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Analysis of Tool Grip Tasks Using a Glove-Based Hand Posture Measurement System

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ABSTRACT

Few studies on the biomechanical analysis of hand postures and tool handling tasks exist because of the lack of appropriate measurement techniques for hand force. A measurement system for the finger forces and joint angles for the analysis of manual tool handling tasks was developed in this study. The measurement system consists of a force sensing glove made from twelve Force Sensitive Resistors and an angle-measuring glove(Cyberglove^{TM}, Virtual technologies) with eighteen joint angle sensors. A biomechanical model of the hand using the data from the measurement system was also developed. Systems of computerized procedures were implemented integrating the hand posture measurement system, biomechanical analysis system, and the task analysis system for manual tool handling tasks. The measurement system was useful in providing the hand force data needed for an existing task analysis system used in CTD risk evaluation. It is expected that the hand posture measurement developed in this study will provide an efficient and cost-effective solution to task analysis of manual tool handling tasks.

1. INTRODUCTION

The comfort of tool grips is an important consideration in the design of hand tools to fit the needs of the user for a given task. It is not unusual for high, localized stress in the hand to occur within one to two hours of continuous use(Fellows and Freivalds, 1991). for a tool grip to be functional, it must : (1) be able to give the user complete control and manipulation capability, (2) provide the user with a proper surface for exerting the forces necessary to operate the tool, and (3)

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minimize the muscular effort needed to maintain this grip for extended periods.

Extensive biomechanical studies on the hand can be found in which the main questions of interest predominantly have been the clinical evaluation of the hand or rehabilitation studies(Chao etal., 1989). Most of the studies, however, did not consider the application or the interface aspects of the hand while it was studied for areas such as sitting surface(Treaster and Marras, 1989) and the temporal region of the head and back(Jensen et al., 1987).

To accomplish these goals, an efficient method to observe the tasks and measure the related variable is essential. The motivation of this study comes from this background. An efficient hand posture measurement and analysis system for manual materials handling tasks will provide a basis of the evaluation of the task, worker, tools and workstations with regard to its design, improvement, and implementation.

2. HAND POSTURE MEASUREMENT SYSTEM

For the purpse of measuring the joint angles of the fingers and wrist joint, an angle transducer glove system(Cyberglove™ CG1801, Virtual Technologies, 1992) and a set of data acquisition programs specific to finger joint measurement were developed. The Cyberglove™ system provided measurements of 18 joint angles. There were two flexion sensors on each of the five fingers. On the thumb, these two sensors measured the metacarpophalangeal(CMC) and interphalangeal(IP) joint flexions. On the remaining four fingers, the two flexion sensors measured the metacarpal phalangeal joint(MP) and proximal interphalangeal(PIP) jonit flexions. Two wrist motions, flexion/extension and radial/ulnar deviation angle, were also measured. For the measurement of finger forces, a sensor matrix with twelve Force Sensitive Resistors(FSRs, Interlink Electronics, 1989) was developed. This set up has been used to measure pressure distributions on foam grip handles(Fellow and Freivalds, 1991), to study finger pinch forces(Radwin et al., 1992), and to evaluate hand-tool coupling effects(Bishu et al., 1993). Each of the FSR sensors were covered with 2mm of plastic glue over 12 mm^2 sensing area for effective force measurements. The sensors had an effective force sensing range of 1 to 50 N with 1 N precision. Voltage outputs from the ten sensors were recorded using a DASH 16/F analog-todigital converter installed in a PC (TOSHIBA 4600). The glove was calibrated to force levels(N) using a second order polynomial regression : Force(N)=0.23-0. 61*voltage(V)+0.56*voltage2(V). The coefficient of determination for the pressure calibration regression was 0.98.

3. VALIDATION EXPERIMENT

Sixteen different hand tool tasks were studied for six subjects. The tasks specified in Table 1. represent the set of typical grasp manipulation tasks in an industrial setting. The tasks were selected based on the assumption that each task defined could cover most real working tool grip tasks in manufacturing industry. As a result, three categories of hand postures(power grip, grasp, and pinch) were considered.

