on the muscle load of arm and shoulder in various directions.

Keywords: One-handed manual material handling, Shoulder, Electromyography, Linear envelope, Dynamic contraction

1. Introduction

Manual material handling occurs widely in the industrial fields such as manufacturing, transportation and raw material transportation industries. As mechanization and automation have been enhanced for years, the frequency of manual material handling decreases. However, simple repetitive work, complex manipulation and narrow spatial work are inevitably needed, and they are forecast to exist continuously. Although, symmetric lifting work using both hands at worksite is recommended, the workers in the production line and manufacturing industry frequently perform motions using asymmetric one hand and one shoulder. Therefore, occupational safety and ergonomic improvement emerge as main issues (Ciriello et al., 1999). As asymmetric one-handed handling occurs with high repetition for long duration, workers frequently use shoulder muscles. This is the main reason causing occupational upper arm and shoulder musculoskeletal disorders, due to chronic load and accumulated fatigue of shoulder. Urwin et al. (1998) reported the incidence of musculoskeletal disorder of the shoulder was about 16% higher than those of other joints. Most workers carrying out manual material handling were reported to complain chronic pain of shoulder (Brox, 2003; Sommerich and Hughes, 2006; Westgaard and Aarås, 1984). Mostly, shoulder disorders become chronic disorders (Macfarlane et al., 1998), and are the disorders having high social and economic burden, due to long treatment period, and therefore, early stage prevention is important (Falla et al., 2003).

Shoulder muscles have broad motion scope, and consist of various muscles and ligaments. Namely, shoulder muscles are composed of complex musculoskeletal system. There is kinematics linkage called scapulohumeral rhythm between shoulder girdle and humerus clinically (McQuade, 1998). Shoulder muscular system has formed as the ball-socket joint with multidirectional instability property. Accordingly, the shoulder muscular system has complex characteristics (Mallon and Speer, 1995; Wickham et al., 2010). Around deltoid, rotator cuff muscles including supraspinatus and subscapularis are connected, and therefore, instability is supplemented. Due to such musculoskeletal system characteristics of the shoulder, chronic pain is caused, according to complex muscle contraction. In this regard, a study for quantitative work such as electromyography according to various motions is needed.

The research on shoulder muscle activity considering manual material handling is performed diversely. A research of Oliveira et al. (2011) analyzed the change of muscle activity (RMS: Root Mean Square), according to repetitive lifting/lowering, using a linear regression analysis. As a result, it was analyzed muscle activity increased linearly, as motion continued. In a research of Koleini Mamaghani et al. (2009) considering one-handed motion, it was analyzed that significant differences of muscle activity (iEMG) occurred, according to working conditions. Diederichsen et al. (2007) analyzed each muscle's activity, according to shoulder joint's abduction and rotation motions. As a result, it was analyzed that used shoulder motions mainly consumed less energy with the ballistic motion of musculoskeletal system.

During the dynamic contraction, errors may occur, according to the change of muscle length and thickness, and skin motion (Kothiyal and Kayis 2001; Omi et al., 2010). Therefore, previous studies that analyzed shoulder muscle activity, according to manual material handling, measured the electromyography signals of some shoulder muscles, according to static motions. Although, the studies of Brookham et al. (2010) and Wickham et al. (2010) analyzed the various muscles activities of upper arm and shoulder, the studies mearing various muscles' activities having widely motion scope during dynamic contraction were limited. As above mentioned, interaction takes place by various muscles in terms of the musculoskeletal system of shoulder (Minning et al., 2007). Therefore, a study on shoulder muscle activity and interaction between muscles is necessary.

The purpose of this research is to quantitatively analyze the activities of various arm muscles during dynamic one-handed manual material handling. This research considers three axis one hand motion occurring frequently at industrial sites. This research effectively identifies muscle activity by selecting the various muscles of shoulder and shoulder girdle for which detection is possible using surface electromyography, and then by applying a proper signal processing technique for dynamic contraction. This research also reviews mutual linkage between muscles in consideration of a variety of directions, and can recommend muscle selection criteria and ergonomic work design.

2. Method

2.1 Subjects

Ten male subjects in their 20s participated in this research. All the subjects were right-handed, and a consent to participate in experiment was gained. All the participants had no history of musculoskeletal disorders of shoulder and cardiovascular disease. All the subjects got familiar with overall protocol of the experiment prior to the experiment, and the experiment was conducted in the familiar environment as much as possible. Table 1 shows the anthropometric characteristics of the subjects.

