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# Kinematic evaluation and reliability assessment of the Nine Hole Peg Test for manual dexterity

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A B S T R A C T

*Background:* The Nine Hole Peg Test (NHPT) is one of the most frequently used tools to assess manual dexterity. However, no kinematic parameters are provided to describe the quality of the motor performance, since time is the only score.
*Purpose:* To investigate test-retest and intra-rater reliability, correlation with clinical test score, and discriminant validity of kinematic indexes during NHPT.
*Study Design:* A clinical measurement study.
*Methods:* Twenty-five healthy right-handed volunteers performed the NHPT. An experienced physiotherapist administered two sessions at a 6-hour interval with two trials for dominant and non-dominant upper limbs. An optoelectronic system was used to detect NHPT performance, which was divided into nine consecutive peg-grasp, peg-transfer, peg-in-hole, hand-return phases, and one final removing phase. Outcome measures were total and single phases times, normalized jerk, mean, peak and time-to-peak of velocity, curvature index during peg-grasp and hand-return phases, and trunk 3D displacement. The statistical analysis included Intraclass Correlation Coefficients (ICCs) for test-retest and intra-rater reliability, Pearson's coefficients for correlation with the NHPT score, and paired t-tests for discriminant validity.
*Results:* Test-retest reliability was excellent for trunk rotation (ICC: 0.91) and good to moderate for the other indexes (ICCs: 0.89-0.61). Intra-rater reliability was excellent for total and removing times (ICCs: 0.91 and 0.94) and good to moderate for the other indexes (ICCs: 0.84-0.66), except for trunk inclination (ICC: 0.37). NHPT phases, normalized jerk, mean velocity, peak of velocity, time-to-peak and curvature index correlated with total time (r-score: 0.8-0.3). NHPT phases and most kinematic indexes discriminated the dominant from non-dominant upper limb, with the greatest effect size for normalized jerk during hand-return ($d = 1.16$).
*Conclusions:* Kinematic indexes during NHPT can be considered for manual dexterity assessment. These indexes may allow for the detection of kinematic changes responsible for NHPT score variations in healthy subjects or patients with upper limb impairments.



## Background

Manual dexterity is defined as the ability to generate voluntary, coordinated and fine movements to grasp and manipulate objects, and is considered an essential motor skill for ensuring a satisfactory upper limb function.[1,2] It is also crucial for the successful performance of several daily tasks and requires the integration of hand biomechanics, highly evolved sensorimotor functions and advanced cognitive processes.[3]

The Nine Hole Peg Test (NHPT) is one of the most frequently used tools for manual dexterity assessment. The test has good to excellent validity and intra-rater reliability in healthy subjects and patients with neurological disorders.[2,4-6] It consists in grasping nine small pegs from a container, inserting them into a nine-hole grid, and replacing the pegs into the container. The test is

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unimanually performed as quickly as possible, and shorter test duration indicates greater dexterity.[2] However, no quantitative parameters are provided to describe the quality of the motor performance, since time is the only score.[77] In this context kinematic indexes, such as smoothness and linearity of hand trajectories, hand velocity profile, compensatory movements with other body structures or duration of some NHPT phases, may provide further information for manual dexterity assessment.[7,8] In particular, kinematic indexes may be effective in revealing slight manual dexterity changes in healthy subjects performing sport or job activities that require advanced manual skills, or in individuals undergoing a motor training. Furthermore, kinematic parameters may allow clinicians to detect initial motor impairments, typical of some pathological conditions.[9] Similarly, segmentation into NHPT phases may provide more detailed information on motor impairment characteristics that are responsible for manual dexterity deficits, and consequently, suitable for planning appropriate rehabilitative interventions. For example, peg-grasp and peg-in-hole phases require a certain amount of finger dexterity, unlike peg-transfer and peg-return phases where accuracy in coordination among upper limb joints is needed.[10,11]

Recently, Johansson and coworkers investigated the validity and reliability of some kinematic parameters during a modified and standardized version of the NHPT, demonstrating good psychometric properties in patients suffering from a stroke[7]. However, the NHPT version designed by these authors was not commercially available, and participants had to transfer the pegs from one grid to another following a standardized order. As a result, the dexterity required to grasp a peg from the heap in the traditional version of the NHPT could not have been identical in the modified version of the NHPT. In addition, this simplified version of the test did not allow for a comparison with normative data.

