Original Article

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Motion adjustment in the pegboard task: Motor analysis of obstacle avoidance behavior in the transport-to-insertion movement

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Abstract

Background: Clinical assessment using the pegboard task has been quantitatively evaluated in terms of time required and amount of work, but it has not been qualitatively evaluated from the movement of the upper limb and fingers. The purpose of this study was to clarify the required ability for motion adjustments of the upper limb and fingers when transport-to-insertion task is performed.

Methods: A total of 51 healthy volunteers (aged 22.3 ± 3.8) were studied. They performed tasks involving pulling a peg from a near-side hole and inserting it into a far-side hole under three conditions: no obstacle, obstacle on the lateral side, and obstacle on the front side. The motion of upper limb and fingers were measured with a three-dimensional ultrasound motion analyzer, and 15 parameters were measured. Ability of motion adjustment was evaluated by factor analysis of related parameters in each condition.

Results: In the no-obstacle condition, the important factors were adjustments of finger motion at transport phase (TP), wrist and finger motion at insertion phase (IP), vertical trajectories, timing and speed of the task. When obstacles were present, in addition to factors that were required in the no-obstacle condition, additional adjustments of the wrist motion at TP and horizontal amplitude were required.

Conclusion: In the transport-to-insertion task, different ability of motion adjustment was required depending on the task conditions. The results of this study may provide useful basic data for assessment of dexterity from the qualitative aspect using the pegboard task.

Key words

dexterity, upper limb and fingers, motor control, pegboard, obstacle avoidance

Background

In patients with impaired dexterity of the upper limb and fingers, their improvement is one of the most important goals in rehabilitation. A number of methods have been used to evaluate dexterity, in which a pegboard task was widely available in the field of rehabilitation and was an instrument for efficiently enhancing dexterity[1]. Clinical assessment of the pegboard is often evaluated from the quantitative aspect with respect to required time and the amount of the task[2]. How the upper limb and fingers work during the pegboard task, however, has not been evaluated qualitatively in clinical use, and few studies have been reported recently[3]. However, for dexterous upper limb function, it is very important to achieve smooth movements in addition to a fast movement from the qualitative point of view.

The pegboard task includes three processes: *reach-to-grasp*, *transport*, and *insertion*, each of

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which requires different adjustments of the motion in each process. A number of studies have been reported about reach-to-grasp movement (so-called prehension movements), but few studies have examined the transport and insertion. Moreover, what adjustment of movement is needed for the transport and insertion has yet to be clarified. The prehension movement consists of two components; namely, transport and grasp components(4). These two components coupled both spatially and temporally for operating tasks smoothly(5). On the other hand, with respect to transport and insertion, Grosskopf et al. examined kinematics of insertion task that was divided into two phases; 'reach to grasp' and 'retraction and insertion'(3). Their study measured time, velocity, trajectory length, grip aperture and so on, but adjustment of movements required in the task had not been discussed.

We hypothesized that the ability of multiple peg-moving task included greater ability than that required for a simple one-peg moving task. When moving pegs in a specific order, surrounding conditions around the target peg would complicate the task. In a normal motion we instinctively adjust the movements of reach-to-grasp, transport, and insertion according to the different situations around the target peg. However, in patients with impaired dexterity in an upper limb and fingers, smoothness may vary substantially depending on the order of movements. This is probably because the motion adjustment in the no-obstacle condition around the target differs from the conditions including some obstacle pegs around the target.

With respect to the prehension movement, the motion of the upper limb and fingers has been adjusted in a coordinated manner depending on the surrounding conditions of the target(6-9). To analyze the ability of adjusting movements required for the pegboard task, authors have examined the motion of grasping a peg in conditions of obstacles on the lateral and front sides of the target(6). This study indicated that hand trajectory and wrist-finger angle were adjusted to the position depending on the presence and absence of obstacles. Previous studies have reported similar motion adjustments in the grasp movement in conditions of setting obstacles around the target(7-9). Tresillian has found that grip aperture and movement time in the prehension movement were adjusted coordinately according to the position of the obstacle(7).

The aim of this study was to clarify the role of the adjustment ability of the upper limb and finger movements for the clinical assessment and training with the pegboard task, especially in the transport-to-insertion task. Our final goal is to develop clinical assessment of the upper limb and fingers dexterity from the qualitative aspect using the pegboard task. Qualitative evaluation, which is not derived from quantitative aspect, is important for guiding treatment and demonstrating therapeutic effects. This study could be the basic data for our purpose of establishing qualitative evaluation of dexterity. Thus, our two hypotheses were as follows: 1) Transport-to-insertion task requires adjustments of the wrist-finger angle, trajectory of hand, timing of motion, and speed, and 2) motion-adjustment ability is more required with the obstacles around the target than without, and required motion-adjustment ability differs from the obstacle position.

Methods

Subjects

A total of 51 healthy female volunteers were recruited into this study. All participants were right-handed as determined by Edinburgh Handedness Inventory(10). Mean age was 22.3 years (range, 19–33 years), mean height was 160.5 cm (range, 148–173 cm), mean sitting height was 83.8 cm (range, 77–90 cm), mean upper limb length was 69.2 cm (range, 62–77 cm), and mean hand length was 16.8 cm (range, 15–20 cm). Informed consent was obtained from all subjects, and Medical Ethics Committee of Kanazawa University approved the study (Receipt No. 332).

