수작업에 수반되는 외부하중 추정방법에 대한 연구 - EXTERNAL LOAD ASSESSMENT FOR HAND INTENSIVE WORK

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ABSTRACT

본 논문에서는 실제 작업 상황에 대한 신체역학적 해석을 할때에 기술적으로어려운 부분중의 하나로 지목되는 외부하중 추정방법을 제시하고 그에대한 결과로, 실제상황에 있어서의 외부하중과 외부모멘트의 분포를 구하였다. 개발된 외부하중 추정방법은 Psychophysics의 RPE(Ratings of Perceived Exertion)의 개념에 근거하였으며, 외부하중은 RPE와 그밖의 작업 혹은 개인적 특성을 나타내는 변수들에 의한 회귀분석으로 추정되었다. 구해진 실제 상황에서의 외부하중분포로 부터 다양한 수작업의 특성과 그리고 그에 따르는 각 손관절의 역할을 해석하였다.

1. Introduction

There are three major mechanical factors in the interaction of the musculoskeletal system inside the body with external environmental systems. First are the active forces of voluntary muscles that exert tension through tendons to produce torque around the axes of joints, causing movement of segments of limbs. Second is the internal passive resistance that limits the application of the force of the muscles and limits of the range of motion of the joints. Third is the system of forces between the surface of the limb and the external environment. These external forces may be initiated by the body and resisted by the environment or may be initiated outside the body to affect the musculoskeletal system, as when one person fights another or helps another.

In order to perform complete biomechanical analysis omusculoskeletal system, information regarding the external force applied is greatly needed. However, external load assessment has practical restrictions since direct measurement of external load during an actual working situation is quite difficult, requiring such measurement methodology as force sensitive resistors or EMG techniques, which require much equipment and time for each subject. Therefore, direct measurement cannot be easily adopted for on-site analysis since it is very - hard to elicit a large number of subjects (workers) from industry and to use large experimental equipment at actual working environment.

In this study, a method that combines direct and indirect measurement of external load is proposed. An indirect measurement here represents an application of psychophysical techniques which can be basically categorized into estimation and production techniques. The first is an estimation method, in which the subjects are asked to estimate given stimuli and assign them

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numbers [4]. The estimation method has been used in studies of heavy aerobic work. However, the value of subjective estimation is also important where the work tasks consist of short-term static work for which valid physiological measurement are difficult to obtain. The basic assumption of the estimation method is that the subject is able to match his/her perception with the numbers. There have been numerous studies about the feasibility of the estimation method. Many studies showed that subjects are able to perform the subjective estimation. Eisler [7] related subjective force to physical force for work. Borg and Noble [1] drew the analogy that a worker's subjective report of perceptions associated with physical work can be used to obtain information about physiological response to work and work level in the same way that medical diagnosis proceeds from a patient's subjective report of physical symptoms. The second is an production method in which the subjects set the test stimulus intensity as a ratio of a standard stimulus. In other words, experimenter has to present the numbers one at a time in an irregular order and subject has to adjust the stimulus to produce an apparent match.

Ratings of perceived exertion are one of the most popular tools in this estimation procedure. They have been a complementary tool for physiological measurement of the indicators of the physical strain. This tool was originally developed for studying the relationship between perceptual and physical intensities. Several studies accounted and described the relationship between perceived exertion and real exertion ([2]: cited in [9]). The biggest contributor in this area is G. Borg who developed the "Ratings of Perceived Exertion" (RPE) scale, belonging to the category of rating scale [2]. He applied this idea to many studies of the psychological aspects of physical work. This scale is designed to increase linearly with exercise intensity. Recently, the category ratio scale (CR-10 scale) was developed as a refined version of RPE ([3]: cited in [12]).

