

Application and adaptation of the Virtual Eggs Test for assessing hand dexterity in subjects with stroke: a pilot study

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ABSTRACT

Objectives: To verify the feasibility of the Virtual Eggs Test (VET) and establish the ranges of fragilities of the Virtual Eggs (VEs) for assessing dexterity of stroke subjects and to collect feedback to improve its usability.

Methods: An observational non-profit study, with a pre-market medical device. It was conducted at a hospital neurorehabilitation unit. Nine subjects with chronic stroke (5 males; mean age 55.8 ± 18.9) performed the pilot with their paretic arm. Time to complete the test (TT), the number of failures for each VE, the threshold (T), and participants' self-reported comfort in performing the test were measured.

Results: The T varied among participants from 1.70 to 4.88 N/N. The average TT was 20.1 ± 6.5 minutes (range 11-33). Only one subject found the test uncomfortable.

Conclusions: The study found that the VET, with minor modifications, is feasible in stroke subjects. It might be useful for assessing sensorimotor impairment in both the affected and the less affected arm. Its metric properties and normative values in the healthy population will be determined in a study currently underway.

Keywords: Movement, Stroke, Technology, Upper extremity

What is already known about this topic:

- Currently, there are many assessment instruments for hand dexterity in stroke subjects; these tests assess the motor capacity of the hand, but do not assess sensory and motor capacity simultaneously.

What does the study add:

- The Virtual Egg Test application could significantly enhance the evaluation of sensorimotor impairments, potentially leading to better-targeted rehabilitation strategies and improved outcomes for individuals affected by stroke.

Introduction

Stroke is a major challenge, causing disability across all age groups and significantly impacting quality of life and the healthcare system (1). It affects over 80 million people worldwide, with about 13.5 million new strokes each year (2). The high prevalence of stroke represents an important economic and social as well as ethical concern (3). The degree

of autonomy of basic (BADLs) and instrumental (IADLs) activities of daily life (ADLs) is a key outcome measure to verify the evolution of recovery over time and the effectiveness of different treatments (4). The extent of disability resulting from the acute event can vary greatly based on the severity and site of injury. In severe cases, sensory and motor functions may be entirely or nearly lost, resulting in a complete or nearly complete loss of motor skills and sensory perception. Motor impairments in persons with stroke include poor voluntary control of movements, poor coordination, and poor muscle strength (5). This is often accompanied by impairment of tactile and proprioceptive perception, further impacting the ability to manipulate objects and perform precise movements (6).

Sensory information is crucial for movement control. The cerebellum utilizes internal models to generate corrective motor commands based on discrepancies between actual and

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predicted sensory inputs from a copy of the motor command sent to the muscles to trigger these corrective actions (7,8). Specifically, according to the Discrete Event-driven Sensory feedback Control (DESC) theory, sensory inputs related to the salient discrete mechanical events of manipulation (i.e., contact, lifting, leaning, and release) are used in the central nervous system to define the beginning and end of the phases of manipulation (9). Each of these phases corresponds to a subgoal of the overall action of grasping objects, for which grasping forces and their timing must be optimized (9-12).

Studies on grip force control carried out on stroke survivors (13,14) show that, following a stroke event, grip force control is impaired. In fact, the force exerted is excessive compared to healthy controls; moreover, the grip force exerted by the hand most affected by the consequences of the stroke (contralesional hand) shows a higher variance than the hand less affected (ipsilesional). This may also arise from sensory impairments because intact sensory functions are essential for the modulation of grip strength based on the manipulated object (15).