Experimental apparatus

Figure 1 shows a schematic diagram of the experimental apparatus. Participants were seated on a chair with a height of 44 cm in front of a table of 70 cm high. During the experiment, their feet were grounded and the back was released from the chair. A pegboard was placed in the midline of

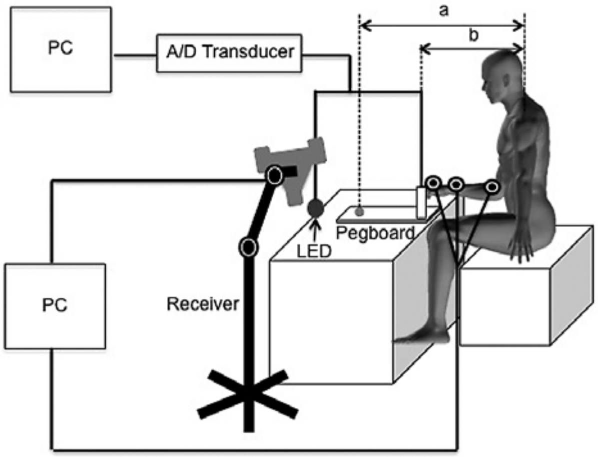

Figure 1. A schematic diagram of the experimental apparatus

The distance between the acromial process and near-side hole was 50% of the arm length (a). The distance between the acromial process and far-side hole was 90% of the arm length (b). A pegboard was placed in the midline of the subjects. LED of the start signal of operation was placed in front of the subject.

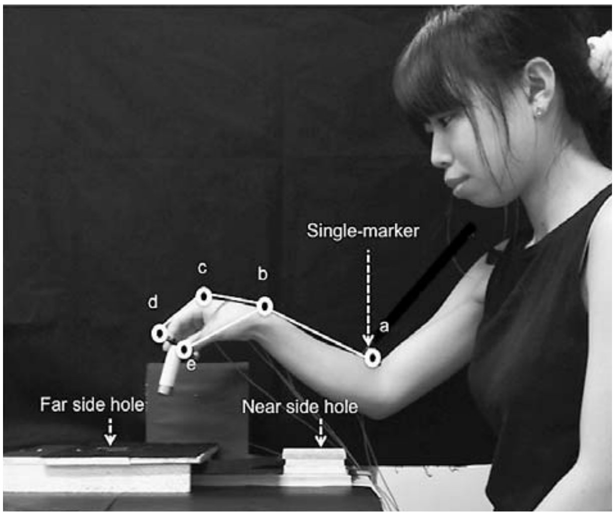

Figure 2. Position of markers and joint angle

Five single-markers (a-e) were placed on the skin surface of the arm; the lateral humeral epicondyle (a), wrist above the styloid process (b), metacarpo-phalangeal joint of the index finger (c), tip of the index finger (d), and tip of the thumb (e). Four angles were calculated from these markers. Angle abc, angle of palmar flexion and dorsal flexion of wrist (wrist PF/DF), and radial flexion and ulnar flexion of wrist (wrist RF/UF); angle bcd, flexion and extension of index finger (index flex/ext); angle cbe, adduction and abduction of thumb (thumb add/abd).

the subject. Two holes (20 mm in diameter, 25 mm in depth) on the pegboard were in the near side and the far side from subjects as shown in Figure 2. The conditions were adjusted to match the physical form of each subject as follows. The distance between the acromial process and near-side hole was 50% of the arm length, and that between the acromial process and far-side hole was 90% of the arm length. A switch circuit was created, by which Light Emitting Diode (LED) was lighted twice when the bottom of the peg had contact with the circumference of the hole and bottom of the hole. Switch signals were imported to the computer (Macintosh G3, Apple Inc.) via an analog-digital converter (Maclab/8 s, AD Instruments Pty Ltd., Australia). The sampling rate for the switch signal was 40 Hz. A peg of wooden cylinder was 18 mm in diameter and 70 mm high, which is one of the large-size pegs in Japan, and the obstacle peg was 18 mm in diameter and 45 mm high. The obstacle was fixed on a flat pegboard surface. The distance between the far-side hole and the obstacle peg was 50 mm.

During each task, hand position data were measured with a three-dimensional ultrasound motion analyzer (Zebris CM10-6, Zebris Medical GmbH, Germany) at a sampling rate of 40 Hz. The recorded data were analyzed using Zebris Win Data software (version 2.19.44, Zebris Medical GmbH, Germany). Five single-markers were placed on the participant's arm, tip of the thumb, tip of the index finger, the metacarpo-phalangeal joint of the index finger, wrist above the styloid process, and the lateral humeral epicondyle (Figure 2). Velocity, trajectory length, amplitude, and movement time were extracted from the tip of the index finger position. Four angles were calculated from these five markers; angles of palmar flexion and dorsi flexion of the wrist (wrist PF/DF), radial flexion and ulnar flexion of the wrist (wrist RF/UF), flexion and extension of the index finger (index flex/ext), and adduction and abduction of the thumb (thumb abd/add).

