Assessing Hand Function in Trans-Radial Amputees Wearing Myoelectric Hands: The Virtual Eggs Test (VET)

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***Abstract*—The evaluation of hand function is of great importance to both clinical practice and biomedical research and is frequently evaluated by manual dexterity. Most of the assessment procedures evaluate the gross or the fine dexterity of the hand, but few of them are devoted to the assessment of both. We developed the Virtual Eggs Test (VET): it resembles the task of transporting fragile and robust objects, thus requiring both gross and fine dexterity. The test is composed of 11 Virtual Eggs that collapse if the grasping force exceeds their breaking thresholds, ranging from 0.4 N to 11.5 N. The test aims to transport each Virtual Egg over the barrier in the centre of the test platform without breaking it and as fast as possible. The metrics measured during the test are combined and provide two indexes that evaluate, respectively, gross and fine dexterity. We verify the concurrent validity and the construct validity of the VET with a target population of 30 trans-radial amputees wearing a myoelectric hand and the test-retest reliability on a control population of 35 healthy individuals. The results suggest the ability of the VET to assess hand function specifically in handling breakable objects, using both gross and fine dexterity over time. However, further research is needed to verify its correlation with other tests and the ability of amputees to perform activities of daily living.**

***Index Terms*—Hand evaluation, hand, motor skills, occupational therapy, myoelectric prosthesis.**

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I. Introduction

ASSESMENT tools are essential to provide the occupational therapist or investigator with relevant information regarding the patient's status, the effectiveness of the treatment program, and the assistive technology prescribed or developed [1], [2], [3], [4]. Tests can be self-reported or performance-based. In self-reported tests, patients are asked to directly judge their behaviour, attitudes, or intentions. Performance-based tests instead are quantitative evaluations of task-related variables [5]. Tests must be reproducible, sensitive to change of the patient status, and less vulnerable to external influences such as cognition, culture, language, and education. Measuring hand functionality for those who have lost their upper limbs is becoming increasingly important for instance. When done methodically, outcome measurements can be used to monitor function and prosthetic satisfaction, evaluate the success of a given treatment, and support the expense of prosthetic devices and rehabilitation services [4]. Given the necessity for lifetime prosthetic care, the need to defend the high prices of prosthetic equipment, and typical insurance constraints on prosthetic coverage, outcome evaluation for people with amputation is particularly crucial [3]. Among the hand evaluation tests, there is particular attention on measuring manual dexterity, that is the ability to coordinate the movements of the hand and fingers to grasp and manipulate objects [6], [7]. There are two types of manual dexterity: gross and fine [8]. Gross dexterity involves the manipulation of large objects and includes the movement of the whole upper limb(s) with little precision. In contrast, fine dexterity entails precise motions associated with controlling small objects using the distal parts of the digits (usually thumb and index) and is characterized by high eye-hand coordination [9]. Several tests measure manual dexterity; however, they evaluate either gross or fine dexterity, not both together, limiting their practicality in clinical settings. Most of them measure gross dexterity, for example, the Box and Block Test (BBT) [10], or the Minnesota Manual Dexterity Test (MMDT) [11], which are both performance-based tests. The BBT measures the number of blocks transferred in 1 minute, regardless of the quality of movement [12]. In the MMDT the participant picks up and places 60 disks in a specific sequence, while standing. The trial is repeated three times, and the output is the cumulative time [13]. Another example is the ABILHAND questionnaire which, instead, is a self-reported test [14]. The questionnaire covers 23 daily activities for which the participants judge their ease or difficulty in performing them (0 = impossible, 1 = difficult, 2 = easy), without further qualitative indication on their execution. The output is the sum of the scores. These tests are widely used for assessing upper limb prosthetic components [15], [19]. Only a few tests assess the fine dexterity, such as the Dexterity Test Strength (S-D) [20] or the Nine Hole Peg Test (NHPT) [21]. The S-D is based on the participant's ability to stabilize compression springs of different stiffness/slenderness by coordinating the ab/adduction and flexion of the digits. However, it is unpractical for assessing off-the-shelf hand prostheses due to the lack of continuous control of the ab/adduction degree of freedom in such devices. In the NHPT, the participant is required to precisely orientate the prosthesis during the insertion of the pegs, although no modulation of the grip force is necessary except for that required to stabilize the peg. This test is widely used clinically [16], [19], [22], albeit it lacks a standard [3].