During many activities in daily life, force must be adjusted according to the weight and fragility of the object being manipulated, and this adjustment requires a complex interaction between sensory information and motor output. The integration of force and position sensory signals allows the central nervous system to deal with the uncertainty of these signals: when grasping fragile objects, force and finger position are correlated, but interactions with rigid objects result in smaller changes in position and larger changes in force than interactions with fragile objects (16). Furthermore, when moving an object, the gripping force must be modulated in parallel with the movement-induced fluctuations of the inertial load, and intact sensory feedback seems necessary for accurate force scaling. In fact, it has been demonstrated that subjects with chronic sensory loss (17) or acute, drug-induced anesthesia (18,19), while being able to anticipate changes in load forces, employ inefficiently high grip forces compared to controls, thus showing an alteration in grip force regulation according to inertial loads. This sensorimotor integration was also found to be impaired in stroke survivors, who frequently show excessive grip forces (6,20).

To evaluate upper arm and hand dexterity, several tests have been developed and validated over the years, such as the Box and Block Test (BBT) (21), the Nine Hole Peg Test (9HPT) (22), the Minnesota Dexterity Test (MDT) (23), the Functional Dexterity Test (24), and the Action Research Arm Test (25). These tests require prehension, manipulation, and/or moving from one point to another of objects, in some cases of varying shapes and sizes, and provide a score linked primarily to the success of the performance and the time required to complete the test. None of them examines the kinematics (trajectory and smoothness of the movement performed) and kinetics (force of prehension) of the action, which may be used to assess the sensorimotor integration. An exception is the use of complex motion analysis systems, inertial sensors (26,27), or robotic devices (28) are required, which are not generally available in clinical practice. However, such an assessment could provide valuable insights into the sensory-motor function of the hand and might also be valuable in detecting subtle sensory-motor impairments

on the less affected side. In fact, though the cerebral lesion affects mostly the contralateral side, some ipsilateral deficits can also be demonstrated in both the acute and the chronic phase post-stroke (29-31).

Researchers of the Scuola Superiore Sant'Anna, Pisa, developed a test that assesses both the fine regulation of grip strength that is needed when manipulating fragile objects and gross dexterity. The test, named Virtual Eggs Test (VET), was originally designed for the assessment of grip strength control in myoelectric prosthesis wearers and consists of picking from a platform, transporting, and replacing objects of different fragility, named Virtual Eggs (VEs) (32,33). VEs are small, roughly cubic-shaped objects, equipped inside with two magnets, so that their facing walls collapse, simulating breaking, when the force of prehension exerted on them exceeds the magnetic force of attraction. Failure occurs with a relative displacement of the gripping walls of the device. The test uses 20 VEs, characterized by a progressively lower force of attraction and therefore progressively more "fragile." The task required in the VET is on the whole similar to that required in the Box and Block Test (even the object manipulated is quite similar in shape and size), with the important difference that the subject must not only be able to grasp and transport from one point to another a small object, but also to regulate the grasping force, which must progressively decrease by manipulating increasingly fragile VEs. In this way, it is possible to assess the ability to fine-tune the force without having to use complex and expensive instrumentation required to measure the grip force exerted.

The VET has been widely used to evaluate the effectiveness of sensory feedback in myoelectric hands (32,34-36), and data on healthy populations have also been collected (37). The aim of this pilot study was to collect insights for the adaptation of the VET in chronic stroke survivors, test its feasibility, and provide information about the VEs' range of fragility for this specific population.

Methods

Study design and setting

This study was an observational, non-profit study, with a pre-market medical device. It was conducted at a hospital neurorehabilitation unit. The study received approval from the local Ethics Committee on 16/03/2023 under the number 23327_spe.

The protocol was developed as part of the Fit for Medical Robotics project (Fit4MedRob, National Plan for Complementary Investments to the National Recovery and Resilience Plan—Legislative Decree no. 59, May 6, 2021, converted with amendments by Law no.101, July 1, 2021—Research Initiatives for Innovative Technologies and Pathways in Health and Care) which aspires to supplement current rehabilitation and care models for individuals of all ages with motor, sensory or cognitive impairments, from hospital to home care, by means of new robotic and digital technologies.

The protocol of the study comprises the following steps:

- Perform a modified procedure of the VET, dubbed the pilot, with the aim of identifying the values of the VEs to be used for assessing post-stroke subjects.

