The impact of digitalization on the quality criteria of measuring instruments for manual dexterity

Development and Validation of the digital Box and Block Test and the digital Nine Hole Peg Test

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1 RESEARCH PROBLEM

Measuring instruments are used in healthcare to assess physical functions and conditions (De Vet et al., 2011; Mokkink et al., 2010). Various healthcare professions (occupational therapy, physiotherapy, nursing) utilize measuring instruments to quantify changes caused by illness, injury or therapeutic measures (Fawcett, 2007; Schädler et al., 2006; Schönthaler, 2016) often in an unchanged (analog) form for decades.

The Box and Block Test (BBT) (see Fig. 1) measures gross manual dexterity (Kontson et al., 2017), while the Nine Hole Peg Test (NHPT) (see Fig. 2) measures fine manual dexterity (Oxford Grice et al., 2003). Both measurement instruments are widely used in clinical settings (Johansson & Häger, 2019; Kontson et al., 2017). The originals are made of wood or plastic and require additional material, such as a stopwatch and documentation sheets, in order to be carried out (Mathiowetz, Federman, et al., 1985; Mathiowetz, Weber, et al., 1985).

Digitalization in the healthcare sector offers important benefits for patients, doctors, healthcare professionals and funding providers. Processes are supported and simplified, which improves outcomes for patients and increases the efficiency of care (Becker et al., 2015). It is to be expected that the digitalization of measuring instruments will also bring benefits for all those involved in healthcare(Ona et al., 2019). However, there is a lack of sufficient studies to provide the necessary evidence (Becker et al., 2015; Day et al., 2022).

The quality of data collection in the assessment of motor functions (as with the BBT and the NHPT) also depends on the methodology of test administration. Errors in the test procedure can lead to an incorrect assessment (Ona et al., 2019). There are potential sources of error in the test implementation for the measurement instruments mentioned, which are explained in more detail in Chapter 3. An appropriate integration of procedures that check the error-free execution of the BBT and the NHPT can lead to more objective data collection.

The research idea is to digitize the BBT and the NHPT in order to gain advantages. By implementing automatic error-check, time measurement and result display, the quality of measurement and evaluation is to be improved.

The aim of this study is to investigate how digitization affects the measurement properties (validity, reliability and clinical utility) of the dexterity measurement instruments. For this purpose, comparisons will be made between the newly developed prototypes and the original versions of BBT and NPHT.

2 OUTLINE OF OBJECTIVES

Prototypes of the digital Block Test (dBBT) and the digital Nine Hole Peg Test (dNHPT) were produced for this purpose. The prototypes of dBBT and dNHPT are manufactured using 3D printing technology and equipped with electronic assemblies and interfaces. The implemented digital electronics provide functions that support the execution and evaluation of

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the hand dexterity measurements. The design of the original measuring instruments is retained, to maintain ease of use.

The newly developed prototypes of the BBT and the NHPT are validated by examining their measurement properties and clinical utility.

3 STATE OF THE ART

Measurement is essential for clinical practice and evidence-based healthcare (Swan et al., 2023). Technology is changing the way medicine is practiced (Coravos et al., 2019). Digitalization in the healthcare sector has developed rapidly in recent years and now affects almost all aspects of healthcare provision (Cohen et al., 2020). This trend still has little influence on the use of measuring instruments, as demonstrated by the examples of BBT and NHPT.

3.1 BBT and NHPT

The BBT and the NHPT measuring instruments for dexterity have been used in the clinical environment in unchanged form for many decades (Mathiowetz, Federman, et al., 1985; Mathiowetz, Weber, et al., 1985).

Both are standardized measurement instruments, which means that defined instructions describe the arrangement, implementation, evaluation and

Figure 1: Box and Block Test (Ona et al., 2020)

Figure 2: Nine Hole Peg Test (Feys et al., 2017)

interpretation of the data collection in a manual (see Appendices). Standardization enables comparable, transparent results to be achieved. Systematic data collection in the context of studies can only be achieved with standardized measuring instruments (De Vet et al., 2011; Schönthaler, 2016).

The test procedure is usually carried out by medical professionals using the standardized test instructions. The future users of the BBT and the NHPT are therefore occupational therapists and physiotherapists.

