Independent Evaluation of Peg Travel and Reach Movement Time Using A Newly Developed Nine-Hole Pegboard

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Abstract

Background: Hand dexterity in patients is often assessed with the nine-hole peg test (NHPT). In this test, the time to complete the test is the only outcome variable. However, the evaluation time alone does not provide detailed information about test execution. By introducing a newly developed PC-connected nine-hole pegboard, we divided the peg test exercise into four parts, calculated the difficulty level, and clarified the characteristics of the NHPT. In addition, we provided baseline data of detailed NHPT performance in healthy young women.

Methods: A pegboard with a container equipped with an accelerometer and nine holes with small photo reflectors at the bottom was developed for the present study. Pegboard features and peg dimensions were the same as those of a commercially available NHPT. Dominant and nondominant hands and container-to-peg hole distances (index of difficulty; ID) were analyzed as dependent variables for the four phases of the task in 16 healthy young women.

Results: Handedness was examined using the Edinburgh Handedness Inventory, and all participants were strongly right-handed. It was possible to accurately measure the total performance time, peg movement time and reaching time for each task. The total performance time was shorter for the dominant (right) hand (15595.4 ± 1039.5 msec) than for the nondominant (left) hand (17494.4 ± 1478.7 msec) ($P < 0.001$). Peg movement time showed an increase in performance time 900 ± 67.7 to 979.3 ± 112.2 as the task difficulty increased from an ID of 7.6 bits to 8.4 bits ($P = 0.035$).

Conclusions: The newly developed pegboard makes it possible to accurately and separately measure movement times with individual pegs and the time to reach pegs, without the need for stopwatch assessments. A detailed evaluation will clarify problems in upper limb function, suggest a training protocol, and identify problems needing intervention to develop future approaches to the rehabilitation of hand dexterity.

Trial registration

Not applicable

Background

For evaluating upper limb function in rehabilitation, hand dexterity is an essential factor. For therapists to assess hand dexterity in patients, various types of pegboards have been developed as tools. The nine-hole peg test (NHPT) has been exploited and used to measure hand dexterity in patients with various neurological diagnoses [1]. The NHPT was developed and created in 1971, and the test protocol, reliability, and validity were confirmed in 1985 [1, 2]. In 2006, the NIH Toolbox for Assessment of Neurological and Behavioral Function, a simple assessment for researchers and clinicians, was created and recommended the NHPT for the assessment of hand dexterity [3-5]. The NHPT can validly measure hand dexterity in healthy adults and elderly people [6], stroke [7, 8], cerebral palsy [9], cerebellar disorders

[10], Parkinson's disease [11], and multiple sclerosis [12]. The NHPT consists of a container with nine pegs and a board with nine holes and requires the user to lift one peg at a time from the container, insert the peg into the hole in the board, and after all the pegs are inserted, return the pegs to the container one by one. The test using the NHPT is done as quickly as possible, and the result is the total time taken from the moment the finger touches a peg in the container to the moment the last peg is moved back to the container.

The advantages of the NHPT include simplicity, low cost, easy portability, and the fact that it does not require much time to measure it. In addition, the time required for a single trial is relatively short, and the test is easy to administer to all age groups, from infants to the elderly. However, there are several disadvantages to testing with the traditional method. First, the NHPT has not been technologically improved in any way since 1971, although there have been attempts to improve it [13]. With advancements in computer technology, alternative pegboards using computer technology may emerge as an alternative to existing measures of hand dexterity [3]. The second is that the test results are based solely on the total time taken to complete the task, making it difficult to evaluate each patient's particular difficulty (e.g., picking up the peg, transferring the peg, putting the peg in a hole, or putting a peg back in the container). Third, the task difficulty varies depending on the distance and the task (removing or inserting a peg), making it difficult to evaluate the time required for each difficulty level in detail. The difficulty of the NHPT is determined by Fitts' law, which has been used as a quantitative definition of difficulty in various studies with clinicians [14, 15], healthy subjects [16, 17], two- and three-dimensional movements [18, 19], and imaginary movements [20, 21]. It predicts that the operation time increases linearly with the task's index of difficulty (ID). Humans can only process a limited amount of information per unit of time, and as the ID increases, more information needs to be processed. When evaluating and training the upper limb function of a subject, it would be beneficial for the therapist to know the temporal details of NHPT performance or the difficulty level of the subject's task.