- Assess the comfort during the execution of the test. The participant was asked to answer the question “How comfortable was it for you to perform the task?” on a Likert scale between 0 (i.e., very uncomfortable) and 7 (very comfortable).

The complete description of the VET, the assessment protocol, and the adaptations implemented to assess hand dexterity in stroke survivors is provided in the Supplementary material.

Participants

Participants were selected among patients referred to the hospital neurorehabilitation unit, based on the following inclusion criteria:

- Age > 18.
- First ischemic or hemorrhagic stroke occurred for 6 months; sufficient motor skills to perform the test (score ≥ 19 on the Motricity Index item “Pinch Grip” and total Motricity Index score at the paretic upper extremity ≥ 57 (38).
- Willingness to participate in the study and sign the consent form.

Participants were excluded in case of:

- Severe wrist and hand hypertension (modified Ashworth Scale > 3) (39).
- severe visual and oculomotor deficits.
- Cognitive deficits that impede comprehension of the task, as evidenced by A Mini-Mental State Examination (MMSE) score < 25.
- Other neurological or musculoskeletal pathologies that impact upper limb function and clinical instability.
- Psychiatric comorbidities.
- A lack of understanding of the Italian language.

Procedure

All participants performed the VET only once with their paretic arm, following the protocol described above. The test

was conducted in an isolated room without distractions. The examiner recorded the total time required to complete the test, including the time required to instruct the participant and the trials required for the participant to become familiar with the task.

The test ended after the completion of fifteen trials. At the end of the test, participants were asked to answer this question: “How comfortable was it for you to perform the task?,” choosing from a 7 points Likert-type scale from -3 to 3, where: 0 = neither comfortable nor uncomfortable; -3/3 = very uncomfortable/comfortable; -2/2 = uncomfortable/comfortable; -1/1 = somewhat uncomfortable/comfortable.

Moreover, the raters were asked to rate the difficulty in understanding the instructions by participants and their comfort in performing the test, using a Likert scale as above. They were also asked to indicate any critical issues they encountered.

Data analysis

The main aim of the pilot is to derive the set of values of the VE for the study with post-stroke survivors. For this reason, we computed the average of failures across the nine subjects for each VE transported. In addition, we derived the threshold at which stroke survivors fail to carry the object correctly. This was retrieved by applying the up/down method. The threshold (T) is calculated as the average of the values of the stimuli of the least four trials, which are typically reversals from a trial with a more fragile VE (failed) to a trial with a less fragile VE (successful), or vice versa. The threshold limit is converged after a certain number of trials (15 trials in the present study).

Results

Characteristics of the participants

Nine subjects (five males and four females, average age 55.8 ± 18.9 , range 29-81; distance from stroke 6-52 months) were consecutively screened for eligibility and were enrolled after signing the informed consent. Their demographic and clinical characteristics are shown in Table 1.

TABLE 1 - Characteristics of participants

ID	Age	TSS (months)	Paretic side	Dominant side	Stroke type	MI Upper Limb	MI pinch	MMSE
ID1	59	52	L	R	ischemic	60	26	28
ID2	42	22	R	R	ischemic	66	26	29
ID3	32	6	R	R	ischemic	66	22	28
ID4	76	10	R	R	ischemic	85	26	26
ID5	54	24	L	R	ischemic	61	22	27
ID6	29	23	L	L	ischemic	92	33	27
ID7	81	17	R	R	ischemic	92	33	22
ID8	55	21	R	R	ischemic	85	26	30
ID9	74	51	R	R	ischemic	92	33	29

ID = Participant's Identification number; TSS = Time since stroke (months); MI = Motricity Index; MMSE = Mini-Mental State Examination.

Test results

The VEs within the range 10.98-28.05 were broken by 1 time out of 5 transports by 50% of the participants. This means that the analysis of the VE with thresholds ≥ 10.98 might not provide additional information about the participant in terms of gross dexterity.

The threshold varied among participants from 1.70 to 4.88 N/N (mean $T = 3.22 \pm 1.26$ N/N) (Figure 1-Figure 2), and the time needed to complete the test ranged from 11 to 33 minutes (mean 20.1 ± 6.5). Data from each participant are reported in Table 2.