Test procedure BBT

With the BBT, the task is to transport blocks one by one from one box, over a partition wall, into another box. As many as possible within 60 seconds. The result of the test is the number of blocks transported in the test period. This can be up to 90 cubes per test, which currently have to be counted manually by the therapist (test administrator). An error in the execution would be if more than one cube is transported at the same time, or if the fingertips do not cross the partition wall during transportation. The therapist must monitor the error-free performance and at the same time the test period must be measured with a stopwatch (Mathiowetz, Volland, et al., 1985).

Test procedure NHPT

The task with the NHPT is to pick up nine pegs one by one from a container, insert them in random order into the holes provided on the test board and then remove the pegs one by one and remove them back into the container. The time required for this task is the result of the NHPT. This time is measured by the therapist using a stopwatch, while ensure the task is performed correctly. If the pegs are not inserted and removed correctly one by one, or are inserted incompletely into the holes, there is an error (Mathiowetz, Weber, et al., 1985).

If there is an error when carrying out a measurement with BBT or NHPT, the result must not be evaluated. The test must be repeated (Mathiowetz, Volland, et al., 1985; Mathiowetz, Weber, et al., 1985).

Measurement properties

The characteristics of measurement instruments are considered as psychometric properties, quality criteria or measurement properties (Fawcett, 2007). Typical properties for measurement instruments include validity, reliability and clinical utility (also known under the term practicability). Validity refers to the extent to which an instrument measures what it was intended to measure. Reliability means consistent or dependable results. Clinical Utility refers to various aspects of handling, such as effort and expense for tested persons, duration of implementation, effort for training test administrators, etc. (De Vet et al., 2011).

Both original measurement instruments (BBT and NHPT) showed high validity (Ekstrand et al., 2016;

Johansson & Häger, 2019; Lin et al., 2010; Platz et al., 2005) and high reliability (Canny et al., 2009; Heller et al., 1987; Mathiowetz, Weber, et al., 1985) in various studies. The practicability of BBT and NHPT is rated as high (Schönherr et al., 2018; Thomas et al., 2016).

3.2. Related work

Several projects have further developed the considered measurement instruments. The research projects dealt with the digitization of BBT and NHPT can be divided into three areas:

- Digitization using the original measuring instrument and additional use of digital technologies such as sensors, cameras, ... (Chih-Pin Hsiao et al., 2013; Johansson & Häger, 2019; Lee et al., 2018; Zhang et al., 2019)
- Digitization without using the original measuring instrument. The BBT is displayed on a screen and the task is carried out using gesture control or a robot arm. (Bowler et al., 2011; Cho et al., 2016; Lambercy et al., 2013; Tobler-Ammann et al., 2016; Xydas & Louca, 2008)
- Digitization using a virtual environment (Ona et al., 2019, 2020)

What all the projects mentioned have in common is that additional technologies (sensors, cameras, computers, VR head-mounted display, …) are required to measure hand dexterity.

On the one hand, the further developments enable additional data to be recorded in order to assess hand function more comprehensively. On the other hand, additional equipment and expertise are required to evaluate and interpret this data. In most cases, a large amount of technical equipment is required to carry out a measurement, which not only causes costs, but also significantly changes the requirements for the testers and the necessary locations(Bowler et al., 2011; Lambercy et al., 2013).

Overall, all these further developments of BBT and NHPT have a strong impact on the practicability of the measurement instruments. Although practicability is not one of the main quality criteria, it is a key factor in the choice of a measurement instrument for practice and for studies (De Vet et al., 2011).

The high practicability of the original BBT and NHPT (short test time, little prior knowledge, quick results/easy interpretation of the results) are the main reasons for the widespread use of NHPT and BBT as instruments for assessing hand dexterity (Desrosiers et al., 1994; Tobler-Ammann et al., 2016). These advantages are completely lost with the described approaches to further development.

So our idea was to digitize BBT and NHPT while retaining the original form of BBT and NHPT. The additional technologies that digitize the measurements are implemented in the original forms of BBT and NHPT. This means that there are no additional requirements in terms of technologies, equipment and user knowledge, when using dBBT or dNHPT.

4 METHODOLOGY

The aim of this study is to investigate how the digitalization of measurement instruments affects their quality criteria - using the example of the BBT and NHPT. The specific aim is therefore the development and validation of dBBT and dNHPT. The necessary steps are shown in the overview in Figure 1.