Table 1. Anthropometric characteristics of subjects

Age (year)	Height (cm)	Body weight (kg)	Elbow height (cm)	Arm length (cm)
27.30 (±1.06)	175.50 (±4.49)	74.81 (±6.57)	108.05 (±3.62)	61.14 (±2.25)

2.2 Equipment

The electromyography signals of repetitive dynamic contraction were measured using Telemyo 2400T DTS telemetry equipment (NORAXON, USA Inc., Scottsdale, Arizona). By using standing workstation of which height can be adjusted, the height was adjusted, according to the subject's elbow height. The height of the work table was set as 15cm below bent elbow height as the height in performing heavy work suggested in the literature of Sanders and McCormick (1993). The weight used in the experiment was a 7kg dumbbell, and the task repetition was controlled by a digital metronome because the auditory signal would be prevent confusion.

2.3 Experimental design

The experiment set the levels of weight, frequency and distance with extreme values to precisely measure the muscle activities of various shoulder muscles. The weight was set at 7kg, frequency at 10cyc/m and distance at 60cm. Mital et al. (1993) suggested that the one-handed maximum acceptable weight should not exceed 9kg weight. In the case of intermittent frequency, this research set 7kg consideration of repetition.

The independent variables of this research were set as six directions and 14 body parts' muscles. As for direction, this research considered six directions (upward, downward, leftward, rightward, forward and backward) in consideration of three axes (X, Y and Z) as shown in Figure 1, Figure 2.

(a) Upward (b) Downward

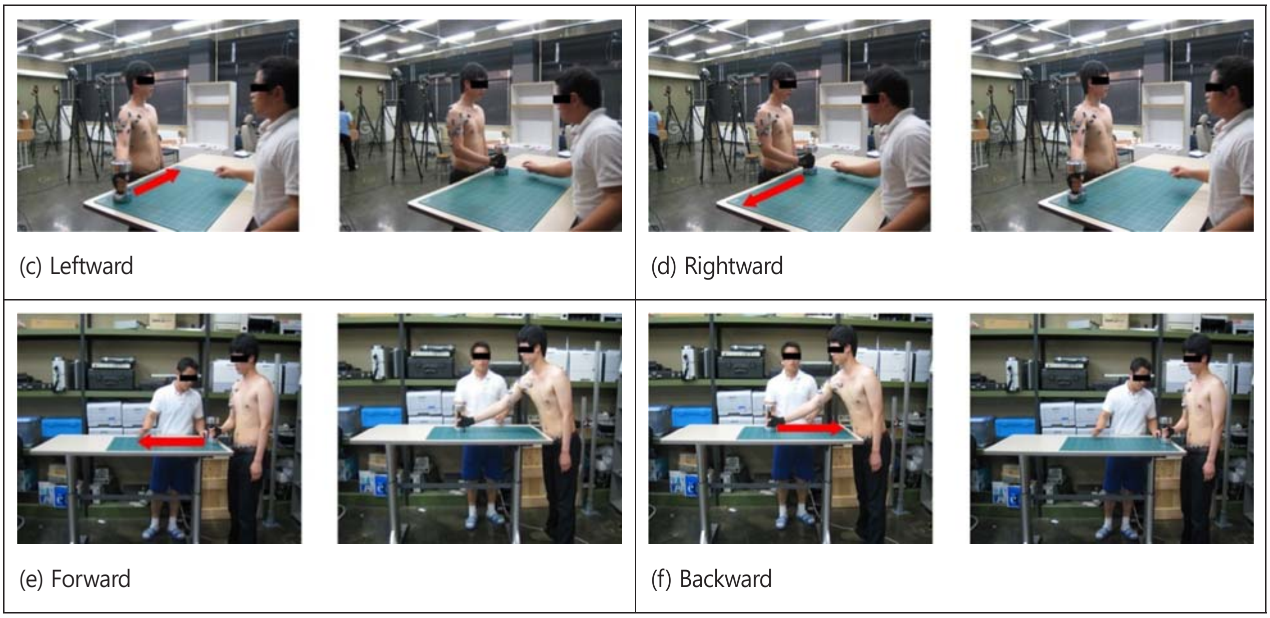


Figure 1. The six directions of one-handed handling: (a) upward, (b) downward, (c) leftward, (d) rightward, (e) forward, (f) backward