The angle measurement system produced 18 angle data points, of which, 16 were analyzed. Both metacarpophalangeal(MP) flexion and proximal interphalangeal(PIP) flexion angle were measured for the index, middle, ring, and little finger. One flexion angle(carpometacarpal(CMC) joint flexion) was measured for the thumb. Five abduction angles from each finger were also measured, as well as both wrist flexion and deviation angles. Distal interphalangeal(DIP) joint angles were not measured from the sensor values since the flexion sensors were not attached to the finger tip area in the Cyberglove™ system. The Cyberglove™ system, however, estimated DIP flexion from the hand configuration model provided with the system. From the preli- minary experiment, the estimation of the DIP flexion from the Cyberglove™ system was calibrated to be accurate within ± 2 degrees using a measured angle from a mechanical

Table 1. Task characteristics : There were 8 power grip tasks, 5 grasp tasks, and 4 pinch tasks. The grip size was measured as the maximum diameter of the tool where the hand contact is made. In case of the power grips where the grip shape is not a cylindrical type, the grip size was defined as the maximum distance of the enclosure provided by the thumb and the opposing fingers.

Grip Type	Tools used	Grip Size	Grip Shape	Simulated Task
Power Grip	Drill	4cm	cylinder	drilling a hole
	Drill/w trigger	6cm	cylinder	drilling a hole
	Knife	2.7cm	shaped cylinder	cutting a carpet
	Hammer	3cm	shaped cylinder	hammering a carpet
	Hook	3.5cm	square	pick up a piece of meat
	Screwdriver	7cm	shaped cylinder	turn a screw
	Pliers	75cm	shaped leg	grip a nut
	Scissors	6.5m	shaped hole	cutting a carpet
Grasp	Pulp grasp	N/A	cylinder	grasp a drum
	Medial grasp	N/A	cylinder	grasp a drum
	Mouse grasp	N/A	square	grasp a muse
	Pen grasp	N/A	cylinder	grasp a pen
Pinch	Pulp pinch	N/A	N/A	pick up a plate
	Lateral pinch	N/A	N/A	pick up a plate
	Palm pinch	N/A	N/A	pick up a plate
	Finger press	N/A	N/A	press onto a surface

(N/A : not applicable)

goniometer as a reference angle.

Results on angle measurement

The experimental design was a three-factor fully-crossed factorial design with repeated measures. Average flexion angle was different between grip type, fingers, and subjects. All main effects(task, subject, and digit) were significant at $p<0.01$ as were all two-factor interactions except subject*digit interaction which was not significant at $p<0.05$. The three way interaction of task*subject*digit was also significant at $p<0.01$.

In Table 2, the average joint flexion angle and finger abduction angles were summarized for all five fingers. For most power grip tasks(drill, knife, hammer, and hook), the MP flexion ranged from 30-45 degrees, except the little finger which showed 10-15 degrees less flexion. Pinch

Table 2. Finger flexion/abduction angle : (Averaged across subjects in degrees) for the index, middle, ring, and little finger.

Tasks	Angles	Index	Mid.	Ring	Little	Tasks	Index	Mid.	Ring	Little
Kinfe	MP flexion	23	35	49	60	Pulp pinch	32	30	26	20
	PIP flexion	62	77	70	62		6	4	1	0
	Abduction	-6	0	6	10		-2	0	2	6
Hammor	Abduction	36	45	51	58	Later pinch	40	40	39	41
	MP flexion	64	68	57	44		61	73	71	73
	Abduction	-9	1	7	12		-3	0	3	7
Hook	MP flexion	49	46	42	42	Palm pinch	49	55	47	53
	PIP flexion	75	84	76	66		88	87	85	74
	Abduction	-8	0	9	16		-4	0	3	9
Pliers	MP flexion	15	16	7	9	Finger press	13	8	0	9
	PIP flexion	48	65	58	45		11	11	9	4
	Abduction	-6	1	5	15		-6	1	5	14
Screw-driver	MP flexion	22	31	50	61	Pulp grasp	21	26	22	16
	PIP flexion	57	71	52	53		37	34	26	15
	Abduction	-10	0	10	15		-4	0	4	10
Scissors	MP flexion	19	12	15	17	Medial grasp	10	19	15	31
	PIP flexion	63	58	52	47		47	40	34	16
	Abduction	-5	0	5	8		-7	1	5	35
Power drill	MP flexion	26	28	18	16	Mouse grasp	27	29	26	35
	PIP flexion	52	64	59	47		40	28	33	33
	Abduction	-10	0	10	15		-12	2	8	14
Power drill (trigger)	MP flexion	34	39	38	37	Pen grasp	45	46	40	35
	PIP flexion	48	71	64	49		35	44	37	39
	Abduction	-9	2	6	12		-4	1	3	7