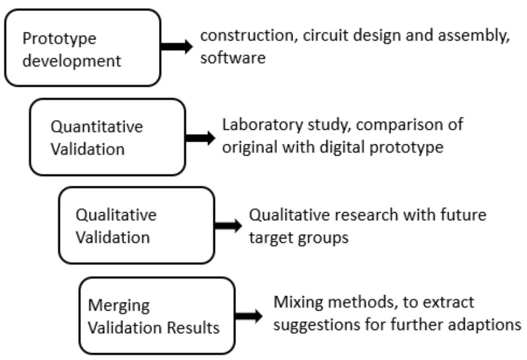

Figure 3: flowchart about the steps planned

The study protocol was in accordance with the Declaration of Helsinki and was approved by the ethics committee (EK Nr 97/2022) of the University of Applied Sciences Campus Vienna. This study has been registered on the Open Science Framework (OSF) under https://osf.io/bw2m4/.

The methods used are now briefly summarized in the following sections. More detailed information can be found in the papers already published (Prochaska & Ammenwerth, 2023a, 2023b, 2024).

4.1 Prototype Development

The development of the prototypes follows the current state of the art (Pahl & Beitz, 2013; VDI, 2019). The housings were manufactured using 3D printing technology and PLA (polylactide) filament, which has material properties suitable for medical products (Raj et al., 2018). The integrated circuits, which are controlled by microcontrollers, enable the functionalities of the prototypes.

The prototype of dBBT automatically counts the valid blocks including error-checking (if two blocks are transported at the same time, the system counts only one block for the valid result) and shows the achieved score (number of blocks in 60 seconds) on a display (Prochaska & Ammenwerth, 2023a)

The prototype of dNHPT is able to record the time of the test procedure, to monitor the correct execution and optionally store the recorded data. The error check verifies that the individual pegs have been correctly inserted into the holes and correctly removed again. (Prochaska & Ammenwerth, 2023b).

4.2 Quantitative Validation

The study design includes two measurement points to assess validity and reliability. In a laboratory situation, the original versions of the measuring instruments are compared with the respective digital prototypes (dBBT, dNHPT). Participants were adults with healthy hand function, the testers were trained in handling the measuring instruments (Prochaska & Ammenwerth, 2023a, 2023b).

For assessing interrater and test-retest reliability, intraclass correlation coefficient (ICC) were used. Standard error of measurement (SEM) is calculated to assess measurement error. The smallest detectable change (SDC) representing an absolute measure of reliability was determined. It is used to interpreting reliability results and to quantify true changes in performance (De Vet et al., 2011).

To analyse the agreement between the original measurement instrument and the new prototype Bland-Altman analysis is used for check systematic bias and estimate the limit of agreement (LOA) (Bland & Altman, 1986; De Vet et al., 2011).

4.3 Qualitative Validation

Consolidated criteria for reporting qualitative research (COREQ) are used for planning, conducting and reporting of this study (Tong et al., 2007). A mixed methods approach, which is a procedure for collecting, analyzing and mixing or integrating both quantitative and qualitative data within in a study is applied (Creswell & Creswell, 2018). In general, a more complete picture of the research problem can be expected if a combination of quantitative and qualitative methods (Guettermann et al., 2015; Tashakkori & Teddlie, 1998).

This part of the study consists of observational studies, focus groups with future users (occupational therapists) and a quantitative survey (system usability scale, SUS) of usability. All participants in the laboratory study and all participants in the qualitative studies completed the usability survey.

4.3 Merging Validation Results

Finally, the findings from all previous steps of this research will be brought together and analysed with integrating qualitative and quantitative data through a transformative process (Creswell & Creswell, 2018). Recommendations for further improvements to the dBBT and dNHPT prototypes will be derived from this analysis.

5 EXPECTED OUTCOME

The advantage of automated assessments is the possibility of generating objective outcomes (Oña Simbaña et al., 2019). The implementation of digital functions in the digital versions of BBT and NHPT is intended to achieve this benefit.