To date, no studies have considered the detection of kinematic indexes to provide kinematic changes responsible for NHPT score variation during the traditional commercially available NHPT. However, the investigation of the psychometric properties of these indexes is the first mandatory step prior to application in clinical practice. Therefore, the aims of the study were to implement a motion analysis algorithm for the detection of kinematic indexes during NHPT and investigate (1) test-retest and intra-rater reliability, (2) correlation with NHPT clinical score and (3) discriminant validity between the dominant and non-dominant upper limbs of these indexes in healthy subjects.

## Methods

### *Participants*

Twenty-five healthy participants aged between 18 and 30 were enrolled. All the participants reported the right hand as dominant at the Edinburgh Handedness Inventory.[12] Exclusion criteria were the presence of pain, and neurological or musculoskeletal disorders affecting manual dexterity. Individuals with a history of traumatic injuries involving the upper limbs in the past year were also excluded. Participants' characteristics are reported in Table 1.

Data collection was performed between July and December 2020 at the Motion and Posture Analysis Lab of our Department. All participants signed a written informed consent as per the Declaration of Helsinki, and the Ethical Committee of our Institute approved the study protocol (n. CLF20/08).

### *Procedures*

A physiotherapist with 10 years of experience in hand therapy administered the traditional commercially available NHPT (Sammons Preston Rolyan, Illinois, USA). The NHPT is characterized by adequate validity (r-score from 0.74-0.75 with the Purdue Pegboard Test) and excellent intra-rater reliability (ICC from 0.92-0.95) in healthy subjects.[2,13] The participants were seated on a height-adjustable chair with no back support, with hips and knees positioned at 90°, and a physiological back posture. The NHPT pegboard was placed on a table (height 70 cm) in front of the participants. In particular, the pegboard was positioned at the participants' trunk midline and at the middle point between the acromion and the extremity of the third finger. The measurement of the middle point was performed with the shoulder at 90° flexion and the elbow fully extended. The peg-container was oriented towards the hand being tested. Participants' starting position was standardized with their forearms leaning on the table and hands adjacent to the pegboard with palms downward.[2]

The participants had to perform the test as quickly as possible, with no specific order of peg insertion. If the peg was dropped on the table, the participants were instructed to pick it up and continue.[2] If the peg was dropped on the floor, the participants were instructed not to pick it up, but to continue with the test.[2] After a familiarization trial, the participants performed the NHPT twice with both the dominant and non-dominant upper limbs. The trials were spaced by 5 minutes of rest[14,15] and a second session was repeated 6 hours later.[16] Overall, each participant performed 8 trials supervised by the same physiotherapist. The order of body sides was randomized, and the participants' performance was recorded with two video cameras (eVixta, BTS, Italy) in order to check a-posteriori the correct execution.

**Table 1**
Characteristics of study participants

| Demographic characteristics | |
|---|---|
| Age [y] | 24.2 ± 2.2 |
| Gender [M/F] | 12/13 |
| Limb dominance [R/L] | 25/0 |
| Height [m] | 1.69 ± 0.13 |
| Weight [kg] | 61.3 ± 9.3 |
| BMI [kg/m$^2$] | 21.2 ± 2.7 |

M = male; F = female; R = right; L = left.
Data are shown as mean and standard deviation.

### *Data collection*

The performance was recorded with an optical motion capture system (SMART-DX, BTS, Italy) (accuracy <0.2mm on a working volume of 3 × 2 × 2 m) equipped with eight infrared cameras located around the participants in a standard position.[17,18] Upper limbs and trunk kinematics were detected through 16 hemispherical retro-reflective markers (diameter 6 mm) placed on specific anatomical landmarks and on the table extremities. A physiotherapist with 5 years of experience in motion analysis placed three markers on the acromial angle of both sides and on the jugular incisura to identify the trunk, two markers bilaterally on the middle phalanx of the index finger to trace hand trajectories, and three markers on the left distal and left and right proximal corners of the table to define the global reference system.[19] Eight additional markers were placed bilaterally on the lateral epicondyle of the humerus, radial and ulnar styloid processes and the head of the second metacarpal bone to simplify the 3D reconstruction of the upper limb motion during pre-processing. After the placement of the markers and before each session, a 10-second static calibration was performed for each participant. The markers were removed and reattached before each session by the same physiotherapist and data were collected using Smart Capture software (BTS, Italy).