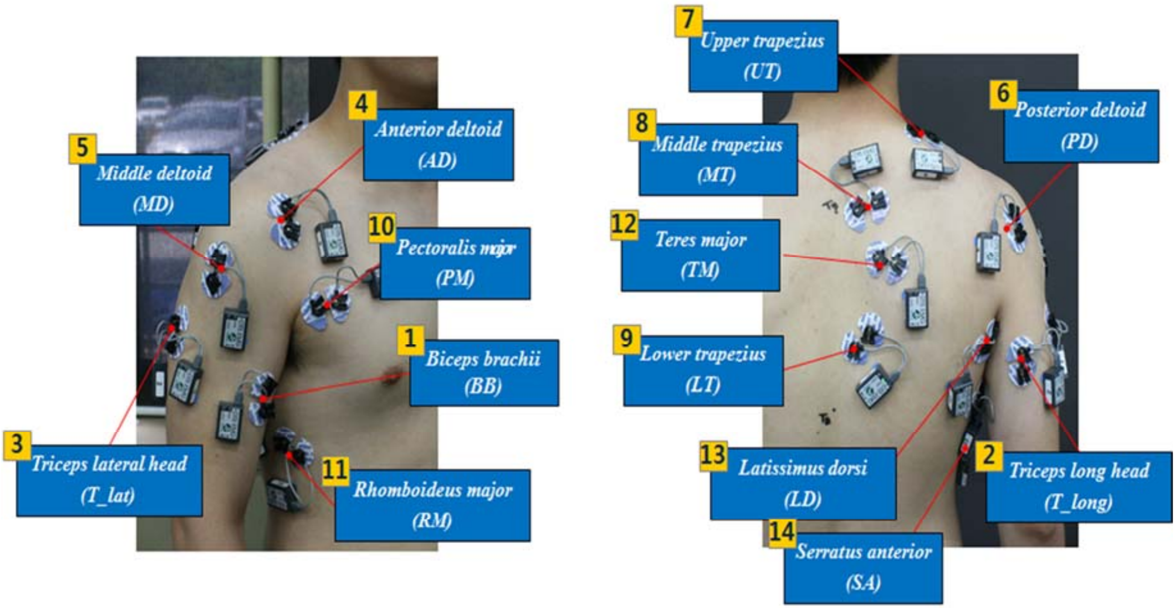


Figure 2. Location of the surface electrode

Each subject participated in the experiment conditions for six times in total using one-way factorial design. All experiment conditions were randomized, and the same experiment condition was conducted ten times repetitively. The dependent variable was set as the mean muscle activity (μV) of muscles according to each direction.

2.4 Protocol

This research measured dynamic electromyography signals in consideration of various muscles related with shoulder motion. This research selected the muscles of arm, shoulder and shoulder girdle by referring to Hislop and Montgomery (2007). For surface electrode attachment location, the recommendations of SENIAM (Surface Electromyography for Non-Invasive Assessment of Muscle) (Hermens et al., 1999) were complied with. This research referred to the literature of Perotto et al. (2005) as to rhomboideus major, teres major, serratus anterior, latissimus dorsi and pectoralis major. Table 2 shows the selected muscles and electromyography location of the electrode.

Table 2. Location of the surface electrode

Muscle (abbreviation)		Location
Biceps brachii (B)		Placed on the line between the medial acromion and the fossa cubit at 1/3 from the fossa cubit
Triceps	Long head (T_long)	Placed at 50% on the line between the posterior crista of the acromion and the olecranon at two finger widths medial to the line
	Lateral head (T_lat)	Placed at 50% on the line between the posterior crista of the acromion and the olecranon at two finger widths lateral to the line
Deltoid	Anterior (AD)	Placed at one finger width distal and anterior to the acromion
	Middle (MD)	Placed from the acromion to the lateral epicondyle of the elbow
	Posterior (PD)	Center the electrodes in the area about two finger widths posterior of the acromion
Trapezius	Upper (UT)	Placed at 50% on the line from the acromion to the spine on vertebra C7
	Middle (MT)	Placed at 50% between the medial border of the scapular ant the spine, at the level of T3
	Lower (LT)	Placed at 2/3 on the line from the trigonum spinea to the eighth thoracic vertebra
Pectoralis major (PM)		Midway between the coracoids process and the sternoclavicular joint 2 cm inferior to the clavicle
Rhomboideus major (RM)		Centered between spine and inferior angle of scapular border
Teres major (TM)		Three fingerbreadths above inferior angle of scapular along the lateral border
Latissimus dorsi (LD)		Placed at three fingerbreadths distal to and along posterior axillary fold
Serratus anterior (SA)		Placed at lateral to inferior angle of scapular

The surface electrode sensor used in the experiment consisted of Ag/AgCl bipolar electrode, and each electrode's diameter was 10mm, and the distance between electrode centers was set at 20mm as suggested from SENIAM. This research used 16 bit ADC, and set CMRR (Common Mode Rejection Ratio) > 100dB, Noise < 1μV, Gain*1000, input impedance >10Ω, first order high-pass filter 10Hz+/-10% cutoff, and sampling rate of 1,500Hz.