In this study, it was assumed that grasp (including power grip) and pinch (including pulp pinch) are the most common and potentially risky hand postures for most hand-intensive jobs. There were two parts (development and application) in the experiment. The first procedure consisted of measurement of grip and pinch strength, hand size, real external load applied and ratings of perceived exertion (RPE). The subjects were 20 non-worker, voluntary participants. The second procedure was the same as the first, except the subjects; this procedure was conducted for 160 workers in real working situations. They were asked their perceived exertion levels for the most physical part of their job instead of measuring real external load applied. The objective of this procedure was to assess the external force of actual working situations based on the relationship (external load and subjective rating) obtained from the first procedure and to see the general shape of the external load distribution in the hand.

2. Method

2.1 Subjects

For the first experiment, twenty subjects (10 men and 10 women between 20 and 40 years of age) without any history of any musculoskeletal problems in their upper extremities voluntarily participated in this experiment. They were carefully instructed about subjective ratings and experimental tasks. The basic information of the subjects in the first experiment is summarized in table 1. The second experiment had 160 subjects (90 male and 70 female between 20 to 60 years of age) from 44 different job titles. For subject selection from the industry, there was no rule or priority. The selection procedure was mainly handled by the line supervisor in most industries. Thus, subject selection was based on production schedules and, as a consequence, workers in less busy schedules had higher priority during subject selection. The basic information of the subjects in the second experiment is summarized in table 2.

Table 1 Subjects information (experiment 1)

Information	Mean	Standard Deviation
age (years)	27.2	4.5
weight (lb)	144.3	31.0
stature (in)	66.5	2.8
max grip strength (lb)	86.0	27.5
max 1-point pinch strength (lb)	12.8	2.6
max 2-point pinch strength (lb)	18.9	4.2
max lateral pinch strength (lb)	21.3	4.6
max finger press strength (lb)	47.1	17.8
hand length (in)	7.1	0.4
hand breadth (in)	3.1	2.6
hand thickness (in)	0.9	0.1
wrist circumference (in)	6.3	0.6
hand span (in)	7.9	0.6

Table 2 Subject information (experiment 2)

Information	Mean	Standard Deviation
age (years)	36.9	9.7
weight (lb)	170.8	37.1
stature (in)	67.1	4.2
max grip strength (lb)	89.9	29.9
max 1-point pinch strength (lb)	15.4	5.1
max 2-point pinch strength (lb)	18.5	5.5
max lateral pinch strength (lb)	15.1	3.3
max finger press strength (lb)	48.6	14.3
hand length (in)	7.2	0.5
hand breadth (in)	3.5	0.5
hand thickness (in)	1.1	0.2
wrist circumference (in)	6.8	0.7
hand span (in)	8.1	0.8

2.2 Apparatus

2.2.1 Equipment

A sensor matrix was developed by attaching twelve Force Sensitive Resistors [11] to a thin cotton glove. This setup was used for the development of external load assessment in the first experiment. FSRs are thin film devices that exhibit decreasing resistance with increasing force applied normal to the device surface. They can be easily interfaced with an analog-to-digital converter by using a voltage divider circuit. This technique was used to measure pressure distributions on foam grip handles [8]. The attaching points of the sensors to the glove are based on their study. Figure 1 shows the layout of the FSRs. Although the response to force changes is not linear, the FSRs can be optimized for force measurement [13]. Voltage outputs from the twelve sensors were recorded using a DASH 16/F analog-to-digital converter installed in a PC. Figure 2 shows the experimental setup. The glove was calibrated to total force (kg) using exponential regression:

$$\text{Force (kg)} = \exp(-2.18 + 1.25mv) \quad (1)$$

The coefficient of determination for the force calibration regression was 0.99. Pinch force was measured with a Best Products Model pinch gauge (range=60 lb (267N)) with an increment of 2 lb (8.9N). Also, hand grip strength was measured with a JAMAR model hand grip dynamometer (range=100kg (981N)) with an increment of 1 kg (9.8N), and hand size and flexibility were measured with a tape measure, caliper and goniometer. A powerdrill, a screwdriver, a hammer and an electrical socket and cord were used to simulate actual working situations.