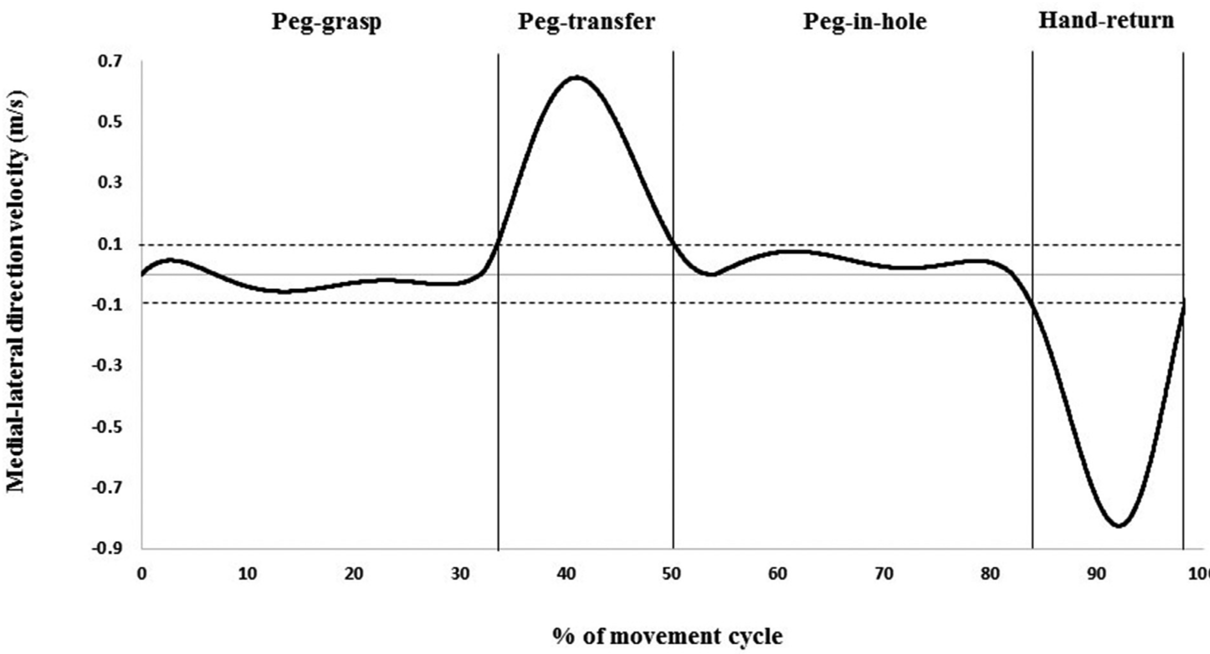


**Figure 1.** Segmentation into Nine Hole Peg Test phases based on the velocity of the marker on the index finger

*Data processing*

Data were processed by a biomedical engineer not involved in the data collection procedures. Raw marker data were sampled at 100 Hz and filtered using a fourth-order low-pass Butterworth filter (cut-off 4 Hz). Each trial was segmented into nine consecutive cycles consisting of four phases each (peg-grasp, peg-transfer, peg-in-hole, hand-return), plus a single final removing phase, based on the velocity profile of the marker on the index finger.[7] The peg-transfer phase was defined when the velocity of the marker on the index finger exceeded and fell below +0.01 m/s for at least 50 ms along the medial-lateral direction. The peg-return phase was defined when the velocity of the same marker fell below and exceeded -0.01 m/s for at least 50 ms along the medial-lateral direction (Figure 1). The peg-grasp and peg-in-hole phases were identified as the time frame between the phases described above, and the removing phase was defined as the period between the end of the ninth hand-return phase and the end of the trial. The total time of the trial was calculated as the time elapsed between the beginning of the first peg-grasp phase and the end of the removing phase, and the duration of each phase was also computed. Specifically, the peg-grasp phase started when the participant touched the first peg in the heap.[2] In addition, kinematic parameters for peg-transfer and hand-return phases were computed, based on the motion of the marker on the index finger. Parameters included mean velocity, peak of velocity, time-to-peak of velocity (expressed as percentage of the cycle), normalized jerk (first time derivative of the acceleration normalized for the time and path length, as recommended by Yan and coworkers) and curvature index (ratio between the actual and the shortest movement paths between the beginning and end of the transfer and return phases).[20] Finally, trunk kinematics was estimated relative to the table coordinate system using the Cardan X-Y-Z sequence, as recommended by the International Society of Biomechanics.[21] Thus, the trunk range of motion (RoM), was described for each trial considering flexion (+X), adduction (+Y) and internal rotation (+Z) as positive.