Concerning the procedure and method to attach surface electrodes, the recommendations of SENIAM were followed basically (Hermens et al., 1999). To minimize electric resistance, subject's skin was dry shaved and then cleaning with alcohol gauze to reduce the electrical impedance. And then, the electrode locations were marked on the skin with waterproof pen.

The motion repetition of a subject was defined as follows: (1) Weight lifting at initial point. (2) Weight movement. (3) Lowering weight at terminal point.). The subjects did not take their hands off a dumbbell coupling, and the assistant was return back a dumbbell. The subjects' right hand was put on working gloves due to reduce palm. The subject performed a total of 6 trials and was allowed to have a break of more than 10 minutes between the experimental conditions.

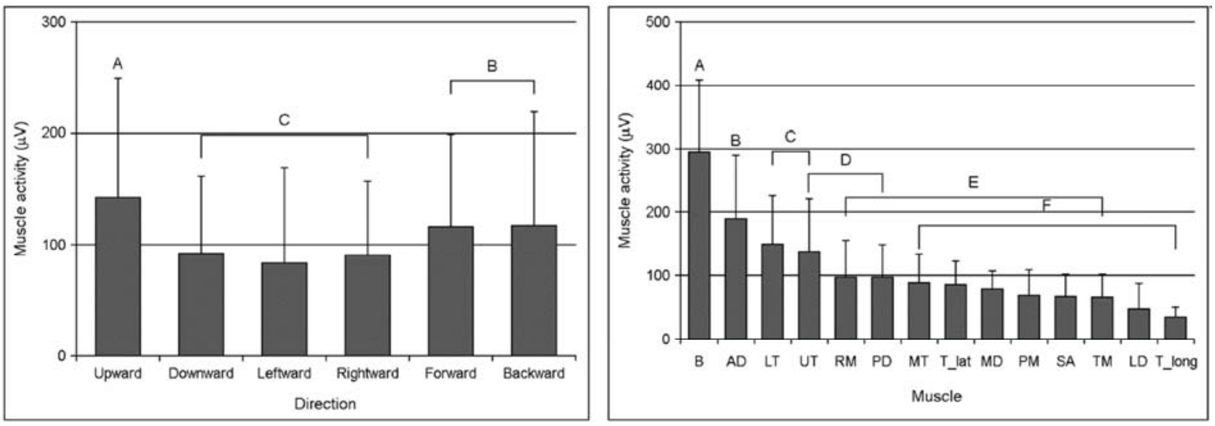
2.5 Signal processing and statistics

To analyze each muscle's muscle activity according to dynamic contraction, all heart beat noise of raw EMG signals reduced by pattern recognition of the ECG reduction function (NORAXON, USA Inc, Scottsdale, Arizona). The EMG signals were extracted from fourth to seventh cycle and those filtered by means of a Butterworth 4th order bandpass filter (10~500Hz). After signal was inverted by full wave rectification, the linear envelope (LE) value was analyzed through low pass filter with cutoff frequency of 5Hz (Hermens et al., 1999; Winter, 2005). The average of LE value was extracted from a 500ms moving average window.

For all electromyography data processing, the MATLAB 7.0.4 (Mathworks, US) was used, and SAS 9.1 (SAS, Institute, Inc.) was used for a statistical analysis. This research analyzed the mean and standard deviation, which are technical statistical values of each factor, performed analysis of variance (ANOVA). For significantly analyzed factors, this research analyzed significance between levels through Tukey test.

3. Results

As a result of ANOVA, the main effect according to direction ($F_{5,\ 45}$ = 25.55 p<.0001) and muscle ($F_{13,\ 117}$ = 28.68 p<.0001) showed statistically significant differences, and interaction was also analyzed to have significant differences ($F_{65,\ 584}$ = 9.77 p<.0001). The mean muscle activity (141.5 ± 107) of the upward direction was highest among six directions, followed by those of backward (116.6 ± 101.5), forward (115.2 ± 84.7), downward (91.6 ± 68.6), rightward (90.0 ± 65.5) and leftward (82.3 ± 86.2) directions. As a result of the Tukey test, significant differences were analyzed as A for upward direction, B for backward direction, and C for downward, leftward and rightward directions. Among the 14 muscles, the mean muscle activities of biceps brachii (347.1 ± 100.3), anterior deltoid (258.2 ± 79.7), lower trapezius (230.9 ± 97.1) and upper trapezius (191.9 ± 151.0) were distributed high (Figure 3).