The expected outcomes of this study are

- prototypes of dBBT and dNHPT
- results for validity and reliability of dBBT and dNHPT
- assessment of the clinical utility of dBBT and dNHPT
- recommendations for future improvement for dBBT and dNHPT

Based on the results in the areas of validity, reliability and clinical utility, statements can be made about the influence of digitalization on measurement instruments. This should contribute to the evidence of the effects of digitalization in healthcare.

6 STAGE OF THE RESEARCH

In this chapter, the current state of research is described separately in subchapters each prototype. Previously published partial results are briefly summarized and reference is made to the publications.

The laboratory studies were carried out in January 2023, the qualitative data collection took place in May and June 2023.

6.1 Digital Box and Block Test

The prototype of dBBT (see Fig. 3) was completed and already been used to investigate validity, reliability and clinical utility.

The results of development and evaluating the concurrent validity, the test-retest reliability and the interrater reliability of the newly developed dBBT have already been published in JMIR Rehabilitation

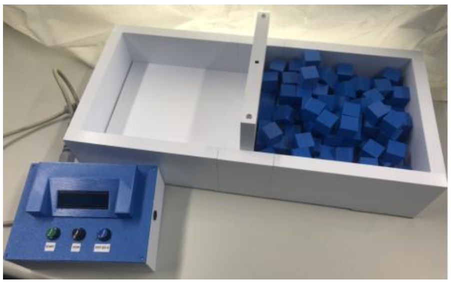

Figure 4: digital Box and Block Test

and Assistive Technologies (Prochaska & Ammenwerth, 2023a). A brief overview of the main results is listed in Table 1.

Table 1: Results of dBBT validation (Prochaska & Ammenwerth, 2023a).

dBBT	Results
Concurrent validity	r_{29}=0.48; p=0.008
Score difference to BBT	-4.97 blocks in 60 sec.
Test-retest reliability	ICC=0.72; p<0.001
Interrater reliability	ICC=0.67; p=0.23

The data collection for the qualitative studies has currently been completed. One focus group for dBBT and several observations of the use of the prototypes were carried out. The data collected was evaluated and analyzed.

In order to evaluate clinical utility several aspects of this construct were identified and examined, which are presented in the current publication (Prochaska & Ammenwerth, 2024). These aspects were evaluated in comparison to the original BBT. In the area of clinical utility, the dBBT achieved comparable results to the BBT in 15 of a total of 17 categories, and better results than the BBT in 2 categories. Usability achieved a very high rating with a SUS score of 83.3. Several issues emerged from the validation study with regard to possible future changes to the dBBT. These issues concerned the following points:

- shape of the blocks (sharp edges make it difficult to remove blocks from the box)
- signaling the End of Test (implementation of an additional audio signal)
- display of time and results during test (the continuous display of the current status of time and block count distracted the administrators).

6.2 Digital Nine Hole Peg Test

The prototype of dNHPT (see Fig. 4) was also completed and already been utilized to investigate his validity, reliability and clinical utility.

The main results are listed in table 2, the paper of the development and investigation of validity and reliability of dNHPT have already been published in the IEEE Access (Prochaska & Ammenwerth, 2023b).

Figure 5: digital Nine Hole Peg Test

The data collection for the qualitative validation part has currently been completed in a laboratory study. This study already showed recommendations for further improvements, e.g. higher contrast between test board and pegs necessary, separate control box from test board for better distance between therapist and tested person.

One focus group and several observations of the use of the prototypes were carried out. The data collected is currently being evaluated and analyzed.

Table 2: main results of dNPHT validation (Prochaska & Ammenwerth, 2023b).

dNHPT	Results
Concurrent validity	R_{31}=0.59, p<0.001
Score difference	+2.47 seconds to NHPT
Test-retest reliability	ICC=0.75; p<0.05
Interrater reliability	ICC=0.76; p<0.05

The next step will be to compile all partial results and draw up recommendations for further development measures for dBBT and dNHPT.

REFERENCES

Becker, K., Braecklein, M., Dickhaus, H., & Habenstein, B. (2015). *Biomedizinische Technik. VDE Expertenbericht*.