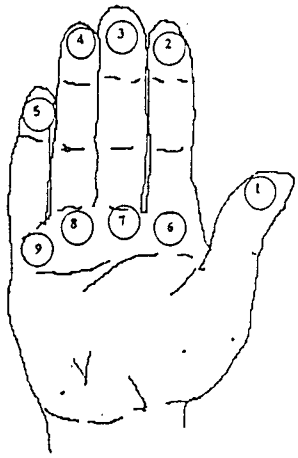

Figure 1 Location of FSRs

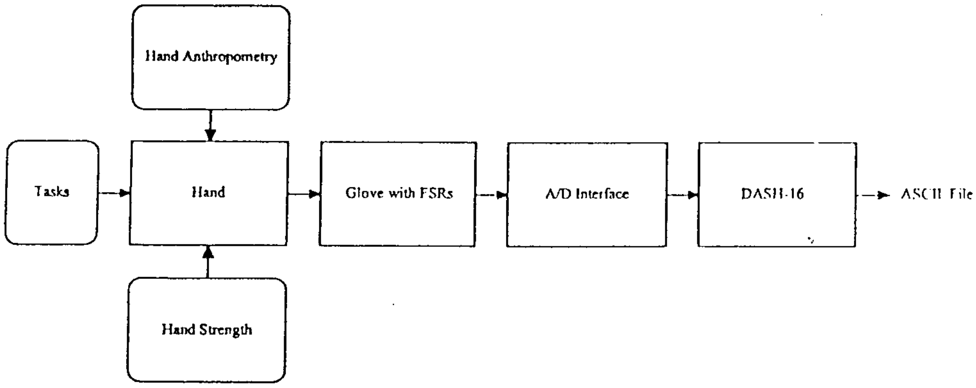

Figure 2 Experimental Setup

2.2.2 Ratings of Perceived Exertion (RPE)

The previously mentioned estimation method has been widely used to describe how the subjective intensity varies with the physical intensity. For practical purposes, simple category rating scales were developed [10]. These scales were constructed to satisfy ratio scaling and level estimation. Several studies demonstrated that there was a linear relationship across a range of work loads between RPE and actual physical exertion [3]. From their studies, they suggested that verbal ratings of perceived exertion are powerful and reliable assessments of physical costs paid during work performance.

The simplest category scale [3] with the ratio properties was used in this experiment. This scale has been used to collect estimates of subjective effort during endurance tasks such as an isometric hand grip task. Figure 3 shows the category scale (Borg's CR-10 scale) used in this study. The number 10 of this scale implies an extremely strong perceptual intensity, which is defined as the strongest effort and exertion a person has ever experienced.

RATINGS OF PERCEIVED EXERTION

0	Nothing at all
.5	Extremely Weak (hardly noticeable)
1	Very Weak
2	Weak
3	Medium
4	Somewhat Strong
5	Strong
6	
7	Very Strong
8	
9	
10	Extremely Strong (almost max)
	Maximum

Figure 3 Borg's CR-10 Scale

2.3 Statistics

For the first experiment, seven tasks - one-point pulp pinch, two-point pulp pinch, lateral pinch, power drilling, screw driving, hammering, and finger pressing were defined. Their sequence was randomized for each subject. However, the two trials for each condition were done in a sequence with at least two minute rest periods between trials. The peak values were obtained and regressed on four categories of independent variables such as RPE, gender, FSR locations, and anthropometric data for each task.

2.4 Procedure

There are three major assumptions in this study:

1) Tasks defined here could cover most real working situations in manufacturing industry.

2) Subjects were well trained for subjective ratings.

3) External force was applied in the y-direction (along the axis projected dorsally, passing through the center of the corresponding system) at the distal end of each joint.

For the first experiment, three types of hand postures (pinch, finger press and power grip) were considered. Pinch was simulated by unplugging the cord while finger press was simulated by punching holes using a three hole-puncher. Actually, many workers complained of finger pressing motion without using any hand tool as the most physical part of their jobs (sewing, box folding, etc.). To simulate power grip, three common hand tools (a hammer, a screwdriver, and power drills) with cylindrical handles were used. The most commonly used tool types were [5]:

1) gun-shape type

2) screwdriver type

3) hammer type

Specific steps for the first experiment were as follows:

1) Measure the hand size of each subject in terms of hand length, hand breadth, hand thickness, joint breadth, joint thickness and phalangeal length according to the anthropometric definitions as follows:

(1) Hand length

: Distance from distal wrist crease to the finger tip of the middle finger at the palm side.

