Towards AI-Based Kinematic Data Analysis in Hand Function Assessment: An Exploratory Approach

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Abstract: Neurological diseases, such as multiple sclerosis (MS), significantly affect hand function, impacting patients' independence and quality of life. The Nine Hole Peg Test (NHPT) is a standardized tool widely used to assess upper limb motor function. This paper explores the integration of artificial intelligence (AI) and machine learning (ML) in the analysis of kinematic data obtained from a digitized NHPT prototype. The digital NHPT captures detailed motion data, including timestamps for each action, movement patterns, and filling sequences, enabling advanced analyses of motor and cognitive processes. AI-driven methods, such as clustering, anomaly detection, and pattern recognition, provide innovative ways to evaluate fine motor skills, detect subtle anomalies, and monitor disease progression. The combination of enhanced data collection and AI-based analytics offers a comprehensive and objective approach to understanding hand function, supporting individualized therapy development, and improving clinical diagnostics. This integration represents a significant advancement in the evaluation and management of neurological diseases.

1 INTRODUCTION

Neurological diseases such as Multiple Sclerosis (MS) are associated with upper limb dysfunction (Lamers et al., 2014). This dysfunction, which is based on sensory and/or motor deficits, has a negative impact on quality of life and independence. Typical upper limb disabilities in MS include a decline in the ability to precisely control grip force, decreased movement speed, muscle weakness and sensory deficits (Lambercy et al., 2013). There is a clear correlation between hand function and the different stages of MS (Balaceanu et al., 2024). Since MS is a progressive disease of the central nervous system in which the immune system attacks the myelin sheaths of nerves, there is an increasing impairment of motor functions, including hand motor skills. The degree of impairment of hand function varies depending on the severity and progression of the disease, which is due to the different stages of MS (Koch et al., 2023). Understanding and quantifying the extent of upper limb disability is critical to the care of people with MS (Lamers et al., 2014) and other neurological diseases.

Measuring hand function is an important part of neurological diagnosis and rehabilitation for neurogenerative diseases. These tests provide valuable information about motor abilities, disease progression and treatment effects. Hand and arm function is commonly assessed in clinical practice using the Nine Hole Peg Test (NPHT).

Figure 1: Commercial NHPT made of wood.

The NHPT is a standardized clinical assessment for neurological diseases to evaluate the motor function of the upper extremities (Feys et al., 2017).

The NHPT consists of a test board with two areas (see Fig. 1). One side consists of a container in which nine pegs are placed before the test begins. The second side consists of a test board with nine holes.

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The task consists of two subtasks: picking up nine pegs individually from a container and inserting them into a board with nine holes, and then returning the pegs individually from the holes back to the container. The total time required for this task is the result. The test is simple, time-efficient and used worldwide in a clinical context.

The integration of modern technologies into the digital Nine Hole Peg Test can offer numerous innovative possibilities to enable precise, objective, and automated evaluations (Balaceanu et al., 2024; Temporiti et al., 2022). These technologies can help to identify subtle changes in motor function through the additional data collected, to monitor the course of the disease, and to evaluate the effects of therapy.

This paper focuses on the application of artificial intelligence (AI), particularly machine learning (ML), to analyse movement patterns in hand function tests, using the example of multiple sclerosis (MS) and the digital Nine Hole Peg Test (dNHPT). Unlike other kinematic data collection methods, the dNHPT eliminates the need for additional technical equipment, such as cameras or portable sensors, while still capturing comprehensive kinematic data. This streamlined approach ensures ease of use without compromising the accuracy or depth of the data collected.

2 DIGITIZED ASSESSMENT

In an earlier study, we digitized and evaluated the digital Nine Hole Peg Test (dNHPT) (Prochaska & Ammenwerth, 2023). Figure 2 show the test board of the dNHPT.

Figure 2: Test board of the dNHPT.

In a further development, the dNHPT includes new, more extensive options for data collection without compromising the standardized test procedure. This means that the dNHPT supports the standardized assessment of hand function, which does not change the manageability compared to the original NHPT and still allows the comparison of previously collected follow-up data (reference data, as well as previously collected data from patients using the original NHPT.

The digitization of the NHPT offers numerous advantages beyond the traditional administration of the test. It expands the possibilities for data collection, analysis, and application and improves both the accuracy and efficiency of motor function diagnostics.