Bland, J., & Altman, D. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*, *1*(8476), 307–310. https://doi.org/10.1016/S0140-6736(86)90837-8

Bowler, M., Amirabdollahian, F., & Dautenhahn, K. (2011). Using an embedded reality approach to improve test reliability for NHPT tasks. *IEEE International Conference on Rehabilitation Robotics*. https://doi.org/10.1109/ICORR.2011.5975343

Canny, M. L., Thompson, J. M., & Wheeler, M. J. (2009). Reliability of the box and block test of manual dexterity for use with patients with fibromyalgia. *Am J Occup Ther*, *63*(4), 506–510. https://doi.org/10.5014/AJOT.63.4.506

Chih-Pin Hsiao, Chen Zhao, & Do, E. V.-L. (2013). The Digital Box and Block Test Automating traditional post-stroke rehabilitation assessment. *2013 IEEE International Conference on Pervasive Computing and Communications Workshops (PERCOM Workshops)*, 360–363. https://doi.org/10.1109/PerComW.2013.6529516

Cho, S., Kim, W. S., Paik, N. J., & Bang, H. (2016). Upper-Limb Function Assessment Using VBBTs for Stroke Patients. *IEEE Comp Graph Appl*, *36*(1), 70–78. https://doi.org/10.1109/MCG.2015.2

Cohen, A. B., Dorsey, E. R., Mathews, S. C., Bates, D. W., & Safavi, K. (2020). A digital health industry cohort across the health continuum. *Npj Digital Medicine*, *3*(1). https://doi.org/10.1038/s41746-020-0276-9

Coravos, A., Goldsack, J. C., Karlin, D. R., Nebeker, C., Perakslis, E., Zimmerman, N., & Erb, M. K. (2019). Digital Medicine: A Primer on Measurement. *Digit Biomark*, 31–71. https://doi.org/10.1159/000500413

Creswell, J., & Creswell, D. (2018). *Research Design. Qualitative, Quantitative, and Mixed Methods Approaches*. Sage Publications, Inc.

Day, S., Shah, V., Kaganoff, S., Powelson, S., & Mathews, S. C. (2022). Assessing the Clinical Robustness of Digital Health Startups: Cross-sectional Observational Analysis. *J Med Internet Res 2022;24(6):E37677 Https://Www.Jmir.Org/2022/6/E37677*, *24*(6), e37677. https://doi.org/10.2196/37677

Desrosiers, J., Bravo, G., Hébert, R., Dutil, É., & Mercier, L. (1994). Validation of the Box and Block Test as a measure of dexterity of elderly people: Reliability, validity, and norms studies. *Arch Phys Med Rehabil*, *75*(7), 751–755. https://doi.org/10.1016/0003-9993(94)90130-9

De Vet, H. C. W., Terwee, C. B., Mokkink, L. B., & Knol, D. L. (2011). *Measurement in medicine: A practical guide*. Cambridge University Press. https://doi.org/10.1017/CBO9780511996214

Ekstrand, E., Lexell, J., & Brogårdh, C. (2016). Test-Retest Reliability and Convergent Validity of Three Manual Dexterity Measures in Persons With Chronic Stroke. *PM & R*, *8*(10), 935–943. https://doi.org/10.1016/J.PMRJ.2016.02.014

Fawcett, A. (2007). *Principles of assessment and outcome measurement for occupational therapists and physiotherapists: theory, skills and application*. John Wiley & Sons Inc.

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

Guettermann, T., Creswell, J., & Kuckartz, U. (2015). Using Joint Displays and MAXQDA Software to Represent the Results of Mixed Methods Research. In M. McCrudden, G. Schraw, & S. Buckendahl (Eds.), *Inform Age Publishing* (pp. 145–176). Information Age Publishing.

Heller, A., Wade, D. T., Wood, V. A., Sunderland, A., Langton Hewer, R., Ward, E., & Hewer, L. (1987). Arm function after stroke: measurement and recovery over the first three months. *Neurosurgery, and Psychiatry*, *50*, 714–719.