tasks showed consistently higher MP flexion.

This result indicated that MP flexion was a good discriminating measure between pinch and power grip providing the difference in the resulting moment at the wrist. In the pinch tasks, low MP angle, when the external load was on the finger tip, generated more vertical torque on the wrist. Power grip tasks compensated the external moment by flexing the MP angle inward. Both scissors and pliers grips showed 15-20 degrees flexion than the other power grips because of their extended grip postures. PIP flexion ranged from 50 degrees to 80 degrees for power grip tasks (drill, knife, hammer, and pliers). Pinch grips such as palm pinch, lateral pinch showed smaller PIP flexion from 30 to 40 degrees.

Comparison of the fingers from index to little finger showed similar flexion angles for power grips, but significant differences

Table 3. Result of the regression on joint flexions : The multiple regression approach showed significantly($p<0.01$) high coefficients of determination(R^2) for all models of estimating joint angles from subject data and task type.

Finger	Joint	Const	Tool	GS	HL	HB	DL	MP
II	MP	172	0.829	-4.07	-9.91	5.69	8.34	
	(R^2)	(86.6)						
	PIP	178	0.926	-3.66	-23.4	2.16	32.9	-0.04
	(R^2)	(54.5)						
III	MP	97.5	-0.46	-5.11	3.48	-14.7	-62.1	
	(R^2)	(62.4)						
	PIP	118	0.24	-6.79	-1.7	9.78	-8.3	-0.19
	(R^2)	(56.0)						
IV	MP	221	-0.92	-6.79	-6.3	-7.1	2.1	
	(R^2)	(72.5)						
	PIP	136	0.717	-7.96	-16.1	-5.32	-30.6	-0.49
	(R^2)	(56.5)						
V	MP	231	-2.46	-6.73	-21.5	10.4	16.6	
	(R^2)	(69.8)						
	PIP	191	0.559	-9.09	35.1	-8.7	-71.8	-0.52
	(R^2)	(75.1)						

TY : Tool type(0 : power grip, 1 : others), GR : Grip Size(cm), HL : Hand Length(cm), HB : Hand Breadth(cm), DL : Digit Length(cm), MP : corresponding MP flexion (Degrees) between fingers for pinch grip tasks. This result supports the previous observation that tools used with an extened wrist posture such as knives, pliers, and scissors require a different grip posture than the other power grip tools.

A multiple regression analysis was performed to estimate the joint angle from the hand anthropometry and grip size data. The regression analysis was conducted for the separate set of power grip and pinch grip tasks. The result of the regression is summarized in Table 3. The coefficient of determination(R^2, the proportion of the variance explained by regression model) ranged from 62.4 to 86.6 for MP flexion and 54.5 to 75.1 for PIP flexion.

Size estimates such as grip size, hand size, and digit lengths were good estimators of MP angle, but not as good when used as estimators for the PIP flexion of a digit. It can also be postulated that the joint articulation of the grasp action can be defined from the human data except for the extreme cases where the hand size of the operator exceeds the normal range.

The plot of finger flexion and abduction angle for the index finger for the different grip sizes is presented in Figure 1. The graph shows that the average MP flexion decreased with increasing grip sizes. The increases in flexion angles were most evident at the MP joints and least evident at the DIP joints at the fingertips. For most grip sizes, the DIP joint angles were stable at about 40 degrees. It can be postulated that the fingers exert their maximum gripping force with the DIP joints flexed at a constant angle regardless of grip sizes ; the fingers adjust themselves to different grip sizes mainly by changing the MP and PIP joint angles.