Assuming that computers can be incorporated into the nine-hole pegboard evaluation in assessing hand dexterity in patients with orthopedic diseases, stroke, neurodegenerative diseases, and spinal cord injury, it is possible that unique hand dexterity characteristics of these patients could be revealed in detail. For example, is the peg movement time too long, is the reaching time too long, or is there difficult reaching near places or reaching far places? With this information, we can identify new treatment methods and problems needing intervention and contribute to rehabilitation in the future. Thus, we introduced a newly developed PC-connected nine-hole pegboard for the automatic measurement of peg insertion and peg lifting and provided detailed baseline data of peg manipulation times and reaching times in healthy young women.

Methods

Participants

Sixteen young healthy females (mean age $\pm$ SD = 24.63 $\pm$ 2.50 years old) participated in this study. The dominant hand was investigated using the Edinburgh Handedness Inventory (Oldfield,1971). All participants showed strong right-handedness (mean LQ $\pm$ SD = 92.90 $\pm$ 8.04). None of them had a history of injuries affecting their hands. Written informed consent was obtained from each participant. This study was approved by the ethics committee at the Kawasaki University of Medical Welfare (No. 17-104) and conformed to the Declaration of Helsinki.

Pegboard developed

As shown in Figure 1, a wooden nine-hole pegboard box (length x width x height = 340 x 145 x 60 mm) with a round container-like lightweight shallow plastic peg container (diameter = 105 mm) was built by the present researchers with reference to the size and depth of the holes and hole-to-hole distance of a commercially available Rolyan nine-hole pegboard (Model A8515, Sammons Preston Co., USA) (Figure 1a). A miniature photoreflector (RPR-220, Rohm Semiconductor Co., Japan) was fixed at the bottom of each hole to detect the light reflected by a small lightweight wooden peg (weight =0.5 g, diameter = 7 mm, length = 32 mm) (Figure 1b). Self-built analog amplifiers for photoreflector signal amplification were also placed inside the pegboard box (Figure 1c). A miniature 3-D accelerometer (ADXL-335, Analog Device Co., USA) was attached to the back side of the container to detect vibration of the container caused by the participant touching a peg. The distances from the hole and container centers were 110 mm for the 1st column, 142 mm for the 2nd column, and 174 mm for the 3rd column. Electrical signals from the photoreflector and the accelerometer were A/D converted (250 Hz/channel) and stored on a PC.

Experimental procedures

The experiment was conducted in a quiet clinical room. Each participant was briefed about the experimental task to be performed after observing a demonstration of the task performed by one of the experimenters. The participant then sat on a chair, faced a test table on which the pegboard was placed, and performed practice trials until they felt comfortable performing the task. The task was first to move the pegs from the container, one by one, and place them into the holes on the board as quickly as possible ('Task A'), and second, without resting, to remove the pegs from the board, one by one, and return them to the container as quickly as possible (a 'Task B') (Figure 2). The experimenter said "start" to initiate the task. When using the right hand, the container was located on the right side of the board, while this was reversed when using the left hand. The peg insertion and removal order were always from the holes in the front line to the third line, from the 1st column to the 3rd column for the right hand, and from the 3rd column to the 1st column for the left hand. For the experimental data collection, each participant performed the task twice for each hand. Adequate breaks were provided between the trials to minimize fatigue. Failing to grasp a peg or dropping of the peg in the middle of the task resulted in retesting.

Data analysis

A MATLAB-based program was developed by the present authors to determine the moments of accelerometer signal onsets for finger-peg contact on the container and the peg drop in the container, and

the photoreflectors onset and offset moments represented insertion of a peg into the hole and removal of a peg from the board (Figure 3). Another MATLAB program was used to compute four temporal variables for each of the nine pegs for the subsequent statistical analysis. These were the durations from the finger-peg contact to the hole insertion ("a" in Figure 3) and from the hole insertion to the next peg contact on the container ("b" in Figure 3) during Task A; the other durations were from the removal of the peg from the board to the container ("c" in Figure 3) and from the drop into the container to the removal of the next peg on board ("d" in Figure 3) during the Task B. Durations "a" and "b" were thus the durations needed to move the pegs, which we termed "*peg movement times*". Durations "c" and "d" were the durations involving the movement of the hand to reach the peg to be moved next, which we termed "*reaching times*".

The total performance time was determined from the initial finger-peg contact moment to the final peg drop in the container moment. The total time in Task A was the sum of peg movement times and reaching times for nine pegs, and the total time in Task B was the sum of peg movement times and reaching times for nine pegs. The time for the intertask interval was also computed by subtracting the total times of the container-to-board and board-to-container tasks from the total performance time.