(a) (b)

Figure 3. Muscle activity according to the (a) direction and (b) muscle independent variables
*Alphabetical order represents *Tukey test*

3.1 Upward

Figure 4 shows the analysis results of mean muscle activity according to upward direction. As a result of the Tukey test concerning the upward direction, where comprehensive muscle activity was analyzed highest, the mean muscle activities of biceps brachii, anterior deltoid, lower trapezius and upper trapezius belonging to A and B groups were analyzed significantly high.

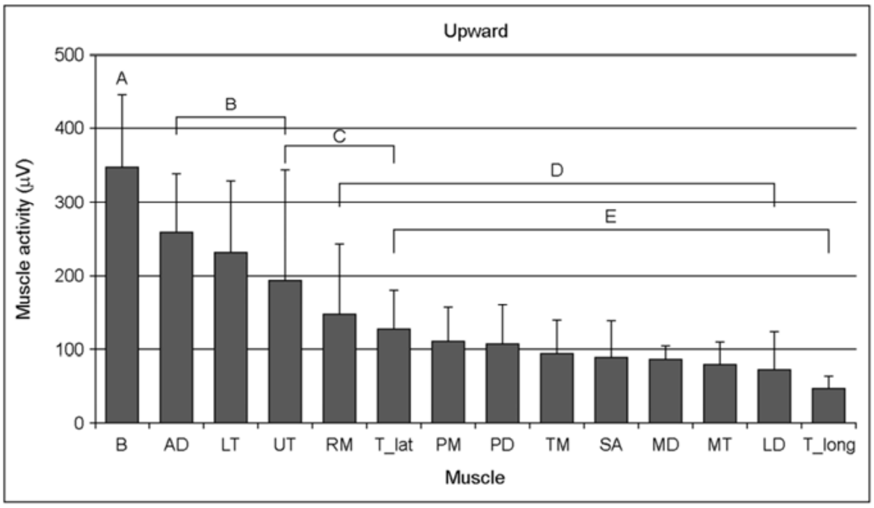


Figure 4. Result of the muscle activity by upward direction
*Alphabetical order represents *Tukey test*

3.2 Downward

Concerning downward direction, overall muscle activity was analyzed low. As a result of the Tukey test, the overall mean muscle activities of biceps brachii, anterior deltoid, lower trapezius, upper trapezius, rhomboid major and pectoralis major muscle belonging to A and B groups were analyzed high. Higher muscle activity was identified by using more biceps brachii than anterior deltoid in the case of one-handed manual material handing in the downward direction (Figure 5).

3.3 Leftward

Regarding leftward direction, where muscle acidity was analyzed lowest, as a result of the Tukey test, the mean muscle activities of biceps brachii, upper trapezius, anterior deltoid, posterior deltoid, middle trapezius, long head of triceps belonging to A and B groups were analyzed high. Especially, that mean muscle activity of biceps brachii was analyzed five times higher than other parts' mean muscle activities. Therefore, high load was analyzed as the main muscle in the case of one-handed manual material handling in the leftward direction (Figure 6).

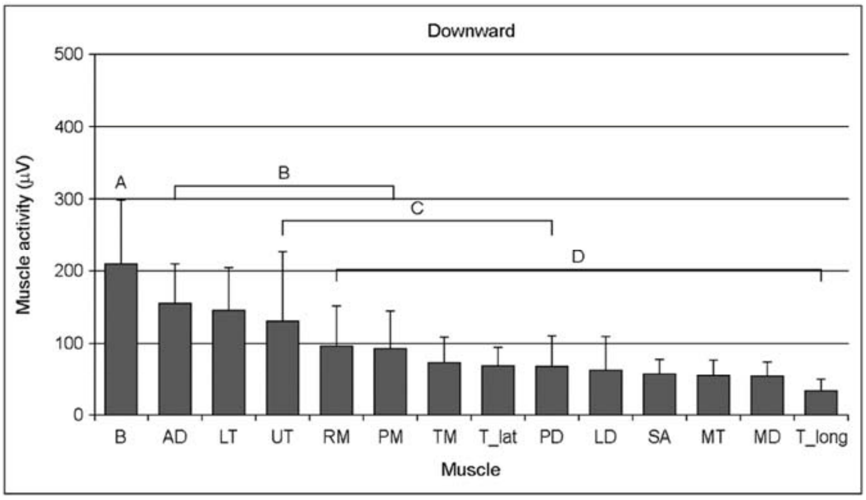


Figure 5. Result of the muscle activity by downward direction
*Alphabetical order represents *Tukey test*