In other words, the grasp action can be explained as a sequential movement from the wrist to the finger tips. It seems that the major flexion of the first joint from the wrist is performed first for the rough sizing of the grasp area. Then, the next joint(PIP joint) is involved in a tighter, and more precise grasping of the objects being handled. And, finally, the finger tip movement(DIP joint) is primarily configured for the enclosure and, for some part, force exertion. Sensing these joints would logically provide us with the majority of the information needed to estimate joint angles to perform similar grasp tasks in industrial settings, The abduction angles were also stable at 10 ± 2 degrees for most grip sizes from the index finger to the little finger. It seems that the grip force was maximized when the fingers were spread by 10 degrees to the grip shape except in the case of very small objects where the extension of the abduction angle was not feasible because of the size of the cylinder.

Results on Force measurement

From three factor ANOVA, the finger force was significantly different between the tools($p<0.01$), subjects($p<0.01$) and fingers($p<0.01$). Both the thumb and index finger force were significantly different, while the middle, ring and little finger showed no significant difference($p>0.1$). Average value for the sum of all five finger forces was 168 N(SD=20). This value was

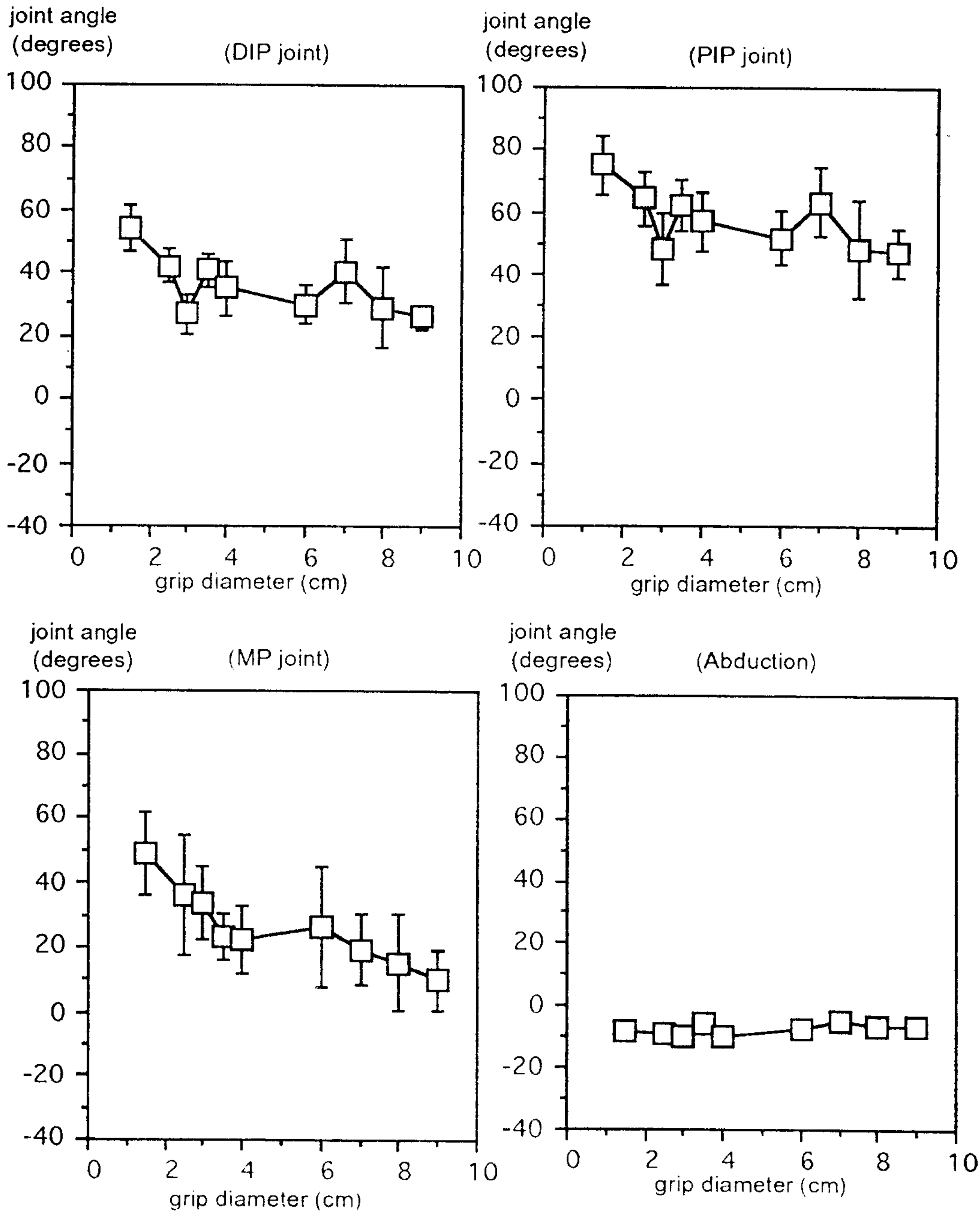

Figure 1. Flexion angles of the index finger

showed that flexion angles decreases as grip diameter increases. Abduction angle showed a very little change for all test conditions.