Statistical analyses

The statistical analysis was performed with IBM SPSS (Statistical Packages for Social Sciences, 21.0) with a chosen significance level of 0.05. Depending on the purpose of the comparison, one-way or 2-way ANOVA with repeated measures was used. When performing the 2-way repeated measures ANOVA, the independent variables used were hand (right and left hands), column (1st, 2nd, and 3rd columns) or task difficulty (index of difficulty).. Post hoc multiple comparisons were performed using a Tukey method when necessary.

Application of Fitts' law to the nine-hole pegboard performance

Fitts studied the relationship between the size of an object, the distance to a target, and its associated motion time from a tapping task with a metal stylus and expressed these relationships in the following equation.

$$MT = a + b \times ID$$

MT (movement time) is the movement time to the target, and ID (index of difficulty) is the difficulty of the movement, which is expressed by the following equation. "a" and "b" are constants. "A" is distance and "W" is width.

$$ID = \log_2 \left(\frac{2A}{W} \right)$$

Results

Total performance time

The mean values of the total time for the right and left hands for all participants were 15595.4 ± 1039.5 msec and 17494.4 ± 1478.7 msec, respectively (Figure 4). The means of the peg movement times for Task A and Task B, reaching times for Task A and Task B, and intertask interval were 8489.0 ± 641.8 msec, 2329.3 ± 215.1 msec, 2327.6 ± 260.2 msec, 2113.5 ± 191.1 msec, and 336.0 ± 41.1 msec, respectively. These values account for 54.4%, 14.9%, 14.9%, 13.6%, and 2.2% of the right-hand total performance time, respectively. The corresponding values for the left hand were 9617.6 ± 970.4 msec, 2519.8 ± 190.0 msec, 2561.3 ± 359.0 msec, 2421.8 ± 370.6 msec, and 374.0 ± 96.3 msec and corresponded to 55.1%, 14.4%, 14.6%, 13.8%, and 2.1% of the total performance time, respectively. One-way repeated measures ANOVA revealed significant right-left hand differences in total performance time ($F_{1,15} = 29.368$, $P < 0.001$), total peg movement time in Task B ($F_{1,15} = 7.545$, $P = 0.015$), total peg movement time in Task A ($F_{1,15} = 18.348$, $P = 0.001$), total reaching time in Task B ($F_{1,15} = 14.164$, $P = 0.002$), and total reaching time in Task A ($F_{1,15} = 11.068$, $P = 0.005$). The intertask interval time did not differ between the hands.

Peg movement time in Task A

Table 1 shows the average movement time of all participants when they moved the pegs with their right and left hands to holes in the first (ID 7.6 bits), second (ID 8.1 bits), and third (ID 8.4 bits) columns. To investigate whether the differences in Peg movement time in Task A were due to differences in hand (right, left) and index of difficulty (ID 7.6, ID 8.1, ID 8.4 bits), we performed an analysis of the variance of the two corresponding factors, with hand and ID as independent variables and time as the dependent variable. The results showed that there was no interaction of hand $\times$ ID ($F_{2,30} = 0.358$, $P = 0.702$), but there was a main effect of hand ($F_{1,15} = 18.348$, $P = 0.001$) and a main effect of ID ($F_{2,30} = 4.397$, $P < .01$) (Figure 5). Task A required approximately three times more time to move the pegs than Task B did. The left hand required more time than the right hand, and an ID of 8.4 bits required more time than an ID of 7.6 bits (Table 1). Multiple comparisons using the Tukey method showed no significant differences between the difficulty levels for the right hand. In contrast, the mean values with an ID of 7.6 bits and 8.4 bits showed a significant difference for the left hand ($P < 0.035$). Note that the analysis of variance for the two interaction terms hand $\times$ distance and hand $\times$ ID yielded similar results.

Reaching time in Task A

The bottom panel of Table 1 shows the mean reaching time for each column in Task A. There was no hand $\times$ distance interaction for reaching time in Task A ($F_{2,30} = 0.788$, $P = 0.464$), but there was a main effect of hand ($F_{1,15} = 11.013$, $P = 0.005$) and a main effect of distance ($F_{2,30} = 122.359$, $P < .01$) (Figure 6). The results of multiple comparisons using the Tukey method showed a significant difference between the mean times for columns one and two for the right hand ($P = 0.018$). There was a significant difference between the mean times for columns one and three for both the left and right hands (right hand: $P < .01$, left hand: $P = 0.006$).