*Statistical analysis*

Categorical variables are shown as proportions, whereas continuous variables are described as mean and standard deviation. All measurements were checked for normality using the Shapiro-Wilk test. All test and retest trials performed in both sessions with the dominant and non-dominant upper limbs (200 trials) were used to assess test-retest reliability, which was investigated as agreement between test and retest trials without removal of the markers. The best performance of each session for the dominant and non-dominant upper limbs (100 trials) was used to assess intra-rater reliability, correlation between total test time and kinematic indexes, and discriminant validity. In particular, intra-rater reliability was investigated as agreement between the two sessions supervised by the same physiotherapist and characterized by removal and reattachment of the markers., Discriminant validity was assessed as the ability to discriminate between the dominant and non-dominant upper limb in order to investigate the ability of kinematic indexes to detect subtle differences in manual dexterity. In fact, when considering normative data, differences in manual dexterity from the dominant to non-dominant limb in healthy subjects[2] have been reported as less marked than those occurring between patients with upper limb motor impairments and healthy subjects.[22-25]

Paired samples t-tests and Intraclass Correlation Coefficients ($ICC_{2k}$ for test-retest and $ICC_{3k}$ for intra-rater reliability) with a 95% confidence interval were used to evaluate relative reliability. ICC values were interpreted as excellent (0.9 or greater), good (between 0.75 and 0.9), moderate (between 0.5 and 0.75) and poor (0.5 or lower).[26] To investigate absolute reliability Standard Error of Measurement (SEM) was computed. It was calculated as SEM = SD $\sqrt{1\text{-ICC}}$, with SD as the standard deviation of the mean difference between two trials, and reported as a percentage of the mean. The relationship between total time (clinical score of the test) and kinematic indexes was assessed using the Pearson's correlation coefficient, and the strength of correlation was interpreted as small (r-score lower than 0.3), moderate (r-score between 0.3 and

**Table 2**
Test-retest reliability results of kinematic indexes during the Nine Hole Peg Test performed with the dominant and non-dominant upper limbs

| Variables | Trial 1(n = 100) | Trial 2(n = 100) | ICC (2,k) | CI 95% | SEM% |
|---|---|---|---|---|---|
| Total time [s] | 19.8 ± 2.0 | 19.1 ± 2.1 | 0.84* | [0.69; 0.91] | 4.2 |
| Removing time [s] | 5.8 ± 0.8 | 5.7 ± 0.8 | 0.89* | [0.83; 0.93] | 4.5 |
| Peg-grasp time [s] | 4.2 ± 0.8 | 4.0 ± 0.8 | 0.61* | [0.42; 0.74] | 12.8 |
| Peg-transfer time [s] | 2.7 ± 0.3 | 2.6 ± 0.3 | 0.68* | [0.53; 0.79] | 7.01 |
| Peg-in-hole time [s] | 3.7 ± 0.7 | 3.5 ± 0.6 | 0.65* | [0.47; 0.76] | 10.9 |
| Hand-return time [s] | 2.2 ± 0.2 | 2.1 ± 0.2 | 0.68* | [0.53; 0.78] | 5.9 |
| Normalized jerk peg-transfer | 1.16 ± 0.26 | 1.03 ± 0.25 | 0.78* | [0.67; 0.86] | 8.1 |
| Normalized jerk hand-return | 1.03 ± 0.18 | 1.01 ± 0.17 | 0.80* | [0.70; 0.87] | 6.1 |
| Mean velocity peg-transfer [m/s] | 0.31 ± 0.04 | 0.31 ± 0.04 | 0.76* | [0.67; 0.85] | 5.9 |
| Mean velocity hand-return [m/s] | 0.36 ± 0.04 | 0.36 ± 0.04 | 0.81* | [0.71; 0.87] | 4.8 |
| Peak velocity peg-transfer [m/s] | 0.62 ± 0.11 | 0.62 ± 0.11 | 0.85* | [0.78; 0.90] | 6.6 |
| Peak velocity hand-return [m/s] | 0.80 ± 0.11 | 0.81 ± 0.11 | 0.86* | [0.79; 0.91] | 5.1 |
| Time-to-peak peg-transfer [%] | 38.8 ± 5.5 | 38.2 ± 5.9 | 0.67* | [0.51; 0.78] | 8.6 |
| Time-to-peak hand-return [%] | 57.9 ± 5.2 | 57.5 ± 5.0 | 0.71* | [0.57; 0.80] | 4.8 |
| Trunk inclination [°] | 0.6 ± 0.2 | 0.6 ± 0.2 | 0.81* | [0.72; 0.87] | 17.5 |
| Trunk rotation [°] | 2.1 ± 0.7 | 2.0 ± 0.7 | 0.91* | [0.86; 0.94] | 10.1 |
| Trunk flexion-extension [°] | 1.0 ± 0.4 | 1.1 ± 0.4 | 0.86* | [0.79; 0.90] | 15.8 |
| Curvature index peg-transfer [%] | 112.6 ± 4.8 | 112.5 ± 4.9 | 0.71* | [0.57; 0.81] | 2.3 |
| Curvature index hand-return [%] | 114.6 ± 5.4 | 113.8 ± 5.0 | 0.83* | [0.74; 0.88] | 1.9 |

ICC = Intraclass correlation coefficient; CI = Confidence interval; SEM = standard error of the mean.
Data are shown as mean and standard deviation.
* $p < .001$.