In this study, we sought to evaluate both gross and fine dexterity of the hand function, in amputees wearing a myoelectric hand. To this aim, we designed the Virtual Eggs Test (VET) which resembles the task of transporting breakable objects (with increasing fragility), and is, to the best of our knowledge, the only test uniquely capable of simultaneously assessing both aspects. Here we propose, for the first time, an attempt to validate the VET. The manipulation of fragile items is a daily task that requires complex motor skill relying on tactile feedback [23] and the coordination of grip and load force [24]. The thorough investigation of the performance in manipulation fragile object required sophisticated setup integrating multiple load cells and motion capture system as done in [24]. While insightful, the object's weight (>0.7 kg), along with the setup's high cost and complexity, make it impractical for clinical assessments of hand dexterity in rehabilitation settings. In contrast, the VET proposed here comprises eleven Virtual Eggs (VEs), each of them collapses for different grasping forces. This challenges the participant in manipulating both fragile and robust items, thus requiring employing different manipulation skills. We were inspired by the work of Meek and colleagues [25] and by the experience gained in assessing different sensory feedback strategies in amputees [26], [27], [28], [29]. The outcome measures of the VET are two indexes computed combining the number of broken VEs and the transport times. One evaluates the fine dexterity (Fine Dexterity Index –FDI– using fragile VEs) and one evaluates the gross dexterity (Gross Dexterity Index -GDI- using robust VEs). Aiming to validating the VET, we first examined the sensitivity to the laterality and level of amputation on a target population of 30 trans-radial amputees while using their myoelectric hand prosthesis. Concurrent validity of the proposed metrics was assessed with two validated measures of hypothesized similar constructs, namely the MMDT and ABILHAND tests [3]. Then, we tested the construct validity by verifying the ability of the VET to discriminate between the target population (myoelectric hand users) and a control population (participants without motor impairments). In addition, we correlated the outcome measures of the VET to Fragile and Robust Ranking Scores, which are two metrics based on hypotheses that were defined a priori. Finally, we assessed the stability of the measure [3], [16] (i.e. reliability of the VET over time) with a control population comprising 35 healthy individuals, by testing the property of test-retest across four trials, within a two-week interval. The FDI and GDI proved insensitive to the level of amputation and laterality, while they correlated to the Fragile and Robust Ranking Scores. We proved a moderate correlation between b and the MMDT score. The results proved that the VET discriminates, in terms of dexterity, between the amputees wearing a myoelectric hand and healthy individuals. We also verified the consistency of the measure on healthy individuals after a familiarization phase. These results suggest that the VET can be used to evaluate both the gross and the fine dexterity in amputees using a myoelectric prosthetic hand. This is particularly important for next generation protheses that will restore sensory feedback after amputation in daily life.

II. Materials and Methods

A. Participants

30 myoelectric hand users (4 female), mono-lateral trans-radial amputees, were enrolled in this study (levels of amputation: 8 distal, 8 proximal, 14 medium). 19 participants had their dominant hand amputated. The age of the participants ranged between 21 and 62 (45 years old on average). These participants carried out the experiment at the premises of the INAIL Prosthetic Center of Vigorso di Budrio (BO).

A control population of 35 participants (healthy individuals, 18 female) was also included. They were aged between 21 and 45 years. The experiment was conducted in full compliance with international legislation and its national transposition concerning clinical trials and the principles of the Declaration of Helsinki. Participants signed the informed consent and read the information sheet of the study. The study was approved by the local ethical committee of the Area Vasta Emilia Centro, Italy (approval number: 0061919).

B. Experimental Procedure

Myoelectric hand users carried out the Virtual Eggs Test (VET), the Minnesota Manual Dexterity Test (MMDT) and the ABILHAND on the same day. They also performed the VET with their contralateral arm, on the same day. The VET protocol was administered according to the protocol described in the following section. The MMDT and the ABILHAND were administered according to the standard protocols [11], [14]. These two tests were selected based on the clinical practice of the Centro Protesi INAIL, avoiding interference with the standard procedures. The control population performed the VET using the dominant hand. To assess the test-retest reliability, the VET was administered to the healthy individuals four times (trial: T1…T4), in two sessions (S1 and S2) with two consecutive trials in each session (S1: T1 and T2, S2: T3 and T4) and a two-week interval between the two sessions.