Conditions of tasks

Each participant was asked to perform the task of lifting the peg from a near-side hole and inserting it to a far-side hole with her dominant hand. Obstacle pegs were placed in three conditions: namely, no obstacles *(no obstacle condition)*, the obstacle on the lateral side *(lateral-obstacle condition)*, and that in the front side *(frontal-obstacle condition)*

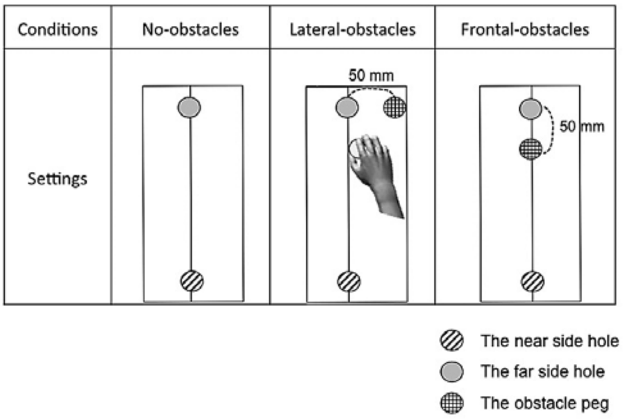

Figure 3. Conditions of the task

Lateral-obstacle condition, obstacles on the lateral side; frontal-obstacle condition, obstacle on the front side.

of the far-side hole (Figure 3). In a preliminary experiment involving healthy adults volunteers and patients with impaired dexterity, we confirmed that the joint angle and trajectory of the hand were adjusted only when an obstacle is in the front or ipsilateral sides of the hand among all possible conditions. For example, when a patient with impaired dexterity tries to insert a peg into the second column from the left side using the left hand, he/she cannot perform the task hampered by the pegs of the first column. Similar situation may occur when he/she tries to inset the peg in the far-side row. The pegs placed in the near-side row may hamper the insertion to far-side rows. Therefore, in this study, as typical locations of obstacles that could represent the situations of most of the pegboard tasks, we selected the ipsilateral and front sides of the far-side hole.

Experimental procedure

At the onset of each trial, a subject gripped the peg in the near-side hole. The style of gripping a peg was in accordance with precision grip defined by Napier[11]. Once the LED was switched on as a start signal, they lifted the peg from the near-side hole and carried it to the far-side hole. The movement finished when the peg was inserted into the far-side hole and the LED came on. They were instructed to perform the task as fast as possible, to avoid touching the obstacle. After rehearsing three times in each condition, motions of subjects were measured three times. The order of obstacle conditions was randomized.

Data processing and analysis

Each movement time was normalized for comparison using a unit of percentage. Start of the movement (0%) was defined as the time when the velocity increased above 10 mm/sec, and the end of the movement (100%) was defined as the time when the bottom of the peg had contact with the bottom of the hole when the LED came on. The transport phase (TP) started from the movement onset and finished when the bottom of the peg had contact with circumference of the hole and the LED came on for the first time. In addition, the insertion phase (IP) started from when the LED came on for the first time and finished when the bottom of the peg had contact with the bottom of the hole and the LED came on for the second time.

The three-dimensional spatial coordinate data were analyzed using analysis software. The parameters of joint angle, velocity, trajectory length, vertical and horizontal amplitude were calculated. The joint angle of the wrist and fingers at the start position was defined as 0° as defined by Nakazawa et al.[12] to analyze adjustment mechanism of the wrist and finger movements of the TP and IP. Movements of the "plus" direction were defined as wrist DF, wrist RF, thumb abd, and index ext. Moreover, movements of "minus" direction were defined as wrist PF, wrist UF, thumb add, index flex. Obtained data were transferred to Excel (Microsoft, Co., Ltd) in the Comma Separated Value format, and parameters of range of motion (the difference between maximum joint angle and minimum joint angle), mean velocity, maximum velocity, maximum horizontal and vertical amplitude, time of maximum horizontal and vertical amplitude (%) were computed. The joint angles were divided into two phases; transport phase and insertion phase. A total of 15 parameters were measured in this study as shown in Table 1.

Statistics

Three statistical analyses were performed. First, after averaging the values of three trials for each participant (n=51), the average values ± standard deviation (SD) were calculated for each parameter. One-way ANOVA with repeated measure and

Table 1. Mean ±SD of kinematic parameters in transport -to- insertion tasks (N=51)

Parameters	Phase	Unit	Statistic	No-obstacle condition		Lateral-obstacle condition		Frontal-obstacle condition	
				mean	SD	mean	SD	mean	SD
Range of motion: wrist PF/DF	(TP)	(deg.)	#2,#3	29.2	9.9	27.6	7.3	24.2	8.6
	(IP)	(deg.)		8.1	11.7	7.1	6.6	5.9	3.5
Range of motion: wrist RF/UF	(TP)	(deg.)		9.3	4.7	9.2	5.4	10.8	5.8
	(IP)	(deg.)		4.2	5.3	4.1	3.5	6.5	14.8
Range of motion: index flex/ext	(TP)	(deg.)		17.4	7.2	16.9	6.3	20.4	9.7
	(IP)	(deg.)		7.0	11.4	4.2	3.7	4.7	4.2
Range of motion: thumb add/abd	(TP)	(deg.)		12.2	6.4	11.8	6.1	14.6	7.4
	(IP)	(deg.)		6.4	11.3	4.0	4.7	4.0	2.6
Trajectory length		(mm)	#2,#3	367.7	30.6	369.9	29.6	395.0	33.5
Max. horizontal amplitude		(mm)	#2,#3	36.7	10.7	36.9	14.2	88.4	18.4
Max. vertical amplitude		(mm)	#2,#3	96.6	15.9	96.5	19.3	71.9	15.8
Mean velocity		(mm/s)		318.3	60.2	299.4	53.8	297.1	59.1
Max. velocity		(mm/s)		765.4	127.9	738.3	134.4	695.7	139.6
Time of max. horizontal amplitude		(%)	#1,#2,#3	35.1	5.7	32.1	5.6	39.5	4.6
Time of max. vertical amplitude		(%)		39.8	5.5	38.2	6.4	37.8	5.2