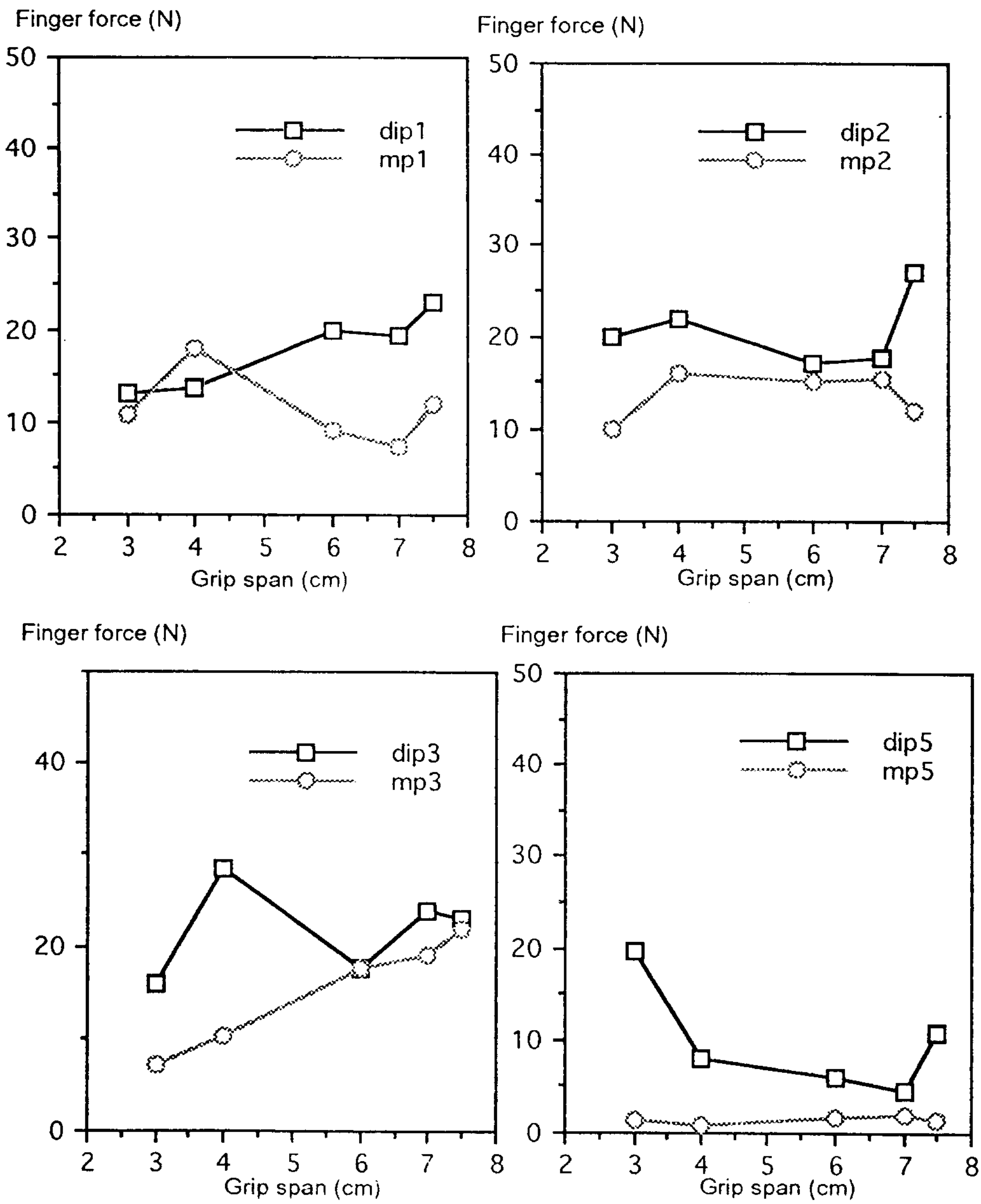

Figure 2. Finger forces by grip diameter

showed that the thumb tip force increases as the grip diameter increases. The index finger force show minimal change due to grip diameter as well as the middle finger force. However, force from the base of the middle finger increased significantly as the grip diameter become larger. Little finger force decreased as the grip diameter increases.

lower than the value reported by Radwin et al.(1992), where the average force was 183 N(SD=15) for maximal static pinch grip force. The effect of finger forces due to different grip size is represented graphically in Figure 2. In general, the finger tip area(DIP joint) was the site of greater force compared to the metacarpal area for all grip sizes. As grip size increased, the force on the finger tip area increased except the little finger that shows the opposite trend.

This result supported the conclusion from the angle measurement that the grip action was a sequential movement of the joint form the wrist to the finger tip. Erkmen and Stephanou(1991) proposed such a sequential grasp function for a hand grasp of a robot. Accordint to their model, the motion of a hand grasp can be divided into five phases : (1) reach, (2) preshape, (3) enclosure, (4) grip, and (5) manipulation. The experimental results supported the action on the enclosure phase and manipulation phase of their model. In the enclosure phase, the finger tip area took the role of the enclosure while the palmar area supports the grasp function. As grip size increased, the finger tip area extended across the diameter of the object to accomplish the grasping. As a result, an increased amount of force acting on the finger tip was noticed in bigger grip sizes.