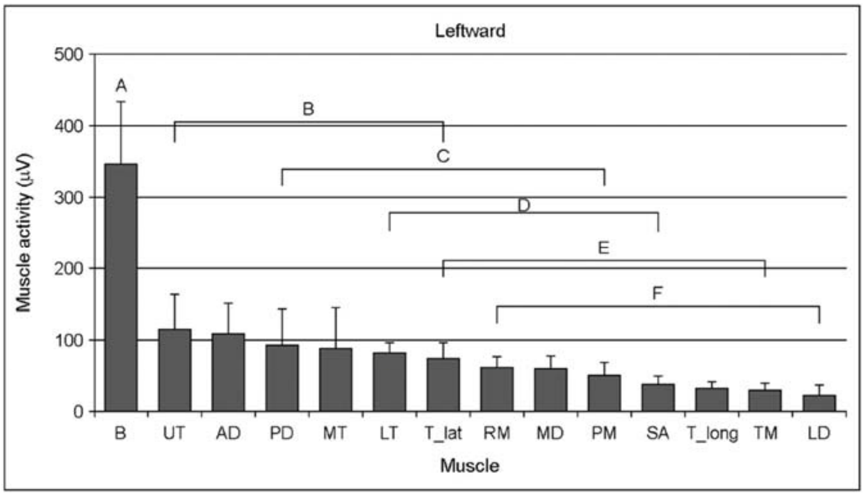


Figure 6. Result of the muscle activity by leftward direction
*Alphabetical order represents *Tukey test*

3.4 Rightward

Concerning rightward direction, where comprehensive muscle activity was analyzed low, as a result of the Tukey test, the mean muscle activities of biceps brachii, anterior deltoid, lower trapezius, posterior deltoid, upper trapezius and middle trapezius belonging to A and B groups were analyzed low. The mean muscle activities of biceps brachii and anterior deltoid were analyzed to have no significant differences statistically in the one-handed manual material handling in the rightward direction, and they were confirmed to have similar loads (Figure 7).

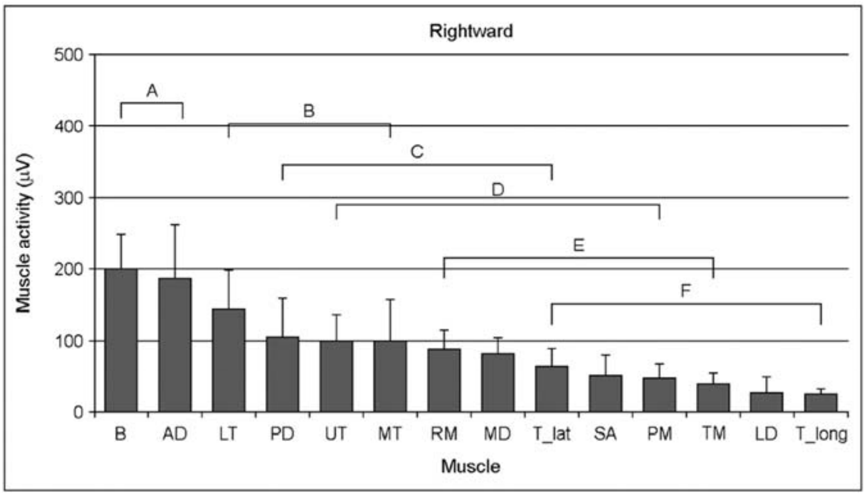


Figure 7. Result of the muscle activity by rightward direction
*Alphabetical order represents *Tukey test*

3.5 Forward

As for forward direction, where comprehensive muscle activity was analyzed third highest, as a result of the Tukey test, the mean muscle activities of anterior deltoid, biceps brachii, lower trapezius, upper trapezius, posterior deltoid, middle deltoid, rhomboid major, serratus anterior, middle trapezius, triceps lateral, and teres major muscle belonging to A and B groups were analyzed high. The muscle activities of anterior deltoid and biceps brachii were analyzed to have two times higher than those of other parts, and they were analyzed to be main muscles (Figure 8).