Johansson, G. M., & Häger, C. K. (2019). A modified standardized nine hole peg test for valid and reliable kinematic assessment of dexterity post-stroke. *J Neuroeng Rehabil*, *16*(1). https://doi.org/10.1186/S12984-019-0479-Y

Kontson, K., Marcus, I., Myklebust, B., & Civillico, E. (2017). Targeted box and blocks test: Normative data and comparison to standard tests. *PLOS ONE*, *12*(5). https://doi.org/10.1371/JOURNAL.PONE.0177965

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. *IEEE International Conference on Rehabilitation Robotics*, *2013*. https://doi.org/10.1109/ICORR.2013.6650494

Lee, T. K. M., Lim, J. G., Leo, K. H., & Sanei, S. (2018). Indications of Neural Disorder through Automated Assessment of the Box and Block Test. *Int Conf on Digital Signal Processing, DSP*, *2018-Novem*. https://doi.org/10.1109/ICDSP.2018.8631815

Lin, K. C., Chuang, L. L., Wu, C. Y., Hsieh, Y. W., & Chang, W. Y. (2010). Responsiveness and validity of three dexterous function measures in stroke rehabilitation. *J Rehabil Res Dev*, *47*(6), 563–572. https://doi.org/10.1682/JRRD.2009.09.0155

Mathiowetz, V., Federman, S., & Wiemer, D. (1985). Box and Block Test of Manual Dexterity: Norms for 6–

19 Year Olds. *Can J Occup Ther*, *52*(5), 241–245. https://doi.org/https://doi.org/10.1177/00084174850 5200505

Mathiowetz, V., Volland, G., Kashman, N., & Weber, K. (1985). Adult norms for the Box and Block Test of manual dexterity. *Am J Occup Ther*, *39*(6), 386–391. https://doi.org/10.5014/AJOT.39.6.386

Mathiowetz, V., Weber, K., Kashman, N., & Volland, G. (1985). Adult norms for the nine hole peg test of finger dexterity. *OTJR*, *5*(1), 24–38. https://doi.org/10.1177/153944928500500102

Mokkink, L. B., Terwee, C. B., Knol, D. L., Stratford, P. W., Alonso, J., Patrick, D. L., Bouter, L. M., & De Vet, H. C. (2010). The COSMIN checklist for evaluating the methodological quality of studies on measurement properties: A clarification of its content. *BMC Med Res Methodol*, *10*(1), 1–8. https://doi.org/10.1186/1471-2288-10-22/FIGURES/3

Ona, E. D., García, J. A., Raffe, W., Jardon, A., & Balaguer, C. (2019). Assessment of Manual Dexterity in VR: Towards a Fully Automated Version of the Box and Blocks Test. *Stud Health Technol Inform*, *266*, 57–62. https://doi.org/10.3233/SHTI190773

Ona, E. D., Jardón, A., Cuesta-Gómez, A., Sánchez-Herrera-Baeza, P., Cano-De-la-Cuerda, R., & Balaguer, C. (2020). Validity of a Fully-Immersive VR-Based Version of the Box and Blocks Test for Upper Limb Function Assessment in Parkinson's Disease. *Sensors*, *20*(10), 5–7. https://doi.org/10.3390/S20102773

Oña Simbaña, E. D., Sanchez-Herrera Baeza, P., Jardon Huete, A., & Balaguer, C. (2019). Review of automated systems for upper limbs functional assessment in neurorehabilitation. *IEEE Access*, *7*, 32352–32367. https://doi.org/10.1109/ACCESS.2019.2901814

Oxford Grice, K., 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

Pahl, G., & Beitz, W. (2013). *Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung* (J. Feldhusen & K. H. Grote, Eds.; 8th ed.). Springer. https://doi.org/10.1007/978-3-642-29569-0

Platz, T., Pinkowski, C., van Wijck, F., Kim, I., di Bella, P., & Johnson, G. (2005). Reliability and validity of arm function assessment with standardized guidelines for the Fugl-Meyer Test, Action Research Arm Test and Box and Block Test: a multicentre study. *Clin Rehabil*, *19*(4), 404–411. https://doi.org/10.1191/0269215505CR832OA

Prochaska, E., & Ammenwerth, E. (2023a). Digital Box and Block Test for hand dexterity measurement: Instrument Validation Study. *JMIR Rehabil Assist Technol*. https://doi.org/10.2196/50474

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

Prochaska, E., & Ammenwerth, E. (2024). Clinical Utility and Usability of the digital Box and Block Test: Mixed Methods Study. *JMIR Rehabil Assist Technol SUMITTED*, 1–19. https://doi.org/10.2196/preprints.54939