The prototype of our digital NHPTv2 is equipped with automatic time measurement (between the start and stop buttons), magnets on the nine pegs, and sensors in the nine holes. The hall sensors recognize the magnets on the pins, which allows time stamps to be recorded at the action level. With the help of the sensors, a variety of kinematic data can be generated from the execution of the dNHPTv2. The action points start, sensor detection in each hole and stop generate data for the following analyses:

- Movement time (total time in seconds, time per pin in seconds)
- Speed (average and maximum speed of hand movement between the actions points: start event, sensor recognition in each hole and stop event)
- Acceleration (linear acceleration and deceleration),
- Coordination (filling patterns of the matrix may allow conclusions to be drawn about cognitive abilities): e.g. 1 4 7 2 3 5 6 8 9 (see Figure 3 with matrix of the dNHPTv2)
- Symmetry of movements (left hand vs. right hand).

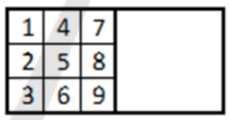

Figure 3: Numbered matrix of dNHPTv2.

2.1 Additional Kinematic Data

The additional digital features of the prototype enable the precise recording of the time course for all events (e.g., inserting and removing pegs) and the analysis of the filling patterns within the 3x3 matrix of the NHPT test board. These capabilities provide detailed insights into the motor skills and potential deficits of patients with neurological diseases, such as multiple sclerosis (MS).

- Timestamp at the action level: Each individual action such as inserting or removing a peg, is recorded with a precise timestamp, allowing for high-resolution temporal analysis.
- Motion pattern analysis: The sequence in which the holes are filled and emptied is

captured, offering insights into movement strategies and the deviations.

- Advanced analyses:
  - Detailed time and motion analyses: These analyses detect subtle deviations in fine motor skills that may be imperceptible to the naked eye, enabling a more nuanced understanding of motor impairments.
  - Qualitative analysis: Movement strategies (e.g., systematic vs. chaotic) are recorded and analysed, providing valuable insights into underlying cognitive processes.
  - Personalized analysis: Automated comparisons with normative values or longitudinal data across multiple time points allow for the documentation of individual progress or deterioration.
- Visualization:
  - Presentation of time and movement profiles: Temporal development of movements and actions can be visualized, along with heat maps to illustrate usage patterns within the matrix.
  - Support for communication: Intuitive visualizations facilitate the interpretation of results, improving communication with patients and healthcare professionals.

The digitization of the NHPT transcends traditional time measurement, offering a more accurate, efficient, and comprehensive assessment of fine motor skills. This approach not only provides deeper insights into the motor and cognitive processes of patients but also supports the development of individualized therapies. Furthermore, it opens new avenues for research and diagnostics by integrating modern technologies such as artificial intelligence (AI), enhancing the NHPT's clinical and scientific relevance.

2.2 Example Data Set

To illustrate the described idea, synthetic data were generated by modelling the time courses of NHPT tests of five individuals. The assumptions for the sample data were total test times and standard deviations according to normative values (Grice et al. 2003) of healthy individuals and a uniform distribution of the data points with few fluctuations between the data points (i.e., the absence of impairment of hand function). The data sets were created and visualized using the Python programming language and the PyCharm 2024.3 software.

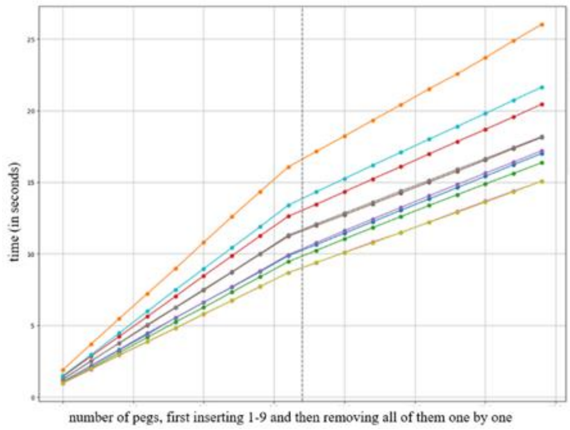

Figure 4: Datasets of five NHPT test runs.

Figure 4 shows the time courses of five tests with the dNHPTv2. Each data point represents the insertion of a peg, or after nine peg points, the removal a peg from the test board. The dashed line indicates the end of the input phase and the beginning of the removal phase.