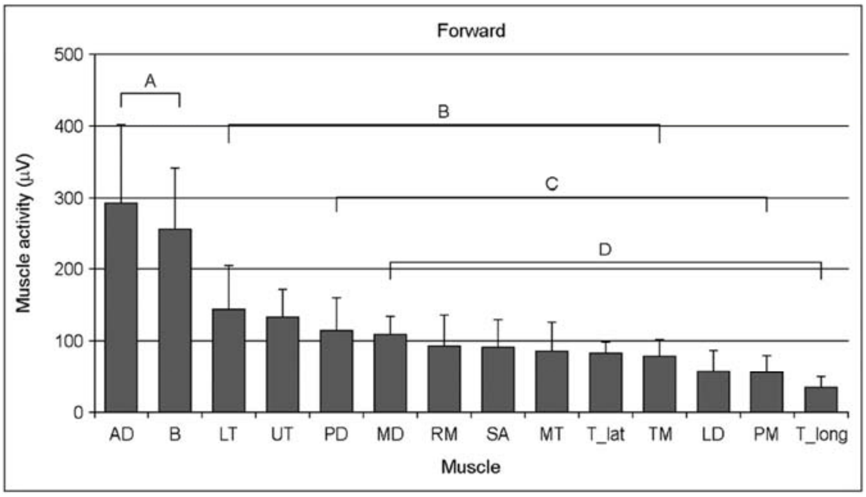


Figure 8. Result of the muscle activity by forward direction
*Alphabetical order represents *Tukey test*

3.6 Backward

Concerning backward direction, as a result of the Tukey test, the mean muscle activities of biceps brachii, upper trapezius, lower trapezius, anterior deltoid, middle trapezius, posterior deltoid, rhomboid muscle and long head deltoid belonging to A and B groups were analyzed high. Especially, the muscle activity of biceps brachii was about four times higher than the mean muscle activities of other parts, and load was analyzed high (Figure 9).

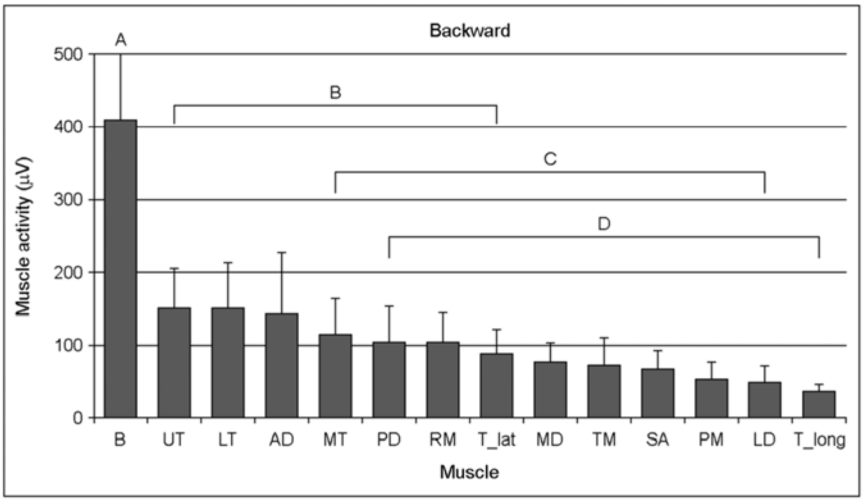


Figure 9. Result of the muscle activity by backward direction
*Alphabetical order represents *Tukey test*

4. Discussions

As a result of this research, the mean muscle activity in the upward direction was analyzed highest. Lifting in the upward direction is lifting motion above shoulder with relatively long vertical movement time. The reason is why high muscle activity was revealed is that gravity has a huge effect on arm and shoulder joints. In the upward direction, the defromation of coracoacromial ligament occurs and joint's contact pressure increases, due to shoulder joint's flexion movement, and therefore, load is considered to be analyzed high (Yamamoto et al., 2010). Wattanaprakornkul et al. (2011) reported that balance is maintained by dispersing shoulder loads, since supraspinatus, one of the rotator cuff muscles, is simultaneously manifested to prevent the load concentration of anterior deltoid in the case of shoulder flexion. Meanwhile, muscle load is considered to be analyzed low, because the weight is moved using gravity in terms of downward direction. Based on the result, this research recommends the avoidance of weight movement to upward direction as much as possible in ergonomic one-handed material handling. Also, a measure to minimize load accumulated to shoulder muscles is needed in consideration of lifting equipment and shelf design.