TP, Transport phase; IP, Insertion phase, SD, standard deviation.
#1 Mean difference between the no-obstacle and lateral-obstacle conditions ($p < 0.05$)
#2 Mean difference between the lateral-obstacle and frontal-obstacle conditions ($p < 0.05$)
#3 Mean difference between the no-obstacle and frontal-obstacle conditions ($p < 0.05$)

paired t-test with a Bonferroni correction were used to compare task conditions. Differences were considered significant at $p < 0.05$. Second, to consider the characteristics of the motion of the transport-to-insertion task, we calculated the average values of vertical and horizontal amplitudes, and range of motion of wrists and fingers at every 10% of the movement time. Third, the least-square method with Promax rotation was used to investigate the components of the transport-to-insertion task. Eigenvalues greater than 1 were accepted, and possibility of interpretation of factors was also considered. Factor loadings of 0.50 or higher were considered meaningful. Data were analyzed with statistical analysis software, SPSS Statistics (Version 19.0.0, IBM institute, Inc., USA).

Results

Comparison of measurements among conditions of tasks

Table 1 shows results of kinematic data (mean ± SD) with 15 parameters. Significant difference between conditions in range of motion was found only in the wrist PF/DF. The range of motion in the wrist PF/DF in the frontal-obstacle condition was smaller than that in other conditions (no-obstacle, 29.2°; lateral-obstacle, 27.6°; frontal-obstacle, 24.2°). There were no significant differences among obstacle conditions on the mean velocity (no-obstacle, 318.3 mm/s; lateral-obstacle, 299.4 mm/s; frontal-obstacle, 297.1 mm/s). The maximum horizontal amplitude differed significantly among task conditions (no-obstacle, 36.7 mm; lateral-obstacle, 36.9 mm; frontal-obstacle, 88.4 mm). The normalized time of the maximum horizontal amplitude was similar with that of vertical amplitude in all conditions (horizontal/vertical; no-obstacle, 35.1% / 39.8%; lateral-obstacle, 32.1% / 38.2%; frontal-obstacle, 39.5% / 37.8%). Considering the transport phase (TP) and insertion phase (IP) separately, the time of the maximum horizontal/vertical amplitudes was as follows: no-obstacle, 50.0% / 56.9% of TP; lateral-obstacle, 45.9% / 54.6% of TP; frontal-obstacle, 56.4% / 54.0% of TP.

General characteristics of finger and wrist motion

Figure 4 shows mean values of the horizontal and vertical amplitudes, and Figure 5 shows mean values of the variation in joint angles. With respect

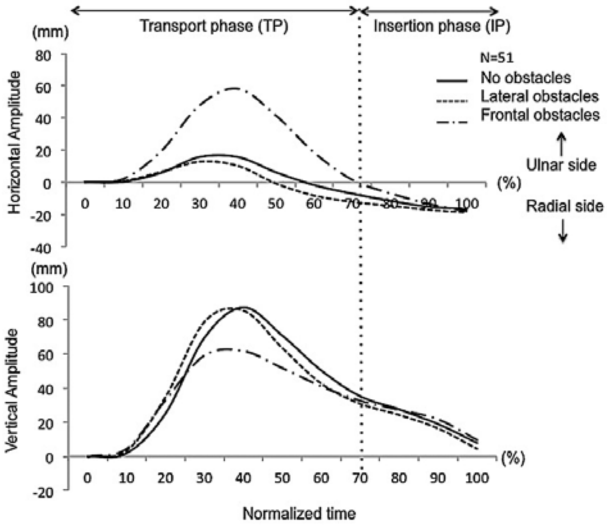

Figure 4. Trajectories of hand in transport-to-insertion task

Upper, horizontal amplitude; bottom, vertical amplitude.

Average values of vertical and horizontal amplitude were calculated at every 10% of the movement time. In all conditions, transport phase was 0% to 70%, and insertion phase was 71% to 100%. In a horizontal amplitude, "plus" direction represents a movement of the ulnar side and "minus" direction represents a movement of the radial side.

to joint angle in all conditions, the time of the maximum change in joint angles was at 40% in the thumb abd/add, at 50% in the index flex/ext, and that in 60% in the wrist PF/DF. However, after joint angle reached the time of the maximum change, the frontal-obstacle condition differed in motion from the no-obstacle and lateral-obstacle conditions. The average values from the time of the maximum variation in joint angle to the end of TP in the frontal-obstacle condition were greater than the other two conditions (no-obstacle, 0.8°; lateral-obstacle, 0.8°; frontal-obstacle, 3.0°). The average value of the amount of change in joint angle in IP was 1.2°, 1.1° and 3.5° for no-obstacle, lateral-obstacle and frontal-obstacle conditions, respectively.