TABLE 2 - Threshold measured in each participant

	T (N/N)	Time
ID01	1.95	33
ID02	4.75	18
ID03	2.19	11
ID04	2.19	19
ID05	4.27	28
ID06	4.88	18
ID07	3.96	19
ID08	1.70	18
ID09	3.14	17

ID = identification number; T = threshold; VE = Virtual Egg; Time = Time of administration in minutes

Times of VET phases

The analysis of the duration of different VET phases showed very inconsistent results with several artifacts, which were most often due to uncertainties by the participant in grasping and releasing the VE during the test. Therefore, no results regarding VET phase times are reported.

Results of the comfort of use questionnaire by participants and the feasibility questionnaire by evaluators

The results of the comfort questionnaire by participants show that the task was rated favorably by most participants (Table 3).

According to the feedback of the evaluators, the participants were able to easily understand the execution instructions, except for one subject who reported some difficulty (Table 3). The evaluators found the test quite feasible, but identified one critical issue: the difficulty in detecting whether the most fragile VEs were broken during the test. The breakage was easily perceived when the trial was conducted with VEs with a higher breakage threshold, because in this case, an easily distinguishable noise was produced. With the more fragile VEs, on the other hand, the noise was almost imperceptible, and the examiner had to carefully look at the VE throughout the test.

Discussion

This study suggests the feasibility of the VET protocol in a population of stroke survivors. The assessment setting was rated as very comfortable or comfortable by all participants except one subject. In addition, the time required to complete the test was relatively short, although significantly longer than that required by classical dexterity tests such as the BBT and 9HPT. For both tests, no conclusive data on the administration time is available, but it has been estimated that both can be completed in about 5 minutes (21,40). We think that the additional time required to complete the VET would be quite acceptable, provided that the information about the ability of grip strength tuning is proved to be relevant in the assessment of upper limb functioning in stroke survivors. This deals with the validity of the VET, which will be addressed, along with reliability, in a future study. However, we decided to make minor modifications in the test protocol to reduce the administration time and the fatigue of participants, as explained below.

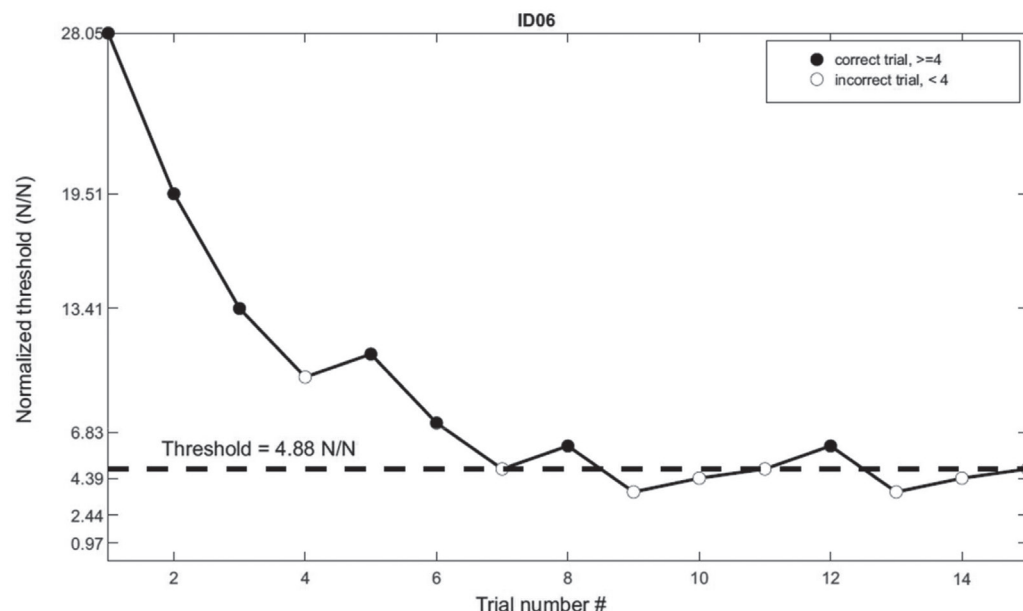


FIGURE 1 - Pilot result of the subject (ID06) with the highest (4.88 N/N) threshold.