Raj, S. A., Muthukumaran, E., & Jayakrishna, K. (2018). A Case Study of 3D Printed PLA and Its Mechanical Properties. *Materials Today: Proceedings*, *5*(5), 11219–11226. https://doi.org/10.1016/J.MATPR.2018.01.146

Schädler, S., Kool, J., Lüthi, H., Marks, D., Oesch, P., Pfeffer, A., & Wirz, M. (2006). *Assessments in der Neurorehabilitation*. Fisio Aktive. https://igptr.ch/wp-content/uploads/2019/03/Fa_Schaedler_fisio05_06.pdf

Schönherr, G., Brugnara, P., Katzmayr, P., Eyl, M. L., Stricker, L., Saria, I. L., Wanner, M., & Hanel, T. (2018). *Empfehlungen Neurorehabilitation nach Schlaganfall. Integrierter Behandlungspfad.* Univ.-Klinik für Neurologie Innsbruck.

Schönthaler, E. (2016). Assessments. In V. Ritschl, R. Weigl, & T. Stamm (Eds.), *Wissenschaftliches Arbeiten und Schreiben. Verstehen, Anwenden, Nutzen für die Praxis* (pp. 249–266). Springer Verlag GmbH.

Swan, K., Speyer, R., Scharitzer, M., Farneti, D., Brown, T., Woisard, V., & Cordier, R. (2023). Measuring what matters in healthcare: a practical guide to psychometric principles and instrument development. *Frontiers in Psychology*, *14*(September). https://doi.org/10.3389/fpsyg.2023.1225850

Tashakkori, A., & Teddlie, C. (1998). *Mixed methodology: combining qualitative and quantitative approaches* (Vol. 46). Sage Publications Inc.

Thomas, S., Elsner, B., Scheffler, B., & Mehrholz, J. (2016). Testverfahren in der neurologischen Physio- und Ergotherapie. *Neuroreha*, *8*(2), 76–85. https://doi.org/10.1055/s-0042-105775

Tobler-Ammann, B. C., De Bruin, E. D., Fluet, M. C., Lambercy, O., De Bie, R. A., & Knols, R. H. (2016). Concurrent validity and test-retest reliability of the Virtual Peg Insertion Test to quantify upper limb function in patients with chronic stroke. *J Neuroeng Rehabil*, *13*(8). https://doi.org/10.1186/S12984-016-0116-Y

Tong, A., Sainsbury, P., & Craig, J. (2007). Consolidated criteria for reporting qualitative research (COREQ): a 32-item checklist for interviews and focus groups.

Int J Qual Health Care, *19*(6), 349–357. https://doi.org/10.1093/INTQHC/MZM042

VDI. (2019). *VDI 2221 Part 1:2019-11: Design of technical products and systems. Model of product design.* https://www.ressource-deutschland.de/fileadmin/user_upload/downloads/leitfaden-ressourceneffizienz/Konstruktionsmethodik.pdf

Xydas, E. G., & Louca, L. S. (2008). Identification of kinematic traits in 3D reaching Tasks with the use of a haptic Nine-Hole Peg-Board Test: Comparison between healthy people and people with Multiple Sclerosis. *Proceedings of the 2nd Biennial IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, BioRob 2008*, 948–955. https://doi.org/10.1109/BIOROB.2008.4762889

Zhang, Y., Chen, Y., Yu, H., Lv, Z., Shang, P., Ouyang, Y., Yang, X., & Lu, W. (2019). Wearable sensors based automatic box and block test system. *2019 IEEE SmartWorld, Ubiquitous Intelligence and Computing, Advanced and Trusted Computing, Scalable Computing and Communications, Internet of People and Smart City Innovation, SmartWorld/UIC/ATC/SCALCOM/IOP/SCI 2019*, 952–959. https://doi.org/10.1109/SMARTWORLD-UIC-ATC-SCALCOM-IOP-SCI.2019.00189

APPENDIX

Box and Blocks Test Instructions

General Information (Mathiowetz, Volland, et al., 1985):

- The patient is allowed a 15-second trial period prior to testing
- Immediately before testing begins, the patient should place his/her hands on the sides of the box
- When testing begins, the patient should grasp one block at a time with the dominant hand, transport the block over the partition, and release it into the opposite compartment
- The patient should continue doing this for one minute
- The procedure should then be repeated with the nondominant hand
- After testing, the examiner should count the blocks
- If a patient transports two or more blocks at the same time, this should be noted and the number subtracted from the total
- No penalty should be made if the subjects transported any blocks across the partition and the blocks bounced from the box to the floor or table