(2) Hand breadth

: Maximum distance between the distal ends of the metacarpal bones of the index and little finger at the palm side.

(3) Hand thickness
: Height of the third metacarpophalangeal joint from the palm side to the dorsal side.
(4) Joint breadth
: Distance between medial and lateral sides of each joint.
(5) Joint thickness
: Distance between dorsal and volar sides of each joint.
(6) Phalangeal length
: Distance between distal and proximal joint of each phalanx.

2) Measure the maximum pinch (1 and 2 point), lateral pinch, finger press and grip strengths for each subject.

3) Conduct task 1, which is plugging in a cord using the index finger and thumb, to assess external load during a one-point pulp pinch. The one-point pulp pinch here represents that index finger is flexed and the thumb is at any posture (flexion, extension, neutral) so that the small object is held in a finely controlled manner between distal phalanges of index finger and thumb.

4) Conduct task 2, which is plugging in a cord using the index finger, middle finger and thumb, to assess external load during a two-point pulp pinch. The two-point pulp pinch here represents that index and middle fingers are flexed and the thumb is at any posture (flexion, extension, neutral) so that the small object is held in a more finely and firmly controlled manner between distal phalanges of two fingers and thumb compared to one-point pulp pinch.

5) Conduct task 3, which is plugging in a cord laterally using the index finger and thumb, to assess external load during a two-point pulp pinch. The lateral pinch here represents that pulp of the thumb is pressed so that the small object is held between pressed part of the thumb and the lateral side of the index finger.

6) Conduct task 4, which is drilling a hole in a wood panel using a power drill, to assess external load during the power grip of a gun-shape handle. The power grip here for tasks 4, 5, and 6 represents that thumb and fingers are flexed at all three joints (two joints for the thumb) so that the cylinder-shaped object (e.g. usual tool handle) is held between the fingers and palm.

7) Conduct task 5, which is driving a nail into a wood panel using a hammer, to assess external load during the power grip of a hammer.

8) Conduct task 6, which is punching holes using four fingers, to assess external load during a finger press. The finger press here represents that all segments of the hand are kept straight so that the external surface is pressed down.

9) Make two replicates for steps 1) to 8).

10) Ask for RPE at steps 3) to 8).

At the second experiment, only RPE for the most physical part of the job was asked after measuring anthropometry and maximum strength in steps 1) and 2).

3. Results

3.1 Experiment 1 (Development)

After collecting data, the external load recorded was calibrated (in kg) and normalized with respect to the maximum 1-point pinch strength for task 1, the maximum 2-point pinch strength for task 2, the maximum lateral pinch strength for task 3, the maximum grip strength for tasks 4, 5 and the maximum finger press strength for task 6. General hand shape was also characterized by taking the ratios between various anthropometric measures (breadth/length etc.). Then the normalized external load was expressed as:

$$EL(normalized) = f\ (RPE, Gender, Location, BMI, HBL, DHL) \qquad (2)$$

NEL(EL / Max. Strength) = g(RPE, Gender, Location, BMI, HBL, DHL) (3)
NEL : Normalized External Load
Location: Location where external load is applied
BMI: Body mass index [weight(lb) / stature(in)]
HBL: Ratio of hand breadth to hand length
DHL: Ratio of digit length to hand length

The regression models for external load assessment are shown in Table 3. These models were used to estimate external load for each subject (industry worker) on the basis of his/her personal and working characteristics. There were nine representative points for external load applied as follows:

1: distal end of thumb
2: distal end of index finger
3: distal end of middle finger
4: distal end of ring finger
5: distal end of little finger
6: palm side of second metacarparpophalangeal joint
7: palm side of third metacarparpophalangeal joint
8: palm side of fourth metacarparpophalangeal joint
9: palm side of fifth metacarparpophalangeal joint

Particularly, indicator variables were used to represent the location of external load applied. The number of external loading points depended on the tasks. For instance, 1-point pinch needed location 1 and 2 while power grip needed all 9 locations. Thus, the number of indicator variables involved also depended on the tasks. For instance, 1-point pinch needed 1 indicator variable while power grip needed 8 indicator variables to express the locations.