0.6) and strong (r-score greater than 0.6).[27] Finally, paired samples t-test was used to investigate discriminant validity between the dominant and non-dominant upper limbs for kinematic indexes. Effect size was also quantified using Cohen's *d* and interpreted as small (0.2), medium (0.5) or large (0.8 or greater).[28] Data were analyzed by a statistician using SPSS 25.0 for Windows and results were interpreted by a physiotherapist and a biomedical engineer not involved in the data collection procedures. The level of significance was set at $\alpha = 0.05$.

## Results

### *Test-retest reliability*

No significant differences were found between test and retest trials for all variables. Excellent reliability was found for trunk RoM along the transverse plane (ICC 0.91, SEM% 10.1), while good reliability was detected for total and removing times, normalized jerk, mean velocity and peak of velocity during peg-transfer and hand-return, trunk RoM along the frontal and sagittal planes and curvature index during hand-return (ICC 0.77-0.89, SEM% from 1.9-17.5). Finally, moderate reliability was found for peg-grasp, peg-transfer, peg-in-hole and hand-return times, time-to-peak during peg-transfer and hand-return and curvature index during hand-return (ICC 0.61-0.71, SEM% from 2.3-12.8) (Table 2).

### *Intra-rater reliability*

No significant differences were found between the best trials of the first and second sessions for all variables. Excellent reliability was found for total and removing times (ICC 0.91-0.94, SEM% from 2.6-4.1), while reliability was good for peg-grasp and peg-in-hole times, normalized jerk and peak of velocity during peg-transfer and hand-return, mean velocity during peg-transfer, curvature index during hand-return and trunk RoM along the sagittal and transverse planes (ICC 0.84-0.75, SEM% from 1.8-19). Finally, moderate reliability was found for peg-transfer and hand-return times, time-to-peak during peg-transfer and hand-return, mean velocity during hand-return and curvature index during peg-transfer (ICC 0.73-0.66 and SEM% from 2.3-8.6), whereas poor reliability was found for trunk RoM along the frontal plane (ICC 0.37 and SEM% 33.9) (Table 3).

### *Correlation with NHPT clinical score*

Total time revealed strong correlations with removing, peg-grasp and hand-return times, normalized jerk during peg-transfer and hand-return (r-score from 0.80 to 0.66, $p < .001$), and peak of velocity during peg-transfer (r-score from -0.78 to -0.62, $p < .001$). Moderate correlations were found for peg-transfer and peg-in-hole times (r-score 0.58, $p < .001$), mean velocity during peg-transfer and hand-return, peak of velocity during hand-return, and time-to-peak of velocity during peg-transfer (r-score from -0.52 to -0.30, $p \leq .004$). A slight correlation was found for curvature index during peg-transfer (r-score 0.25, $p = .013$) (Table 4).

### *Discriminant validity*

Participants performed the test significantly faster with the dominant compared to non-dominant limb ($p < .001$). Similarly, lower duration was detected for all the phases in favor of the dominant limb ($p < .001$). In addition, normalized jerk was lower in the dominant limb ($p < .001$), whereas peak of velocity was higher in the dominant limb during both peg-transfer ($p = .029$) and hand-return ($p = .002$). Moreover, time-to-peak of velocity resulted closer to 50% of the distance between initial and final hand position in the dominant limb during both peg-transfer and hand-return ($p < .001$). Finally, greater trunk rotation ($p = .004$) and curvature index during hand-return ($p = .007$) were found for the non-dominant limb (Table 5).

## Discussion

The kinematic indexes showed good test-retest and intra-rater reliability, and most of these indexes revealed strong to moderate correlations with the clinical score of the test. Moreover, the kinematic indexes were able to discriminate the better quality of movement of the dominant compared to the non-dominant upper limb.