Factor analysis

As a result of factor analysis (the least-square method, Promax rotation) about 15 parameters, a 5-factor solution provided adequate factor numbers under conditions of the no-obstacle and lateral-obstacle conditions. In addition, a 4-factor solution provided an adequate factor number under the frontal-obstacle condition. Tables 2-1 to 2-3 show

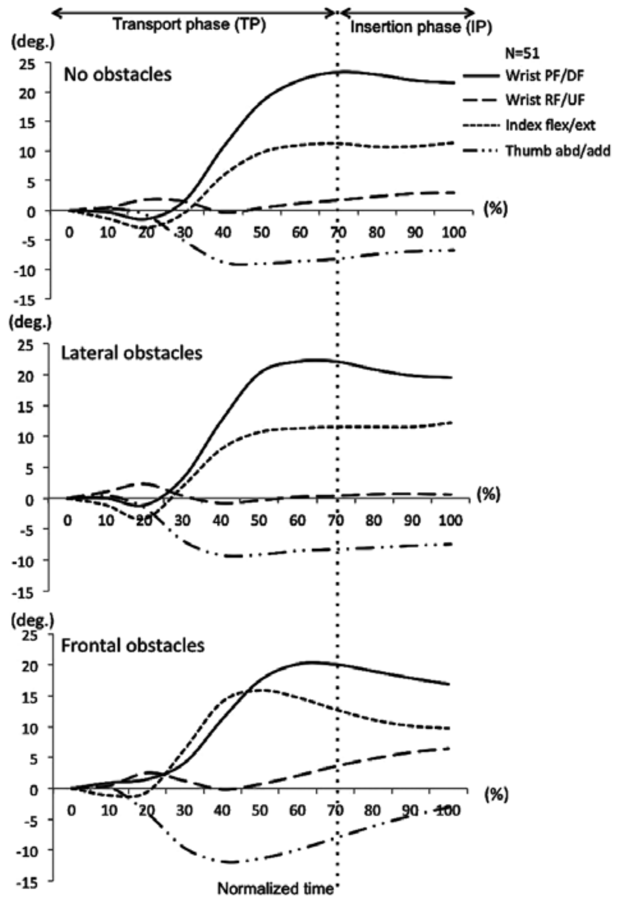

Figure 5. Changes of joint angle of the wrist and fingers

Top, no-obstacle condition; middle, lateral-obstacle condition; bottom, frontal-obstacle condition. Average values of joint angle were calculated at every 10% of the movement time. Initial position was defined as baseline (0°). The "plus" direction was defined as wrist DF, wrist RF, index ext, and thumb abd. The "minus" direction was defined as wrist PF, wrist UF, index flex, and thumb add.

factor structures of parameters and factor correlations.

1. No-obstacle condition (Tables 2-1 and 3)

Based on the factor analysis, five factors were identified, which explained 81.7% of the total variance. The first factor loaded highly on the range of motion of thumb add/abd (IP), wrist PF/DF (IP), and index finger flex/ext (IP), wrist RF/UF (IP). We labeled this factor as *adjustment of the wrist and finger motion (IP)* factor. The second factor loaded highly on range of motion of index flex/ext (TP) and thumb abd/add (TP), which was *adjustment of finger motion* (TP) factor. The third factor loaded highly on trajectory length and maximum vertical amplitude, which was labeled as *adjustment of vertical trajectory*. The fourth factor loaded highly on the mean velocity and maximum

Table 2-1. The factor structure in the no-obstacle condition (N=51)

Items	Phase	Factors 1	2	3	4	5
Range of motion: thumb add/abd	(IP)	0.99				
Range of motion: wrist PF/DF	(IP)	0.96				
Range of motion: index flex/ext	(IP)	0.96				
Range of motion: wrist RF/UF	(IP)	0.89				
Range of motion: index flex/ext	(TP)		0.97			
Range of motion: thumb add/abd	(TP)		0.90			
Trajectory length				0.92		
Max. vertical amplitude				0.86		
Mean velocity					0.96	
Max. velocity					0.77	
Time of max. vertical amplitude						0.99
Time of max. horizontal amplitude						0.74
Factor correlation						
1		–	0.08	0.21	-0.10	0.06
2			–	0.14	0.27	0.10
3				–	0.36	0.01
4					–	0.11
5						–

The least-square method, Promax rotation
Items with loadings of <0.50 were not written from the table, which included three items from Table 2-1, two items from Table 2-2, and five items from Table 2-3.

Table 2-2. The factor structure in the lateral-obstacle condition (N=51)

Items	Phase	Factors 1	2	3	4	5
Range of motion: thumb add/abd	(IP)	0.95				
Range of motion: index flex/ext	(IP)	0.88				
Range of motion: wrist PF/DF	(IP)	0.71				
Max. vertical amplitude			1.00			
Trajectory length			0.81			
Range of motion: thumb add/abd	(TP)			0.91		
Range of motion: index flex/ext	(TP)			0.83		
Time of max. vertical amplitude					0.67	
Time of max. horizontal amplitude					0.65	
Mean velocity					0.63	
Max. velocity					0.54	
Range of motion: wrist RF/UF	(TP)					0.61
Range of motion: wrist PF/DF	(TP)					0.54
Factor correlation						
1		–	-0.02	0.06	0.03	0.23
2			–	0.26	0.35	-0.02
3				–	0.09	0.01
4					–	-0.11
5						–

The least-square method, Promax rotation

velocity, which was labeled as *adjustment of speed*. The last factor loaded highly on the time to the maximum vertical and horizontal amplitudes. We labeled it as *adjustment of timing* factor. Since the loading of three factors, range of motion of wrist RF/UF (TP), wrist PF/DF (TP), and the maximum horizontal amplitude were not over 0.5, these were residual items.