Based on horizontal plane, it was analyzed that weight movement with smaller muscle strength of latitudinal direction than that of longitudinal direction was possible. The initial point of weight movement in this research was subject's body center. In the experimental conditions in the leftward and rightward directions, only internal/external rotation of shoulder muscles mainly occurred, and therefore, lower muscle activity was revealed than other part muscles. Diederichsen et al. (2007) reported that muscle activity was lower in the internal rotation than abduction of shoulder muscle in manual material handling, which was similar to the result of this research. Kothiyal et al. (2001) showed that horizontal lifting of 90° direction was analyzed the highest muscle activity in sitting posture, Strasser and Müller (1999) reported that reported that arm abduction inadequate for 90~150° angle based on static and dynamic components of EMG and subjective preference. This means that burden to latitudinal shoulder muscles can be reduced on the basis of horizontal plane, which needs to be considered in designing ergonomic worksite layout design in the future.

Upon latitudinal motion in which mainly shoulder joint's rotation movement occurs, low muscle activity was revealed in the leftward direction. Because, internal rotation mainly occurs with a motion to bring the weight towards subject's body in the leftward direction in this experiment, it may consider that internal rotation was greater strength than external rotation due to the mass of anterior musculature (Julienne et al., 2007). Kinematically, upon external rotation of glenohumeral joint, muscle activity increases complexly, according to passive stabilizer effect to promote joint stability (Happee, 1992; Southgate et al., 2009). Generally, repetitive shoulder's external rotation movement has a high probability to cause injuries and pain to glenohumeral joint, shoulder girdle muscles and ligaments, according to accumulated load. For this reason, rightward directional one-handed manual material handling design at intermittent work frequency is recommended (Crétual et al., 2015; Ropars et al., 2010).

From downward, leftward and rightward directions, where a subject brought a weight to the front of his body, muscle activity was analyzed low overall. This has high relevance with a concentric ballistic motion between muscles. It is because that the concentric phase was used stored elastic energy in the eccentric phase (Bosco et al., 1983). This effect may be possible to faster motion. The motion to move a weight to subject's body internally does not need fine adjustment, and therefore, low muscle activity is judged to be revealed.

Since flexion and extension motions of elbow joint mainly occur in the one-handed manual material handling in six directions carried out in the experiment, the muscle activity of biceps brachii, which is main agonist, was analyzed high. Anterior muscle activity among deltoids was analyzed high. This seems that the muscle activity of anterior deltoid was analyzed high to lift the weight located in front of a subject. Higher muscle activity was analyzed in the order of lower trapezius, upper trapezius and middle trapezius. This is similar to the study result of Falla et al. (2007) that analyzed muscle activity in the case of repetitive shoulder flexion. And, the muscle activity of lower trapezius is considered to be analyzed higher a bit to maintain the stability of shoulder girdle in manual material handling (Arlotta et al., 2011; Kendall et al., 2005).

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Generally, a normalizing technique (%MVC, %RVC) with relative muscle activity is used, based on maximum voluntary contraction (MVC) and reference voluntary contraction (RVC) by subject and by muscle in analyzing the amplitude of electromyography signals. However, this research analyzed muscle activity with absolute signal value (μV), not normalized relative muscle activity by subject and muscle in consideration of various directions and muscles complexly, according to one-handed manual material handling, and the standard deviation by muscle is regarded as being analyzed high. A comparative analysis of relative muscle activity is needed by normalizing muscle activity, according to maximum activity criteria that can be exerted by each muscle as a future research direction. Existing MVC measurement is difficult to apply to actual dynamic contraction normalization by analyzing maximum activity, according to isometric contraction by which muscle length does not change. Therefore, research on the normalization technique of highly reliable dynamic muscle activity, based on maximum dynamic contraction (MDC), using the equipment such as Isokinetic Cybex dynamometer, should be conducted.

5. Conclusion

This research comparatively analyzed muscle activity differences in consideration of various directions and muscles, according to one-handed manual material handling. This research actually identified muscle activities effectively by applying the envelope detection technique, according to dynamic contraction. Using the research results, basic data on the quantitative load of muscles can be presented, according one-handed manual material handling. The research results can be applied to ergonomic work design to minimize muscle load, according to each direction. The highly effective shoulder muscle load information through this research is expected to be used for the prevention of musculoskeletal disorders and for physiotherapy in the industrial sites and rehabilitation medical field.

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