Table 3 Regression models for external load

Task	Model	R2	p-value
1	NEL=0.211 + 0.074 Gender + 0.032 RPE + 0.059 BMI - 0.149 HBL + 0.308 D1HL - 0.611 D2HL - 0.078 LOC(1)	44.1 %	0.001
2	NEL=0.747 + 0.014 Gender + 0.011 RPE + 0.032 BMI - 0.544 HBL - 0.747 D1HL - 0.719 D2HL + 0.177 D3HL - 0.058 LOC(1) -0.159 LOC(2)	34.7 %	0.001
3	NEL=0.825 - 0.007 Gender + 0.009 RPE + 0.026 BMI - 0.238 HBL + 0.553 D1HL + 0.006 D2HL + 0.166 LOC(1)	39.8 %	0.001
4	NEL=0.011 - 0.012 Gender + 0.001 RPE + 0.027 BMI - 0.142 HBL - 0.034 D1HL + 0.207 D2HL - 0.201 D3HL - 0.328 D4HL + 0.383 D5HL - 0.010 LOC(1) - 0.012 LOC(2) - 0.020 LOC(3) + 0.004 LOC(4) + 0.023 LOC(5) + 0.039 LOC(6) + 0.016 LOC(7) + 0.051 LOC(8)	60.0 %	0.001
5	NEL=0.199 - 0.026 Gender + 0.007 RPE + 0.022 BMI - 0.396 HBL + 0.317 D1HL + 0.060 D2HL - 0.161 D3HL - 0.230 D4HL + 0.037 D5HL - 0.043 LOC(1) - 0.020 LOC(2) - 0.023 LOC(3) - 0.024 LOC(4) - 0.006 LOC(5) + 0.023 LOC(6) + 0.016 LOC(7) - 0.017 LOC(8)	54.5 %	0.001
6	NEL=0.134 - 0.017 Gender + 0.009 RPE + 0.027 BMI - 0.204 HBL + 0.301 D1HL - 0.074 D2HL - 0.470 D3HL + 0.090 D4HL + 0.097 D5HL - 0.036 LOC(1) - 0.022 LOC(2) - 0.010 LOC(3) - 0.004 LOC(4) - 0.001 LOC(5) + 0.015 LOC(6) + 0.005 LOC(7) - 0.010 LOC(8)	40.1 %	0.001
7	NEL=0.005 - 0.043 Gender + 0.025 RPE + 0.018 BMI + 0.084 HBL - 0.181 D2HL + 0.323 D3HL - 0.586 D4HL + 0.139 D5HL - 0.007 LOC(1) + 0.040 LOC(2) + 0.037 LOC(3)	34.6 %	0.001

where, LOC(i): indicator variable for location of external load
location i+1=1
otherwise =0
BMI: body index mass
HBL: ratio of hand breadth to hand length
D1HL: ratio of thumb digit length to hand length
D2HL: ratio of index digit length to hand length
D3HL: ratio of middle digit length to hand length
D4HL: ratio of ring digit length to hand length
D5HL: ratio of little digit length to hand length

All information needed in these models was collected from personal interviews and anthropometric measurements. Based on the external load obtained, corresponding external moments were computed by the following equation:

$$EM_{i1} = \sum_{k=1}^{i-1} EM_{k1} + S_i \cos\left(\sum_{k=0}^{i-1} \theta_k\right) E_1 \qquad (4)$$

$$EM_{i3} = S_i E_3 \qquad (5)$$

* For joints 1, 2, 3, apply eq. (4)
For joint 4, apply eq. (5)

Where, EM_i : external load applied at joint i

S_i : phalangeal length between i-1 and i joints

θ_i : deviation angle of joint i

$\theta_0 = 0$

3.2 Experiment 2 (Application)

On the basis of the regression models obtained from the first experiment, external load applied at actual working situation was estimated. The main objective of this experiment was to figure out a general shape of external load distributions at the hand through indirect assessment. Specifically for the profile of the external moment applied, thumb and index finger were studied since they have been frequently employed during most hand-intensive tasks.