2. Lateral-obstacle condition (Tables 2-2 and 3)

Based on the factor analysis, five factors were identified, which explained 74.4% of the total variance. Identified factors of the first to fourth factors were the same factor items as the no-obstacle conditions, but the fifth factor extracted

Table 2-3. The factor structure in the frontal-obstacle condition (N=51)

Items	Phase	Factors 1	2	3	4
Range of motion: thumb add/abd	(IP)	0.88			
Range of motion: index flex/ext	(IP)	0.88			
Range of motion: index flex/ext	(TP)	0.75			
Range of motion: thumb add/abd	(TP)	0.60			
Trajectory length			0.93		
Max. horizontal amplitude			0.81		
Max. velocity				0.94	
Mean velocity				0.87	
Time of max. vertical amplitude					0.95
Time of max. horizontal amplitude					0.75
Factor correlation					
1		–	0.31	0.03	0.36
2			–	0.26	0.36
3				–	0.05
4					–

The least-square method, Promax rotation

Table 3. Names of factors in the factor analysis

Factors	No-obstacle condition	Lateral-obstacle condition	Frontal-obstacle condition
1	Adjustment of the wrist and finger motion (IP)	Adjustment of the wrist and finger motion (IP)	Adjustment of finger motion (TP-IP)
2	Adjustment of finger motion (TP)	Adjustment of vertical trajectory	Adjustment of horizontal trajectory
3	Adjustment of vertical trajectory	Adjustment of finger motion (TP)	Adjustment of speed
4	Adjustment of speed	Adjustment of speed and timing	Adjustment of timing
5	Adjustment of timing	Adjustment of the wrist motion (TP)	–

was different from factors of the no-obstacle condition. The first factor was labeled as *adjustment of the wrist and finger motion (IP)*, the second factor as *adjustment of vertical trajectory*, the third factor as *adjustment of finger motion (TP)*, and the fourth factor as *adjustment of speed and timing*. The fifth factor loaded highly on range of motion of wrist RF/UF (TP) and wrist PF/DF (TP), which was labeled as *adjustment of the wrist motion* factor. Since the loading of two factors, range of motion of wrist RF/UF (IP) and maximum horizontal amplitude were not over 0.5 these were residual items.

3. Frontal-obstacles condition (Tables 2-3 and 3)

Based on the factor analysis, four factors were identified, which explained 64.7% of the total variance. Identified factors of the first and second factors were the different factor items from the no-obstacle and lateral-obstacle conditions. The first factor loaded highly on the range of motion of thumb add/abd (TP, IP), index finger flex/ext (TP, IP). We labeled it as *adjustment of the finger motion (TP, IP)* factor. The second factor loaded highly on trajectory length and maximum horizontal amplitude, which was labeled as *adjustment of horizontal trajectory* factor. The third factor was labeled as *adjustment of speed*, and the fourth factor as *adjustment of timing*, which were the same factor items as the no-obstacle and lateral-obstacle conditions. Since the loading of five factors was not over 0.5 including the range of motion of wrist RF/UF (TP, IP), wrist PF/DF (TP, IP) and the maximum vertical amplitude, these were residual items.

Discussion

In this study, we measured the movement of the upper limb and fingers in the transport-to-insertion task when obstacles were located around the insertion hole. To validate the first hypothesis, ability of motion adjustment in the transport-to-insertion task was evaluated from the no-obstacle condition. To validate the second hypothesis, difference in ability required for motion adjustments was evaluated depending on the positions of obstacles.

The ability for motion adjustment for the transport-to-insertion task

Adjustment abilities required in transport-to-insertion task were finger motion at transport phase (TP), finger and wrist motion at insertion phase (IP), vertical trajectory, timing, and speed.

Finger motion at TP is considered as anticipatory posturing of the hand for inserting a peg into a hole[13]. In the prehension movement, an action of preparing the hand shape to an object, in other words, that of forming an anticipatory posturing occurs before grasping[4,13]. The action of forming anticipatory posturing in the prehension movement is called pre-shaping[14]. In the pre-shaping movements, fingers are opened continuously from the start of reaching movement, and a grip aperture reaches the maximum in the second half of reaching movement. Then, grip aperture is adjusted to match the object size, and the shape of hand suitable for grasping an object is completed before fingers touch an object[15,16]. When the amount of angle change of fingers reached maximum at 40% to 50% of the movement time, it converged gradually toward the baseline until the end of the TP. This change was considered to be similar to the prehension movement. Moreover, the amount of angle change of the wrist also reached the maximum at 60% of the movement time, and it converged gradually toward the baseline until the end of TP. The transport-to-insertion task would form anticipatory posturing that is appropriate for inserting a peg by the wrist and fingers until reaching to the circumference of the target hole.

In addition, the factor of the motion of the wrist and fingers was identified. As described in a previous study[3], the final adjustment of direction of a peg would be performed by the wrist and fingers while completing the insertion after reaching the circumference of the hole.