However, as size increased, the little finger was the first finger that exceeded the active enclosure range. Thus, the little finger decreased its contribution to the grip force resulting in the increased force in the index and thumb. At the manipulation phase, the distribution of force across the finger took place depending on the nature of the task. Grip type became active for the manipulation of the tool rather than the size variable in the enclosure phase. The result also supported the observation that the forces acting on the tool were mainly controlled by the finger tip area rather than the force acting on the other joints. When the opposing action between the thumb and the other fingers happens, the thumb acted primarily as a stationary base against which grasping took place with the opposing force of the fingers.

4. BIOMECHANICAL HAND MODEL

In order to express hand posture in a mathermatical form, introduction of the three-dimensional hand model is necessary. Since biomechanical analysis in this study used the data from the hand posture measurement system, it was necessary to define the hand model customized to the data obtained from the measurement system. The 3-D coordinate system for the hand grip posture was developed for this purpose. Corresponding force analysis and estimation of muscle force procedures were also developed.

Modified from the general 3-D hand model developed by Chao et al.(1989) that used a polar coordinate system, a 3-D Cartesian coordinate system defined at each joints of the finger and the wrist joint was developed in this study. The coordinate of the wrist joint was defined as the origin point and three local coordinate systems were difined at each joint of the hand and finger tip. The coordinate of the other joints were defined at the MP joint(next right to wrist), PIP joint(second next to wrist), and DIP joint(closest to finger tip) in the same way. At each joint, the proximal system (wrist side) was related to the distal system(finger tip side) through transformation.