Peg movement time in Task B

Regarding peg movement times in Task B, there was no interaction of hand $\times$ ID (1st column: ID 1.0 bits; 2nd column: ID 1.5 bits; 3rd column: ID 1.8 bits) ($F_{2,30}=0.747$, $P=.482$), but there was a main effect of hand ($F_{1,15}=7.547$, $P=.015$) and a main effect of ID ($F_{2,30}=77.465$, $P < .01$) (Figure 5). Multiple comparisons using the Tukey method revealed a significant difference between ID 1.0 bits and ID 1.8 bits (right hand: $P < .01$, left hand: $P < .01$), between ID 1.5 bits and ID 1.8 bits (right hand: $P=0.008$, left hand: $P=0.021$), and between ID 1.5 bits and ID 1.8 bits (right hand: $P=0.008$, left hand: $P=0.021$) for both hands. However, only the left hand showed a significant difference between ID 1.0 bits and ID 1.5 bits ($P=0.042$). Note that the analysis of variance for the two factors hand $\times$ distance and hand $\times$ ID was the same result observed with Task B.

Reaching time in Task B

There was no interaction between hand and distance ($F_{2,30}=0.571$, $P=0.571$). There was also no main effect of distance ($F_{2,30}=2.505$, $P=0.099$), although the main effect of hand was significant ($F_{1,15}=14.899$, $P=0.002$) (Figure 6).

Discussion

This study introduced a PC-connected nine-hole pegboard for automatic measurement, which made it possible to measure the peg operation time and reaching time. Although previous reports on the NHPT only reported the total time spent using a stopwatch [2, 6, 21], the peg movement time for Task A accounted for approximately 55% of the total performance time with both the left and right hands. The ratio of each task to the total performance time was also accurately measured. Regarding the peg movement time, it became clear that the peg manipulation time became longer as ID increased in both Task A and Task B. We showed that the NHPT can be used to evaluate hand dexterity across difficulty levels using Fitts' law and that performance can be divided into phases during movement. We also provided detailed baseline NHPT performance data from healthy young women.

The IDs of the peg movement of Task A and Task B were 7.6–8.4 bits and 1.0–1.8 bits, respectively. The peg movement time in Task A was approximately 3.7 times longer than that in Task B. The peg movement time for both Task A and Task B tended to increase as the ID increased, which supported the results of previous studies [15, 22, 23]. The time required for the left and right hands increased as task difficulty increased, as the difference between the left hand and right hand was 191 msec for Task B, while it was 1129 msec for Task A. These results are consistent with previous studies showing that the dominant hand has greater elaboration and shorter motor time than the nondominant hand [6, 24-26].

In Task A, the movement times became longer as the distances to the object increased. These results supported the findings of a previous study on online feedback and trajectories in pointing tasks in which the time required for reaching increased as the distance to an object increased [27-29]. However, in

Task B, which showed no significant differences, there was a reversed phenomenon in which the movement time was shorter for the third column than for the first column. To clarify the cause of these results, we used a simple video camera to film several subjects performing the study. Throwing the peg into the container was frequently observed as the peg movement distance became longer. This reversal may have occurred because the reaching distance became shorter because participants were throwing the peg.

The NHPT is an evaluation method that includes two types of tasks: grasping and manipulating an object and reaching for an object, accompanied by two types of tasks that differ in difficulty. The results for peg movement times and reaching times in Tasks A and B suggested that the degree of difficulty of each task differs. Even for peg manipulation, inserting a peg in Task A and removing it in Task B have different characteristics. It may be necessary to instruct the participants to place the pegs in the container to prevent them from throwing the pegs during Task B to correctly perform the NHPT.

One problem with our nine-hole pegboard is that we cannot determine the phase in which errors occur. The accelerometer installed in the container detects minute signals, making it challenging to identify errors, such as failing to grab the peg, slipping off the peg, or having many pegs rolling in the container, when the participants are lifting the peg from the container. These errors may occur more frequently in stroke patients, patients with neurodegenerative diseases, and postsurgical orthopedic patients, and our nine-hole pegboard needs to be improved. The pegs used in the NHPT are thin (0.64 cm in diameter and 3.2 cm in length), making them difficult for patients to grasp. For that reason, the current assessment with a standard nine-hole pegboard is limited to patients with the ability to perform elaborate movements. Patients with low voluntary control and sensory impairments were unable to perform the NHPT, so they may be excluded from the evaluation. In the future, it will be necessary to create a peg test with a larger diameter and create a tool that can be used to evaluate patients with stroke and dyskinesia. Additionally, it is necessary to increase the number of age groups and sexes tested and measure baseline data to compare patients with each disease.