The mean external load (normalized) applied during performing actual tasks for thumb and fingers were presented in figure 4. One interesting point from this plot was the relationship of pinching tasks. The 2-point pulp pinching task showed a dramatic increase in external load applied at index finger while 1-point and lateral pinching tasks showed relatively constant distributions between thumb and index finger. The index finger seemed to have a special role during 2-point pulp pinching task. For power gripping tasks (drilling and hammering), external load was evenly distributed at thumb and four fingers. It also showed that power drilling generally had larger external load applied than hammering (Figure 5). This might be due to different characteristics of each task. In figure 5, it was observed that both power gripping task had no external load at joint 3 (metacarpophalangeal joint). It was compared with the results from [6]. They showed average external load distribution among phalanges during power gripping task. Specifically, they took the ratio of corresponding phalanx with respect to the distal phalanx. Table 4 presented the comparisons between this study and [6] in terms of average external load ratio of the proximal to the distal phalanx. Even though statistical analysis were not conducted due to unavailability of full data from referred material, it did not seem to have major deviations from the results of [6] except little finger. Regarding finger pressing task, little finger seemed to have a minor role although all four fingers were employed.

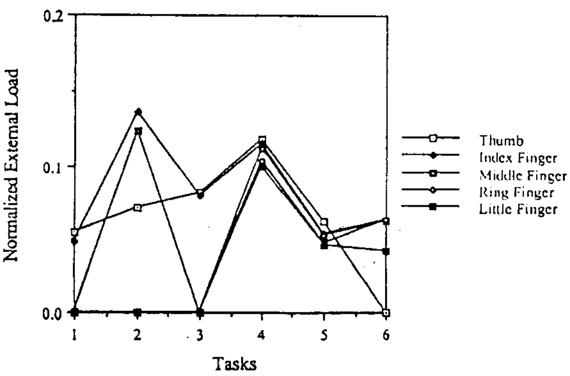

Figure 4 External Load Distribution for Hand Tasks

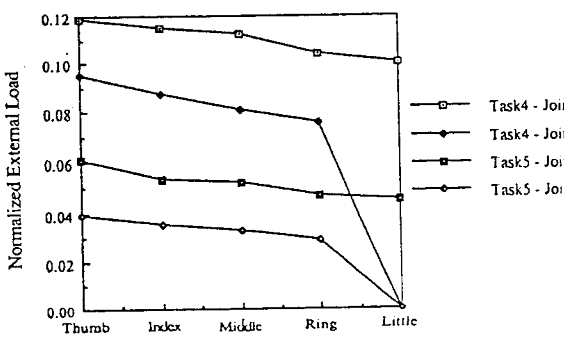

Figure 5 External Load Distribution for Thumb & Fingers

Table 4 Average external load ratio of proximal to distal phalanx

Fingers	Power Drilling (This Study)	Hammering (This Study)	Power Gripping (Chao's Study)
Index	0.75	0.66	0.66
Middle	0.72	0.63	0.53
Ring	0.73	0.61	0.60
Little	0	0	0.22

In figures 6 and 7, external moment applied at each joint were shown for thumb and index finger respectively (Joint 1 : distal interphalangeal joint, Joint 2 : proximal interphalangeal joint, Joint 3 : metacarpophalangeal joint, Joint 4 : carpometacarpal joint). In fact, the order of the amount of external moment applied were always the same for thumb and each finger. The power-drilling had the worst condition in terms of external moment distributions. The hammering task that belonged to the same category of power gripping task, however, were in a lot better condition (less external moment applied) than the power-drilling. The relationship identified from the above two power-gripping tasks could be explained by static vs dynamic effects. Among