An Eulerian angle was introduced to handle the transformation of the coordinates to the wrist origin. The reference position of each hand segment in this system was defined as zero degrees of articulation for all joints with respect to the more proximal segments. Using a Eulerian angle transformation, proximal coordinate of a point defined at the distal coordinate system was calculated(Craig, 1988). Details of the 3-D hand model is reported in Yun et al.(1994). A microcomputer-based system that takes data on grip force, joint and wrist angle during a task is used to produce the data necessary for biomechanical analysis. The data then was analyzed using the hand biomechanical models developed in the previous section. The procedure also provided a graphic representation of the measured data. The graphic interface for the biomechanical analysis displayed the measured hand posture, joint angle and the joint torque in three directions.

Evaluation of tool grip tasks

Physical parameters and calculated parameters were analyzed to provide relative degradation of the tool grip tasks in terms of its force requirement, flexion/extension torque and radial/ulnar deviation torque. The grip tasks were rank-ordered and categorized both on the radial/ulnar deviation axis and on the total grip force axis.

As shown in Figure 3., the grip tasks can be grouped together in terms of their relative scale of total grip force and the radial/ulnar deviation torque. The degradation function of grip tasks tested in the experiment can be defined based on these values. Tasks such as power drill, knife and screwdriver procuced high force and high torque since the tools required high force in on direction. Most of the grasp tasks and primitive grip tasks such as took grip showed relatively low torque and low force relationship. Pulp pinch and pliers showed a high torque but did not show a high force while pulp grasp and hammer grip showed low torque and high force relationship. Overall, it was found that the power grips closer to the original hook grip showed relatively low values of postural load on the hand while grips with modified power grip and the grips with rotational torque requirement from the task showed higher load on the hand.

5. CONCLUSIONS AND FURTHER STUDY

Both flexion angles and finger forces were found to vary for the fingers engaged in different grip tasks. Control of the joint angle changes for the different grip sizes seemed to be achieved primarily by the changes in the MP angle. The gripping process was a sequential flexion of finger