Within specific upper extremity functional assessments, such as the NHPT, Purdue Pegboard Test [30], and O'Connor Finger Dexterity Test [31], the task difficulty differs due to changes in the transmission distance. However, the index for these assessments is the total time required to perform the task. Suppose that task difficulty was quantified as shown in this study. In this situation, we can accurately identify the patients' problems and develop training content and new treatment methods, leading to rehabilitation.

Conclusion

This study introduced a newly developed PC-connected NHPT that automatically measures peg insertion and peg lifting to provide detailed baseline data on peg movement time and reaching time in healthy young women. As a result, it is now possible to measure peg movement time and reaching time in milliseconds for each of the peg movement times and hand reaching times, which was not possible with

the previous conventional NHPT. In addition, it was found that the peg movement time prolonged as the difficulty of the task increased.

Abbreviations

NHPT: nine-hole peg test

MT: movement time

ID: index of difficulty

Declarations

Ethics approval and consent to participate

All participants provided written informed consent, and the study was approved by the Kawasaki University of Medical Welfare (No. 17-104).

Consent for publication

Written informed consent for publication was obtained from all the participants.

Availability of data and materials

The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Not applicable

Authors' contributions

KT, DK, HK and RO conceived and designed the study. KT and DK carried out the data collection, data analysis and manuscript writing. HK and RO contributed to the development of the equipment and the manuscript writing and revision. TF contributed to the manuscript writing and revision. All authors read and approved the final manuscript.

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Tables

Table 1. Average values of peg movement times and reaching times in Task A and Task B

*1) 1st column vs. 2nd column $P=0.018$

*2) 1st column vs. 3rd column $P<.001$

*3) 1st column vs. 3rd column $P=0.006$

<u>Peg movement time</u>				
Column	Task A		Task B	
	Right hand	Left hand	Right hand	Left hand
1st	900(67.7)	1006.6(129.7)	240.3(22.4)	257.6(19.5)
2nd	950.4(100.2)	1079.8(118.5)	253.6(24.4)	279.1(25.6)
3rd	979.3(112.2)	1119.5(125.4)	282.5(30.5)	303.2(27.5)

<u>Reaching time</u>				
Column	Task A		Task B	
	Right hand	Left hand	Right hand	Left hand
1st	258.4(38.8) ^{*1 *2}	295.4(48.6) ^{*3}	273.5(40.9)	303.4(50.5)
2nd	295.7(35.2)	318.1(47.1)	268.6(28.8)	309.8(59.1)
3rd	321.5(37.4)	350.4(46.9)	252.3(27.6)	294.8(45.1)

(msec)

Figures

Figure 1

PC-connected nine-hole pegboard.

a. A nine-hole pegboard with sensors was developed. **b.** The electrical circuits installed inside the pegboard **c.** One of the photoreflexors and operational amplifiers.

Figure 2

Procedural operation.

Task A. The task is to take the peg from the container and put it in the hole, then reach for another peg in the container. **Task B.** The task is to return the peg inserted in the hole to the container and then reach the peg inserted in the hole.

Figure 3

Signal output from the sensor pegboard and the examined temporal variables.

a. Peg movement time during the container-to-board task; **b.** reaching time during the container-to-board task; **c.** peg movement time during the board-to-container task; **d.** reaching time during the board-to-container task. **Task A.** The task is to take one of the nine pegs in the container and put each in a hole, and then reach for another peg in the container. **Task B.** The task is to return the nine pegs already inserted in the hole back to the container, and then reach for another peg that is inserted in the hole.

Figure 4

Total performance time for right hand and left hand.

Performance with the right hand was significantly faster than that with the left hand. $*P<0.001$.

Figure 5

Peg movement times for each task difficulty with the right and left hands.

For the index of difficulty, 1.0 bits represents the 1st column, 1.5 bits represents the 2nd column, and 1.8 bits represents the 3rd column. Additionally, 7.6 bits represents the 1st column, 8.1 bits the 2nd column, and 8.4 bits the 3rd column. As the task difficulty increased, it took longer to complete the task with both the left and right hands.

□ $P < 0.05$ ▤ $P < 0.01$ ▥ $P < 0.001$

Figure 6

Reaching time with the right and left hands.

The 1st column represents the holes close to the container, the 2nd column represents the holes in the middle of the pegboard, and the 3rd column represents the holes far from the container. In Task A, the reaching time increased as the distance increased. In Task B, reaching took more time at closer distances than at farther distances.