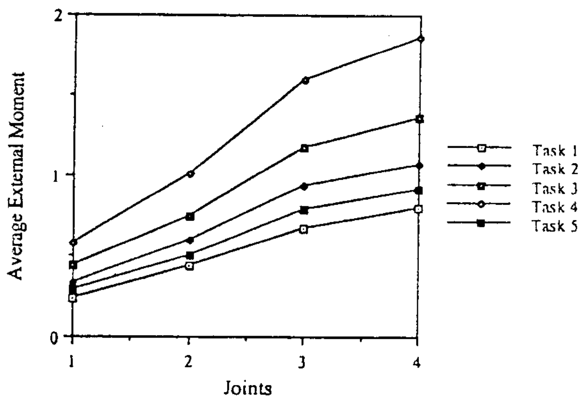

Figure 6 External Moment Applied at Thumb

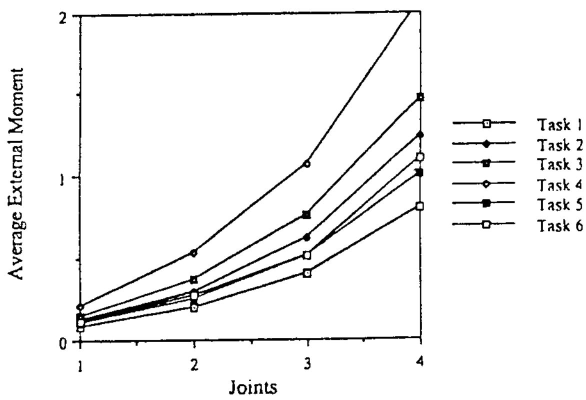

Figure 7 External Moment Applied at Index Finger

Figure 7

pinching tasks, lateral pinching task carried a lot more external moment than two pulp pinching task. It might be due to the fact that lateral pinching task was associated with a lot of total joint deviation while two pulp pinching task had relatively small joint deviation angle in each finger.

4. Conclusion

There have been many biomechanical studies on various parts of musculoskeletal system. Most biomechanical studies, however, have been too much mechanics oriented, so that they usually handled just ideal situation. Consequently, their studies couldn't be directly applied to industrial ergonomics field. Specifically, modeling for hand-intensive work in actual working environment could not be associated with their studies. Therefore, development of external load assessment, in this respect, would be the first step to go through for an application of biomechanical concept to industrial ergonomics study.

This paper has attempted to propose a methodology of external load assessment and to apply corresponding methodology at actual working situation. The main tool adopted in this study was "Ratings of Perceived Exertion (RPE)" which might have been argued since its validity has not been fully demonstrated. However, there has been no better or more objective methodology in generalizing the theme of external load assessment during actual working. Most problematic aspect would be fundamental and connected with the nature of measurement itself. Therefore, it is important to know the fact that the individual report of perceived exertion constitutes a distal reaction. The extent to which this distal reaction is a reflection of the proximal reaction within the individual organism relies on the adequacy of the measurement. For this reason, subjects were trained repeatedly for subjective ratings and tested about their subjective differentiability on ratings prior to conducting the experiment,. The tests were performed for four approximate levels based on the CR-10 scale [3] and were repeated three times for each level. The pearson product moment correlations between each trial fluctuated from 80.4 percent to 99.8 percent. All of these correlations were significant at $\alpha = 0.01$. These numbers were consistent enough to use these subjects' differentiability for the external load experiment. Also, a paired t-test was conducted to compare the trials for each subject. The paired t-test showed that there were no significant differences between the trials. Specifically, p-values for each comparison (trials 1 and 2, trials 1 and 3, trials 2 and 3) were 0.34, 0.38, and 0.93. Thus, no statistically significant differences were observed for comparisons between the perceptual differentiability of the trials.

The results of the assessment in this study has shown a general shape of external load distribution. These results can be used as an index of the biomechanical loads on the hand joints in various hand tasks. Thus, an application of the results may be extended to the areas of hand tool design and of evaluation regimen for working condition. Furthermore, a full model combining this results with biomechanical and physiological ones to predict, and therefore to prevent musculoskeletal injuries, will probably an eventual terminus in this research.

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