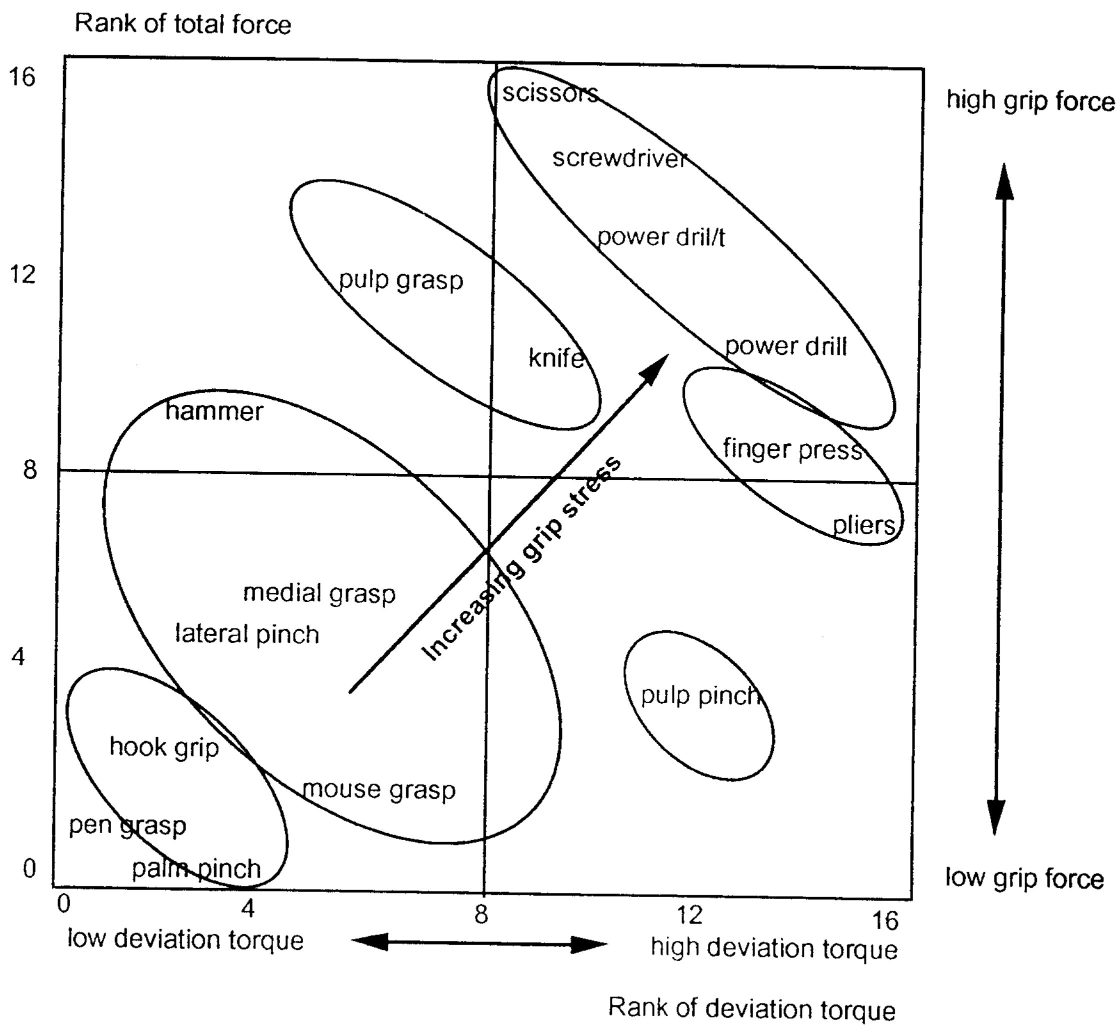

Figure 3. Degradation of grip function

Grip tasks tested were evaluated in terms of due their grip force and deviation torque. As shown in the diagram, the stress on the hand due to the grip increased as the deviation torque and total force increase. The circle represents arbitrary grouping of the tasks with similar amount of stress.

joints from the proximal side to the distal side of the hand. The result of force analysis for the different grip sizes showed that the main force exertion was executed by the thumb and index finger while the other fingers showed a supporting action during most of the tasks in the experiment. The support function for the minor fingers was most distinctive when the grip size was large. Most importantly, the results suggested that hand anthropometry and task characteristics such as grip span and grip type can be used to estimate the hand MP flexion and PIP flexion and, therefore, could be used to calculate grip forces and torques on the hand joints for most of the tool grip tasks. The use of the force sensors to measure the forces acting vertically on the grip surface produced the force data necessary to calculate the torques actiong on the hand during tool grip tasks. A task analysis using the physical and calculated parameters of the program showed that the grip tasks with rotational torque requirements(screwdriver, power drill) and open-and-shut actions (scissors and pliers) produced relatively heavier loads on the hand while tasks with grasps(medial grasp, pulp grasp) and primitive power grips(hook grip) showed relatively lighter values of postural load. Using the rank-ordering of the calculated parameters, a degradation function for the typical hand grip tasks was defined.

It is expected that the control of cumulative trauma disorders can be conducted comprehensively using the system of hand posture measurement system. The hand posture measurement system can execute a key role of finding the source of a problem in the task and suggesting a possible cause through a biomechanical analysis. It was found from this application study that the hand posture measurement system was a convenient and effective method to evaluate the manual material tasks in industry. Finally, hand posture and force, which define aspects of the way an objects is grasped, are features of robotic manipulation.

The hand posture measurement system developed in this study can also be used for robotic manipulation in Vitual Reality based Point-and-Direct(VR-PAD) robotics implementation. Rather than requiring full duplication of forces and kinesthetic movement throughout a task, as is required in manual telemanipulation, the grasp parameters can be specified directly from the operator using, the 'glove-based', angle and force specification system developed in this study. An exploratory attempt in the Computer Integrated Manufacturing(CIM) Laboratory at Penn State showed promising results(Yun, et al., 1994).

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