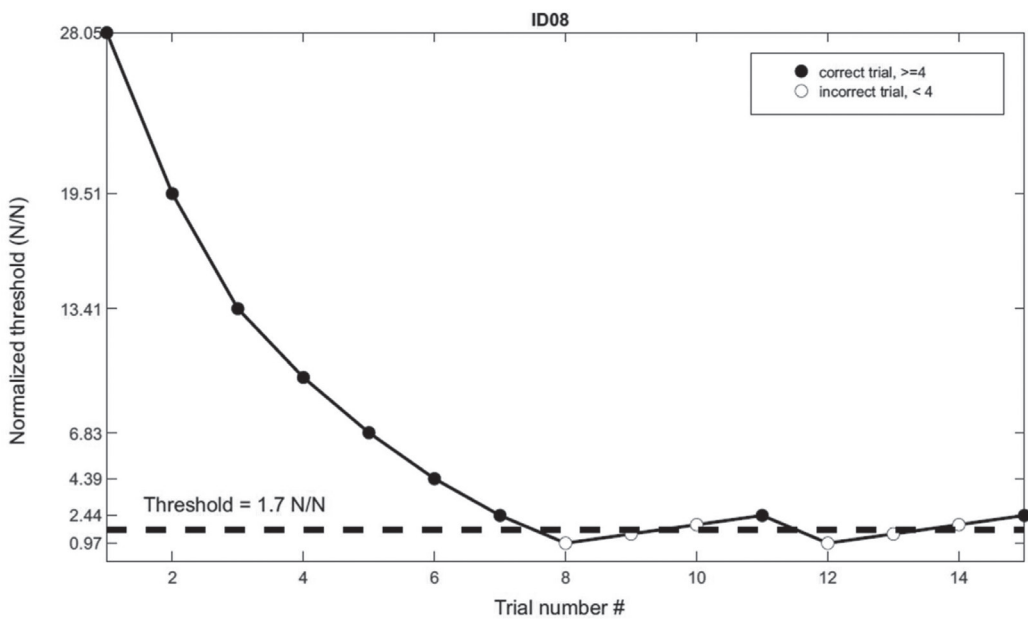


FIGURE 2 - Pilot result of the subject (ID08) with the lower (1.70 N/N) threshold.

TABLE 3 - Questionnaire results

	Occurrence						
Likert Scale	-3	-2	-1	0	1	2	3
Question							
Comfort questionnaire by participants:							
How comfortable was it for you to perform the task?		1		1	3	1	3
Feasibility questionnaire by evaluators:							
How difficult was it for the participants to understand the instructions?		1					8
How comfortable were the participants in performing the test?					2	3	4

Currently, apart from assessments that require complex robotic or computerized devices, the subject's ability to control grip strength may be evaluated by means of the Strength Dexterity Test (SDT) (41). This test, which also takes longer than classical dexterity tests, measures the ability to fully compress by a lateral pinch a set of springs with plastic end caps without buckling; the mechanical properties of slender springs are used to quantify the subject's ability to dynamically control fingertip forces. The SDT, however, assesses the ability to finely control the direction of the force exerted between the two fingers as the required force increases, rather than the amount of force that must be exerted to manipulate objects of varying fragility. Furthermore, this ability is assessed by the SDT in a relatively static condition, without involvement of other joints of the upper limb. In contrast, most manipulation tasks require close coordination between the activation of proximal and distal muscles, so that the grip force must be adjusted during a simultaneous variable activation of other muscle groups. From this point of view, the VET most closely resembles the common manipulative tasks of everyday life.