Set-up for Box and Block Test:

- A test box with 150 blocks and a partition in the middle is placed lengthwise along the edge of a standard-height table
- The patient should be seated on a standard height chair facing the box
- 150 blocks should be in the compartment of the test box on the side of the patient's dominant hand
- The examiner should face the patient so she or he could view the blocks being transported

Patient Instructions (Mathiowetz, Volland, et al., 1985):

"I want to see how quickly you can pick up one block at a time with your right (or left) hand [point to the hand]. Carry it to the other side of the box and drop it. Make sure your fingertips cross the partition. Watch me while I show you how."

Transport three cubes over the partition in the same direction you want the patient to move them. After a demonstration say the following:

"If you pick up two blocks at a time, they will count as one. If you drop one on the floor or table after you have carried it across, it will still be counted, so do not waste time picking it up. If you toss the blocks without your fingertips crossing the partition, they will not be counted. Before you start, you will have a chance to practice for 15 seconds. Do you have any questions?"

"Place your hands on the sides of the box. When it is time to start, I will say ready and then go."

Trial period: Start the stop watch at the word go. When 15 seconds has passed, say "stop." If mistakes are made during the practice period, correct them before the actual testing begins.

On completion of the practice period, transport the cubes to the original compartment.

Continued with the following directions:

"This will be the actual test. The instructions are the same. Work as quickly as you can. Ready." [Wait 3 seconds]

"Go."

"Stop." [After 1 minute, count the blocks and record as described above]

"Now you are to do the same thing with your left (or right) hand. First you can practice. Put your hands on the sides of the box as before. Pick up one block at a time with your hand, and drop it on the other side of the box."

"Ready." [Wait 3 seconds]

"Go."

"Stop." [After 15 seconds]

Return the transported blocks to the compartment as described above.

"This will be the actual test. The instructions are the same. Work as quickly as you can."
"Ready." [Wait 3 seconds]
"Go."
"Stop." [After 1 minute, count the blocks and record as described above]

Scoring:

The score is the number of blocks carried from one compartment to the other in one minute. Score each hand separately.

Nine Hole Peg Test Instructions

General Information (Mathiowetz, Weber, et al., 1985):

- The Nine Hole Peg Test should be conducted with the dominant arm first.
- One practice trial (per arm) should be provided prior to timing the test.
- Timing should be performed with a stopwatch and recorded in seconds.
- The stop watch is started when the patient touches the first peg.
- The stop watch is stopped when the patient places the last peg in the container.

Set-up of Nine Hole Peg Test:

- A square board with 9 holes, o holes are spaced 3.2 cm (1.25 inches) apart o each hole is 1.3 cm (.5 inches) deep
- 9 wooden pegs should be .64 cm (.25 inches) in diameter and 3.2 cm (1.25 inches) long
- A container that is constructed from .7 cm (.25 inches) of plywood, sides are attached (13 cm x 13 cm) using nails and glue
- The peg board should have a mechanism to decrease slippage. Self-adhesive bathtub appliqués were used in the study.
- The pegboard should be placed in front of the patient, with the container holding the pegs on the side of the dominant hand.

Patient Instructions:

The instructions should be provided while the activity is demonstrated. The patient's dominant arm is tested first. Instruct the patient to:

"Pick up the pegs one at a time, using your right (or left) hand only and put them into the holes in any order until the holes are all filled. Then remove the pegs one at a time and return them to the container. Stabilize the peg board with your left (or right) hand. This is a practice test. See how fast you can put all the pegs in and take them out again. Are you ready? Go!"

After the patient performs the practice trial, instruct the patient: o "This will be the actual test. The instructions are the same. Work as quickly as you can. Are you ready? Go!" (Start the stop watch when the patient touches the first peg.) While the patient is performing the test say "Faster" When the patient places the last peg on the board, instruct the patient "Out again…faster." Stop the stop watch when the last peg hits the container.

Place the container on the opposite side of the pegboard and repeat the instructions with the non-dominant hand.

Scoring:

The score is the number of seconds to complete the task. Score each hand separately.