Test-retest reliability resulted higher for total time when compared to findings of Grice and coworkers.[2] Previous studies attributed low test-retest reliability of NHPT to the lack of standardized order of peg insertion in the grid. However, in our study

**Table 3**
Intra-rater reliability results of kinematic indexes during the Nine Hole Peg Test considering the best performance of each session with the dominant and non-dominant upper limbs

| Variables | Session 1(n = 50) | Session 2(n = 50) | ICC (3,k) | CI 95% | SEM% |
|---|---|---|---|---|---|
| Total time [s] | 18.9 ± 1.9 | 18.8 ± 2.0 | 0.94** | [0.89; 0.96] | 2.6 |
| Removing time [s] | 5.7 ± 0.8 | 5.6 ± 0.7 | 0.91** | [0.84; 0.95] | 4.1 |
| Peg-grasp time [s] | 3.9 ± 0.8 | 3.8 ± 0.7 | 0.82** | [0.69; 0.90] | 7.9 |
| Peg-transfer time [s] | 2.6 ± 0.3 | 2.7 ± 0.3 | 0.67** | [0.42; 0.81] | 7.0 |
| Peg-in-hole time [s] | 3.5 ± 0.6 | 3.5 ± 0.6 | 0.75** | [0.55; 0.86] | 8.4 |
| Hand-return time [s] | 2.1 ± 0.2 | 2.1 ± 0.2 | 0.72** | [0.50; 0.84] | 5.1 |
| Normalized jerk peg-transfer | 1.21 ± 0.25 | 1.26 ± 0.27 | 0.84** | [0.72; 0.91] | 6.2 |
| Normalized jerk hand-return | 1.02 ± 0.16 | 1.02 ± 0.17 | 0.83** | [0.70; 0.91] | 5.2 |
| Mean velocity peg-transfer [m/s] | 0.31 ± 0.04 | 0.31 ± 0.04 | 0.75** | [0.56; 0.86] | 6.6 |
| Mean velocity hand-return [m/s] | 0.36 ± 0.04 | 0.36 ± 0.04 | 0.72** | [0.51; 0.84] | 6.3 |
| Peak velocity peg-transfer [m/s] | 0.62 ± 0.11 | 0.62 ± 0.12 | 0.84** | [0.72; 0.91] | 7.2 |
| Peak velocity hand-return [m/s] | 0.81 ± 0.12 | 0.81 ± 0.13 | 0.81** | [0.66; 0.89] | 6.6 |
| Time-to-peak peg-transfer [%] | 38.0 ± 5.9 | 38.7 ± 5.3 | 0.66** | [0.40; 0.81] | 8.6 |
| Time-to-peak hand-return [%] | 57.9 ± 4.7 | 57.5 ± 5.5 | 0.73** | [0.52; 0.85] | 4.6 |
| Trunk inclination [°] | 0.6 ± 0.3 | 0.5 ± 0.2 | 0.37* | [-0.11; 0.64] | 33.9 |
| Trunk rotation [°] | 2.0 ± 0.7 | 2.0 ± 0.6 | 0.83** | [0.69; 0.90] | 13.5 |
| Trunk flexion-extension [°] | 1.0 ± 0.4 | 1.1 ± 0.5 | 0.81** | [0.66; 0.89] | 19.0 |
| Curvature index peg-transfer [%] | 112.5 ± 5.3 | 112.4 ± 4.8 | 0.73** | [0.53; 0.85] | 2.3 |
| Curvature index hand-return [%] | 114.3 ± 5.4 | 113.3 ± 4.8 | 0.83** | [0.70; 0.90] | 1.8 |

ICC = Intraclass correlation coefficient; CI = Confidence interval; SEM = standard error of the mean.
Data are shown as mean and standard deviation.
* $p < .05$.
** $p < .001$.

**Table 4**
Correlation results between kinematic indexes and Nine Hole Peg Test clinical score considering the best performance of each session with the dominant and non-dominant upper limbs