When measuring the hand function with the dNHPT, a number of data points are collected for each person tested, in addition to the total time required for the task. These data points are stored digitally for further analysis.

2.3 Analysis Using AI

Hand function in MS patients is influenced by a variety of factors, including neurological damage to the central nervous system, muscle weakness, spasticity, tremor, ataxia, fatigue, sensory disturbances, emotional factors, medications and their side effects. These symptoms can vary depending on the stage of the disease and the location of the lesion, and can significantly affect the ability to perform activities of daily living. Treatment and management of these symptoms are critical to improving hand function and quality of life for patients.

The kinematic analysis of dNHPTv2 results can be significantly enhanced through ML, offering innovative opportunities for precise, objective, and automated evaluations. The following key areas highlight the potential of ML in optimizing NHPT data analysis.

2.3.1 Analysis of Time Series

- Clustering: Grouping patients based on movement profiles to identify common patterns or subgroups.

- Anomaly Detection: Identifying tests with unusual progressions, such as inconsistent movements or extended pauses, using time series analysis.
- Applications:
  - Speed analyses, including time per peg insertion/removal and acceleration profiles.
  - Examination of consistency and variability in movement sequences.
  - Detection of anomalies, such as irregular patterns or interruptions.

2.3.2 Pattern Recognition of Sequences

Advanced sequence analysis techniques, such as hidden Markov models (HMMs) for modeling common strategies and pattern mining for identifying frequent or rare behaviours.
Applications:

- Analysis of filling and emptying sequences to identify systematic or chaotic behaviours.
- Comparison of filling strategies with clinical factors, such as hand dominance or neurological impairments.
- Benchmarking results against normative values (healthy individuals or patients with specific conditions) or longitudinal follow-up data.

2.3.3 Overall Performance and Cognitive Aspects

Leveraging feature engineering, regression, and classification for comprehensive evaluations.
Applications:

- Integration of time and sequence data to assess overall efficiency and precision.
- Comparison of filling and removal strategies to detect performance discrepancies.
- Recognition of thought patterns that may guide sequencing choices, shedding light on underlying cognitive processes.4. Group and progression analysis: through time series analysis or clustering,

2.3.4 Group and Progression Analysis

Time series analysis and clustering to explore broader trends and disease progression.
Applications:

- Comparative analysis between patient groups (e.g., MS severity levels).
- Classification of disease severity based on movement profiles.
- Longitudinal tracking to observe changes across multiple tests, influenced by therapy, medication, or disease progression.

2.3.5 Visualization and Reporting

Advanced visualization tools enable intuitive interpretation of results.
Applications:

- Heatmaps to visualize filling or emptying sequences and their frequencies.
- Time diagrams to illustrate the temporal sequence of actions.
- Sequence diagrams, such as arrow plots, for clear representation of the filling order.

With the extended data provided by the new NHPT prototype, AI-driven analyses can deliver comprehensive insights across three critical domains: motor skills (e.g., timing and efficiency), cognitive processes (e.g., strategies and thought patterns), and clinical diagnostics and therapy monitoring. These capabilities not only advance the precision and depth of NHPT evaluations but also support the development of personalized therapeutic strategies and facilitate long-term patient monitoring.

3 CONCLUSIONS

The digitization of the Nine Hole Peg Test (NHPT) represents a substantial advancement in the assessment of hand function for patients with neurological diseases such as multiple sclerosis (MS). By capturing detailed kinematic data, the digital NHPT (dNHPT) facilitates a more comprehensive understanding of both motor and cognitive processes. Unlike other kinematic data collection methods, the dNHPT eliminates the need for additional technical equipment, such as cameras or portable sensors, thus maintaining simplicity and ease of use while ensuring robust data acquisition.

The integration of artificial intelligence (AI) and machine learning (ML) into the analytical pipeline enhances the precision, objectivity, and efficiency of evaluations. Advanced techniques, including time series analysis, pattern recognition, and anomaly detection, enable the identification of subtle motor deficits that might otherwise go unnoticed, while also providing novel insights into disease progression and therapeutic outcomes. While traditional time series analyses can yield useful indices for tracking the progression of MS, AI offers distinct advantages: it recognizes complex patterns, automates personalized analyses, and integrates data with normative values and longitudinal trajectories. Moreover, AI-driven tools enable advanced visualizations such as heat maps, increase analytical efficiency, and open new avenues for research and diagnostics in the context of neurological diseases.