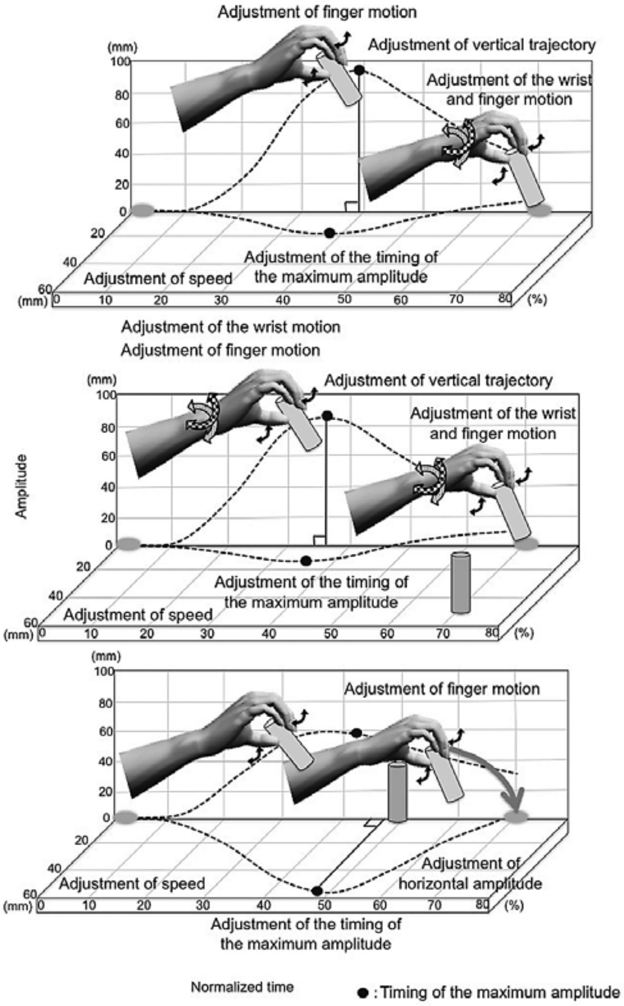

Figure 6. Motion adjustments of the transport-to-insertion task

Top, no-obstacle condition; middle, lateral-obstacle condition; bottom, Frontal-obstacle condition. Black circle represents the maximum vertical and horizontal amplitudes. Large dots arrow represents wrist PF/DF, Small dots arrow represents wrist RF/UF. Trajectory was drawn based on the mean value of horizontal and vertical amplitudes at every 10% of the movement time (Figure 4).

Since the factor of timing adjustment was identified, the transport-to-insertion was the task that required temporal adjustment. In this study, the timing of maximum vertical amplitude was 50% of TP, and that of maximum horizontal amplitude was 56% of TP. These results indicated that the timings of maximum amplitude of horizontal and vertical directions were in agreement (Figures 4 and 6). Previous study revealed that prehension movement could draw U-sharped

Table 4. Factors required for each condition

Category	Factors	No-obstacle condition	Lateral-obstacle condition	Frontal-obstacle condition
Spatial	Adjustment of finger motion (TP)	○	○	○
	Adjustment of the wrist motion (TP)		○	
	Adjustment of vertical trajectory	○	○	
	Adjustment of horizontal trajectory			○
	Adjustment of the wrist and finger motion (IP)	○	○	○
Temporal	Adjustment of the timing of maximum amplitude	○	○	○
Speed	Adjustment of speed	○	○	○

Circles represent identified factors based on factor analysis. The identified factors were classified into three categories: temporal adjustment, spatial adjustment, and speed adjustment.

trajectory, in which the tip of vertical direction was approximately the midpoint of trajectory[4,17]. This finding was similar to the trajectory of TP of this study. Our findings indicated that parabolic trajectory, in which the tips of horizontal and vertical directions were midpoints, contributed to the smooth movement in the transport-to-insertion task.

The difference of motion adjustment due to the obstacle location

Different factors were extracted depending on the position of obstacles (Table 4). Identified factors could be classified into three categories: *spatial adjustment, temporal adjustment*, and *speed adjustment*. Spatial adjustment refers to a change of movement trajectory and joint angle, and temporal adjustment refers to the coordination of movement time and timing[18, 19]. The movement of the upper limb and fingers are coordinated temporally and spatially, which are required for smooth motion[17, 20]. If there are any obstacles around the target, the speed should be adjusted depending on the location and existence of obstacles[7, 21]. Therefore, for the transport-to-insertion task, comprehensive ability of motion adjustment is required for smooth movements.

Our results revealed that in addition to the factors required under the no-obstacle condition, factors of *adjustment of the wrist motion* and *adjustment of horizontal trajectory* were required in the presence of the obstacle peg. First, *adjustment of the wrist motion* would be necessary in the lateral-obstacle condition. In a prehension movement, the wrist joint plays a role in adjusting the hand to the right direction regardless of the existence of an obstacle[8, 22]. The role of the final adjustment of direction in a transport-to-insertion task by the wrist will be greater than that of the prehension movement, because the freedom of finger movement was limited in gripping a peg. When the task conditions of the range of motion of the wrist were compared in TP, significant difference was found only in the wrist PF/DF. This result suggested that the motion of the wrist PF/DF was important for adjusting directions. Second, *adjustment of horizontal trajectory* would be necessary on the frontal-obstacle condition. In the prehension movement in the frontal-obstacle condition, a strategy of enlarging a horizontal amplitude is essential in order to prevent the hand from making contact with an obstacle[7]. In the transport-to-insertion task in the frontal-obstacle condition, adjustments of the trajectory to enlarge the amplitude of horizontal direction are necessary for avoiding an obstacle.