| Variables | (n = 100) | r-score | *p*-value |
|---|---|---|---|
| Total time [s] | 18.9 ± 2.0 | - | - |
| Removing time [s] | 5.7 ± 0.8 | 0.79 | **<.001** |
| Peg-grasp time [s] | 3.8 ± 0.7 | 0.80 | **<.001** |
| Peg-transfer time [s] | 2.6 ± 0.3 | 0.58 | **<.001** |
| Peg-in-hole time [s] | 3.5 ± 0.6 | 0.58 | **<.001** |
| Hand-return time [s] | 2.1 ± 0.2 | 0.66 | **<.001** |
| Normalized jerk peg-transfer | 1.17 ± 0.25 | 0.75 | **<.001** |
| Normalized jerk hand-return | 1.06 ± 0.17 | 0.78 | **<.001** |
| Mean velocity peg-transfer [m/s] | 0.31 ± 0.04 | -0.51 | **<.001** |
| Mean velocity hand-return [m/s] | 0.36 ± 0.04 | -0.36 | **.001** |
| Peak velocity peg-transfer [m/s] | 0.62 ± 0.11 | -0.63 | **<.001** |
| Peak velocity hand-return [m/s] | 0.81 ± 0.12 | -0.52 | **<.001** |
| Time-to-peak peg-transfer [%] | 38.3 ± 5.6 | -0.30 | **.004** |
| Time-to-peak hand-return [%] | 57.7 ± 5.1 | 0.02 | .816 |
| Trunk inclination [°] | 0.6 ± 0.2 | -0.07 | .468 |
| Trunk rotation [°] | 2.0 ± 0.6 | 0.10 | .341 |
| Trunk flexion-extension [°] | 1.0 ± 0.4 | -0.15 | .147 |
| Curvature index peg-transfer [%] | 112.5 ± 5.0 | 0.25 | **.013** |
| Curvature index hand-return [%] | 113.8 ± 5.1 | 0.13 | .284 |

Data are shown as mean and standard deviation. Significant results are shown in bold text.

no specific order was imposed on participants.[7,29] Furthermore, good test-retest reliability was found for most kinematic indexes, except for time-to-peak of velocity and curvature index during peg-transfer, which showed moderate reliability. The highest ICC value was detected for trunk rotation. This represents the most described compensatory movement during upper limb tasks along the transverse plane, as in the case of peg-transfer and hand-return during the performance of the NHPT.[30] Interestingly, the total times were similar between test and retest trials, suggesting that the same task performed in the same condition was often executed with similar kinematic patterns.[31] The segmentation into phases revealed good test-retest reliability for the removing phase, whereas correlations resulted moderate for the other phases. These findings revealed less within-subject variability for precision grasp when the peg was removed from the hole and replaced into the container. In this situation, less manual dexterity and coordination among upper limb joints were required compared to the other phases[7].

When considering the intra-rater reliability, our results were similar to those reported in the literature for total time.[2] Good intra-rater reliability was found for normalized jerk and peak of velocity during peg-transfer and hand-return, and for curvature index during hand-return and mean velocity during peg-transfer. Coherently, studies reported good intra-rater reliability for these kinematic indexes during functional upper limb tasks for gross manual ability assessment, for instance reaching or transitive daily tasks in healthy subjects or patients with disability.[32-35] For the first time, our results demonstrated the accuracy of these indexes during a fine manual dexterity task, such as NHPT. Good intra-rater reliability was also detected for trunk displacement along the sagittal and transverse planes, irrespective of the movement occurring along the frontal plane, showing low intra-rater reliabil-

**Table 5**
Discriminant validity results of kinematic indexes during the Nine Hole Peg Test considering the best performance of each session with the dominant and non-dominant upper limbs

| Variables | Dominant limb(n = 50) | Non-dominant limb(n = 50) | *p*-value | Effect size |
|---|---|---|---|---|
| Total time [s] | 18.1 ± 1.7 | 19.7 ± 1.9 | **<.001** | 1.01 |
| Removing time [s] | 5.5 ± 0.7 | 5.8 ± 0.8 | **<.001** | 0.57 |
| Peg-grasp time [s] | 3.6 ± 0.7 | 4.0 ± 0.7 | **.001** | 0.51 |
| Peg-transfer time [s] | 2.5 ± 0.3 | 2.7 ± 0.3 | **<.001** | 0.61 |
| Peg-in-hole time [s] | 3.2 ± 0.5 | 3.7 ± 0.6 | **<.001** | 0.56 |
| Hand-return time [s] | 2.0 ± 0.2 | 2.2 ± 0.2 | **<.001** | 1.07 |
| Normalized jerk peg-transfer | 1.14 ± 0.23 | 1.32 ± 0.25 | **<.001** | 0.83 |
| Normalized jerk hand-return | 0.92 ± 0.13 | 1.07 ± 0.14 | **<.001** | 1.16 |
| Mean velocity peg-transfer [m/s] | 0.32 ± 0.04 | 0.31 ± 0.04 | .156 | - |
| Mean velocity hand-return [m/s] | 0.36 ± 0.04 | 0.35 ± 0.04 | .090 | - |
| Peak velocity peg-transfer [m/s] | 0.64 ± 0.11 | 0.61 ± 0.11 | **.029** | 0.31 |
| Peak velocity hand-return [m/s] | 0.83 ± 0.12 | 0.78 ± 0.11 | **.002** | 0.47 |
| Time-to-peak peg-transfer [%] | 40.1 ± 5.6 | 36.6 ± 5.2 | **<.001** | 0.55 |
| Time-to-peak hand-return [%] | 55.6 ± 4.8 | 59.7 ± 4.6 | **<.001** | 0.66 |
| Trunk inclination [°] | 0.6 ± 0.3 | 0.6 ± 0.2 | .693 | - |
| Trunk rotation [°] | 1.9 ± 0.5 | 2.2 ± 0.8 | **.004** | 0.43 |
| Trunk flexion-extension [°] | 1.1 ± 0.5 | 1.0 ± 0.4 | .275 | - |
| Curvature index peg-transfer [%] | 112.0 ± 4.9 | 112.9 ± 5.2 | .167 | - |
| Curvature index hand-return [%] | 112.8 ± 4.7 | 114.7 ± 5.3 | **.007** | 0.40 |