This approach not only reinforces the clinical relevance of the NHPT but also supports the development of personalized therapeutic strategies and facilitates long-term patient monitoring. Ultimately, the digital NHPT bridges the gap between conventional clinical assessments and state-of-the-art, technology-driven diagnostics, thereby advancing both clinical practice and research in neurological disease management.

4 OUTLOOK

Looking ahead, the integration of artificial intelligence (AI) with the digital NHPT offers transformative opportunities for research, diagnostics, and therapeutic applications. Future developments may include real-time AI models capable of providing immediate feedback during testing, advanced visualizations such as interactive dashboards for enhanced data interpretation, and seamless integration with telemedicine platforms to enable remote assessments. Expanding normative databases through larger-scale studies is essential to further refine diagnostic thresholds and improve the accuracy of disease classification.

To support these advancements, additional studies are planned to collect comprehensive reference datasets in the form of time series. These datasets will serve as a robust foundation for training AI algorithms, facilitating the identification of movement patterns, detection of subtle motor deviations, and precise classification of disease states. As these algorithms evolve, their outputs are expected to significantly enhance the diagnostic and monitoring capabilities of the digital NHPT, equipping clinicians with actionable insights for personalized care.

Furthermore, integrating NHPT data with complementary sources, such as wearable sensors or imaging modalities, could yield a holistic perspective on patient motor and cognitive health. These advancements will not only solidify the NHPT's role in clinical practice but also advance the broader understanding of neurological diseases, ultimately contributing to improved patient outcomes and quality of life.

REFERENCES

Balaceanu, A., Puertas, I., Alonso de Leciñana, M., Tallón, A., Gutiérrez-Tenorio, Vargas, P., Torres, G., & Gutiérrez. (2024). Automatic evaluation of the Nine-Hole Peg Test in multiple sclerosis patients using machine learning models. *Biomed Sign Proc and Control*, *92*, 106128. https://doi.org/10.1016/J.BSPC.2024.106128

Grice, K. O., Vogel, K. A., Le, V., Mitchell, A., Muniz, S. & Vollmer, M. A. (2003) Adult Norms for a commercially available Nine Hole Peg Test for Finger Dexterity. *Am J Occup Ther, 57(5),* 570-573. https://doi.org/10.5014/ AJOT.57.5.570

Feys, P., Lamers, I., Francis, G., Benedict, R., Phillips, G., Larocca, N., Hudson, L. D., & Rudick, R. (2017). The Nine-Hole Peg Test as a manual dexterity performance measure for multiple sclerosis. *Mult Scler*, *23*(5), 711–720. https://doi.org/10.1177/1352458517690824

Koch, M. W., Repovic, P., Mostert, J., Bowen, J. D., Comtois, J., Strijbis, E., Uitdehaag, B., & Cutter, G. (2023). The nine hole peg test as an outcome measure in progressive MS trials. *Multiple Sclerosis and Related Disorders*, *69*(November 2022), 104433. https://doi.org/10.1016/j.msard.2022.104433

Lambercy, O., Fluet, M. C., Lamers, I., Kerkhofs, L., Feys, P., & Gassert, R. (2013). Assessment of upper limb motor function with MS using the virtual Peg insertion test: a pilot study. *Int Conf Rehabil Robot*, *2013*. https://doi.org/10.1109/ICORR.2013.6650494

Lamers, I., Kelchtermans, S., Baert, I., & Feys, P. (2014). Upper Limb Assessment in Multiple Sclerosis: A Systematic Review of Outcome Measures and their Psychometric Properties. *Arch Phys Med Rehabil*, *95*(6), 1184–1200. https://doi.org/10.1016/J.APMR.2014.02.023

Prochaska, E., & Ammenwerth, E. (2023). Validity and Reliability of a new developed digital version of Nine Hole Peg Test. *IEEE Access*, *11*, 97169–97176. https://doi.org/10.1109/ ACCESS.2023.3311270

Temporiti, F., Mandaresu, S., Calcagno, A., Coelli, S., Bianchi, A. M., Gatti, R., & Galli, M. (2022). Kinematic evaluation and reliability assessment of the Nine Hole Peg Test for manual dexterity. *J Hand Therapy*, *36*(3), 560–567. https://doi.org/10.1016/ j.jht.2022.01.007