Preliminary data on the application of the VET in a healthy population showed that the average threshold for these subjects is less than 2 (37), whereas the average threshold for stroke survivors presented in our pilot study is 3.7, with high variability among participants. Such variability in the performance of stroke survivors was expected, since the severity of motor impairment largely varies among these patients. This result suggests that the VET can discriminate between healthy subjects and stroke survivors, but this finding needs to be confirmed in a future study with adequate sample sizes. It also appears necessary to verify the reliability of the test and to collect normative data in the healthy population.

The VET might have a promising role in the clinical assessment of subtle motor deficits in the limb ipsilateral to brain injury, which should be referred to the less affected, rather than the healthy, side (42). A relatively recent study (43) compared the performance in a forward reaching task of individuals with stroke outcomes, age, and gender-matched healthy controls, collecting kinematic data by means of an optoelectronic motion analysis system. Subjects with stroke were assessed both in the acute and the subacute phase. The



authors found a consistently worse performance of stroke participants who showed reduced smoothness of movements, range of motion, and power. These deficits were more pronounced in the acute phase and in subjects with greater motor deficits on the affected side. Some data have also been published on the ability of classical dexterity tests, such as the MDT and the Purdue Pegboard Test (30) and the 9HPT (44), to detect motor deficit in the ipsilateral side of stroke subjects, but the differences compared to healthy controls were minimal, although significant. For example, Son et al. (44) found that stroke participants took on average 2 seconds more than healthy individuals to complete the 9HPT. Moreover, data were collected in very limited samples (27-30 participants with stroke outcomes). The VET promises to be a simple, more sensitive clinical tool that can detect motor deficits in the less affected side after stroke since it includes both quantitative (time to complete the task) and qualitative (ability to finely control grip strength) measures.

Based on the results of the pilot, the set VEs should have a range of thresholds between 1 and 10.5 (N/N) to increase the accuracy of the outcome. The execution of the pilot was based on an up/down procedure, and this can be exploited as the revision of the original protocol of the VET (37) to minimize the time required to execute the test.

The answers to the questionnaires did not reveal any issues in performing the VET by the enrolled subjects. However, the addition of visual feedback for the VEs with lower break thresholds might increase the detection of the failure. This was also reported by the raters in a study involving amputees (37).

This study has some limitations. First, although calculating the threshold as the mean of a number of reversals is a widely used method in psychophysics (45), in the present study, the limited number of reversals may have led to an inaccurate threshold estimate for some participants. In future studies with the VET, we aim to replace the current criterion for the termination of the test (15 trials completed) with the criterion of having reached five reversals, and to calculate the threshold as the mean of all such reversals. Moreover, the software couldn't accurately measure VET phase durations for all participants, especially when tremor caused uncertainty in grasping or releasing the VE. To solve this problem, the software will be modified to calculate lifting times (initial grasp to complete VE lifting) and releasing times (initial VE contact with the platform to full release), and thus have more accurate and detailed information on the timing of the different phases. Conceivably, these additional metrics would improve phase discrimination and provide valuable insights into the hand dexterity of stroke survivors. An intrinsic limitation of the VET, in fact, is the impossibility of measuring the movement kinematics, for which different and more expensive instrumentation would be required. However, the time needed to grasp and transfer the VE, if accurately measured, could be an important parameter for quantifying both gross and fine hand dexterity. When handling the first, 'stronger' VEs, the difficulty in fine-tuning the grip forces recedes into the background, and the subject can concentrate on the speed of the movement. Conversely, as the breaking threshold decreases, acceleration must be minimized, since the

greater the acceleration, the greater the force that must be exerted to compensate for inertial load, thus increasing the risk of "breaking" the VE.

In conclusion, we believe the VET is a promising tool for evaluating hand dexterity in stroke survivors, even if some modifications can be implemented to increase its potential. A new study will be carried out with the aim of verifying the reliability and validity of VET in stroke survivors on both the paretic and the less affected limb and identifying normative data for the healthy population.

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Conflict of interest: The authors declare no conflict of interest

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