Anticipatory posturing of the hand under the lateral-obstacle condition differed from that in the frontal-obstacle condition (Figures 5 and 6). Moreover, the lateral-obstacle condition showed similar movement pattern to the no-obstacle condition. Since anticipatory posturing of the hand was different depending on the obstacle conditions, and the trajectories of the hand in the lateral-obstacle and the fontal-obstacle conditions were different, the directions for inserting a peg into the hole were also different. The peg approached the hole from the front in the lateral-obstacle condition, but from outside in the frontal-obstacle condition.

The anticipatory posturing and its timing seemed to be adjusted based on the approaching direction to the hole. When the peg approaches from the front, global adjustment of direction was completed until the time of the maximum change in the wrist-finger angle. In other words, after anticipatory posturing of the hand was almost completed, additional fine adjustments of the peg direction were performed by the wrist and fingers during the insertion into the hole. On the other hand, when approaching from the lateral side, after the time of the maximum change in the wrist-finger angle, the wrist and fingers worked together in association with the change of trajectory to the hole. Since the anticipatory posturing action was almost completed in the middle of TP, movement approaching from the front could be adjusted with a higher accuracy compared with that by the lateral approach.

Our data showed no significant difference in the mean velocity between task conditions of the frontal and lateral approaches. Two ways of avoiding obstacles cannot coexist: namely, changing a trajectory and changing a speed[7)]. The way of changing a trajectory is a strategy for moving fast to avoid the obstacles, because the process does not depend on a visual feedback. On the other hand, the way of changing speed is a strategy of moving slowly to avoid obstacles at the minimum distance. This way of movement is slow because it depends on visual feedback. In this study, subjects used the former way of changing the trajectory. Subjects chose a fast speed with a sufficient distance to avoid touching obstacles rather than a slow speed with a minimum distance to avoid obstacles, because subjects were asked to move quickly in this study. Hence, when a fast speed is demanded of the subjects in a transport-to-insertion task, they will select a way of adjusting trajectory while maintaining a fast motion.

Study limitation and future challenge

Our results showed the basic data of the assessment of dexterity from the qualitative aspect using the pegboard task. Factors extracted from the factor analysis were a part of movement adjustment ability to perform pegboard task smoothly. These factors should be further investigated to provide a new viewpoint for movement analysis. However, there may be a gender differences because this study include only female. Due to characteristics of the measured values, factors in this study dealt with mainly spatial adjustment rather than timing and speed adjustments. Although present study was analyzed focusing on the transport-to-insertion task, more complicated factors of motion adjustment will be required in the pegboard task, because the actual pegboard task needs to repeat transport-to-insertion and reach-to-grasp. An implementation method of the task, appropriate parameters for measurement, and gender difference should be further studied. Clinical indicators of observation using a pegboard task for assessing dexterity of the upper limb and fingers should be further refined. Since we have investigated basic data in the present study, comparative study to patients with impaired dexterity would clarify the usefulness of our qualitative approach.

Conclusions

A total of 51 healthy volunteers performed the transport-to-insertion task in three conditions, namely, no-obstacle, lateral-obstacle and frontal-obstacle conditions, and the movement of the upper limb and fingers were measured. Factor analysis was applied using 15 parameters. From various identified factors, we investigated the ability of motion adjustment in the wrist and fingers using a pegboard task. In the no-obstacle condition, important factors included adjustments of direction by the wrist at TP, direction by the wrist and fingers at IP, vertical trajectories, timing, and speed. If there were any obstacle pegs, in addition to factors required in the no-obstacle condition, adjustments of direction by the wrist at TP and horizontal amplitude were required. The results of this study may provide useful basic data for assessment of motion from qualitative aspect in patients with impaired dexterity.

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ペグボード課題の運動調整：
運搬から挿入における障害物回避動作の分析

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要　　旨

【背景】 ペグボードを用いた臨床評価は、作業量や所要時間という量的側面からの評価が多く、上肢手指の動き方に関する質的側面からは評価されていない。本研究の目的は、ペグボード課題（運搬・挿入課題）に要求される上肢手指の運動調整能力を明らかにすることである。

【方法】 対象は健常成人ボランティア51名（22.3±3.8歳）とした。課題はペグ１本を手前のボード穴から抜いて奥のボード穴に挿入することとした。課題条件は、ペグボードを想定した障害物なし、障害物側方、障害物前方の３条件とした。上肢手指の動きは超音波式三次元動作解析装置を用いて測定し、15項目の測定値を算出した。測定値の条件間の比較と因子分析から、各条件で必要とされる運動調整能力を検討した。

【結果】 障害物なしの条件では、運搬相の手指による調整、挿入相の手指・手関節による調整、垂直軌道の調整、タイミングの調整、そして速さの調整が必要であった。障害物があると、障害物なしの条件に加え、運搬相の手関節による調整、水平軌道の調整が必要となった。

【結論】 本研究より、運搬・挿入課題は条件により異なる運動調整能力が要求されることが明らかになった。本研究は、ペグボードを用いて巧緻性の質的側面を評価する際の基礎的データとして有用である。