Data are shown as mean and standard deviation. Significant results are shown in bold text.

ity. However, it is worth noting that the degree of trunk inclination during NHPT was limited. Intra-rater reliability was excellent for removing time and good for peg-grasp and peg-in-hole times, whereas lower ICC values were found for peg-transfer and hand-return times, perhaps due to the lack of standardized peg insertion order.

The duration of the peg-grasp phase showed the highest correlation with the total time of the test, proving that fine manipulative abilities required to pick up the peg quickly from the container can be considered an indicator of manual dexterity. In fact, moving fingers independently from each other, coordinating finger movements, and controlling force during grasp were described as key determinants of manual dexterity.[7,36] Normalized jerk is an index of trajectory smoothness, and reveled highest correlation with the total time of the test. The ability to perform smooth trajectories during upper limb movements that involve multiple joints was described as an indicator of motor control, essential to ensure manual dexterity.[3,31] Interestingly, the kinematic indexes showed higher correlations during peg-transfer compared to hand-return, suggesting that the peg-transfer phase is more indicative of manual dexterity. Previous studies demonstrated that smoothness and linearity of trajectories is proportional to precision of the task to be accomplished, in order to maximize the economy of the sensorimotor system.[31] Coherently, peg-transfer anticipated the peg insertion movement where more precision is needed in contrast to picking up the peg from the container.

As expected, total time resulted lower for the dominant compared to the non-dominant upper limb. Moreover, all phases allowed for discrimination between the two body sides with the hand-return duration that revealed larger effect size than total time. Normalized jerk revealed the largest effect size, indicating greater smoothness for movements performed with the dominant upper limb. This finding is consistent with previous studies reporting smoother trajectories during upper limb tasks for the dominant side as an index of higher motor control.[37,38] Velocity showed a moderate effect size for time-to-peak, which resulted closer to 50% of the trajectory in favor of the dominant limb. This result is consistent with previous findings describing the velocity profile of well-controlled movements as characterized by one velocity peak occurring approximately halfway through the movement.[24] In fact, the time-to-peak of velocity usually moves farther from the 50% of the movement cycle with the increase of task difficulty or the decrease of manual dexterity.[39]

Some limitations of this study must be acknowledged. First, the sample was relatively small, and the generalizability of results needs to be further investigated in a broader population. It is also worth underlining that the kinematic indexes results were based on the psychometric properties of the NHPT and accuracy of our motion capture system.

In conclusion, the kinematic indexes during NHPT resulted in reliable parameters for manual dexterity assessment, revealing an association with the clinical test score and ability to discriminate the dominant from the non-dominant upper limb in healthy subjects. These parameters may influence detection of slight manual dexterity changes in healthy subjects or in patients with upper limb impairments and provide detailed information on characteristics of motor impairments. Further studies are needed to investigate the psychometric properties of these indexes in patients with upper limb disorders due to musculoskeletal or neurological conditions.

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\# 1. The only score of the NHPT is
  a. coordination
  b. time
  c. accuracy
  d. dexterity

\# 2. Reliability was tested using
  a. matched pairs quotients
  b. Kappa's Alpha
  c. an ANOVA
  d. an ICC

\# 3. Testing was performed by
  a. a surgeon-therapist team
  b. a tenured OT professor
  c. a single hand therapist
  d. 5 CHTs

\# 4. The velocity marker was on the
  a. thumb
  b. index finger
  c. middle finger
  d. little finger

\# 5. The data are applicable to normal subjects, but not so for actual patients
  a. not true
  b. true

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