TABLE I

VIRTUAL EGGS BREAKING THRESHOLDS. BREAKING THRESHOLDS F_G IN NEWTON (N) AND CORRESPONDING NORMALIZED VALUE TO THE WEIGHT OF THE OBJECT, ø. THE FIRST 5 VIRTUAL EGGS WERE DEFINED AS FRAGILE, WHILE THE OTHERS AS ROBUST

VE number	1	2	3	4	5	6	7	8	9	10	11
F_g (N)	0.4	1	2	3	4	5	6	7	8	9	11.5
ø	0.7	1.8	3.7	5.5	7.3	9.2	11.0	12.8	14.7	16.5	21.1
Behaviour	Fragile					Robust					

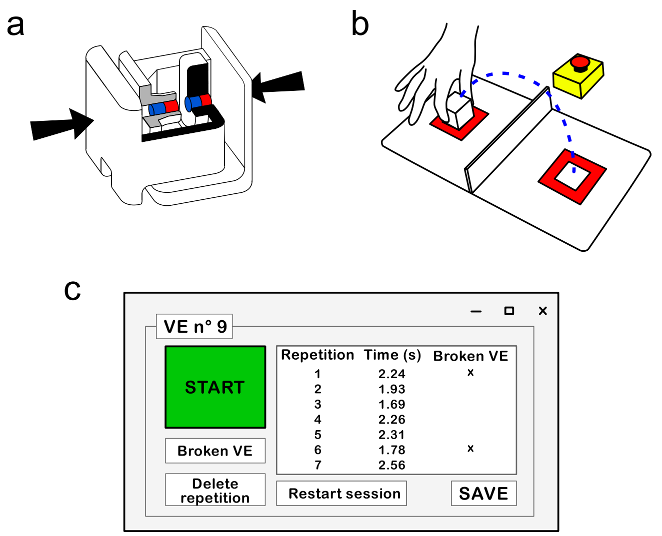

Fig. 1. Cross section view of the Virtual Egg (VE) (a), the board and transport motion of the VE (b), and the GUI interface of the Virtual Eggs Test (VET) (c).

C. The Virtual Eggs Test

1) Setup: The main component of the VET is the Virtual Egg (VE) (Fig. 1a). It is composed of two plastic parts (material: PA2200), with graspable surfaces, sliding over each other. A "reversible magnetic fuse" integrated in the device maintains a fixed distance between the two opposite graspable surfaces of the VE. When the grasp force applied on the surfaces is greater than the attraction force of the magnetic fuse, the two parts slide over each other and the object collapses (or "breaks"). The breaking thresholds can be modified by changing the characteristics of the magnets (i.e., dimension and magnetization) and/or their relative distance. The VET comprises 11 Virtual Eggs (VEs), software, a button, and a platform. The VEs are blocks that collapse if the grasping force exceeds a defined and tunable breaking threshold. Five of the VEs are considered as fragile and collapse with grasping forces ranging from 0.4 N to 4 N. The other VEs are considered robust and collapse with a force ranging from 5 N to 11.5 N (absolute and weight-normalized breaking thresholds, Ø, in Table I). The collapse force thresholds were selected to ensure a meaningful challenge to participants. These ranges were based on the experience gained on previous clinical trial [26], [27], [28], [29] and refined by means of pilot studies conducted prior to the study. While these values may not represent specific real-world fragile objects, they were selected to simulate the varying demands of handling delicate and robust items, thereby providing a controlled assessment of dexterity. The platform is made of two sides divided by an 8 cm high barrier (Fig. 1b). In each side, a red square marks the starting/arrival position for the VE. The software runs on a personal computer. It helps the examinator to collect the data during the session and creates a .txt file which includes both the transport times and the broken VE (Fig. 1c).

2) Protocol: The VET is divided into two phases. In the first one, that lasts for a maximum of 4 minutes, the participant familiarises with all the VEs by grasping them as to understand when they collapse. In the second phase, the participant is asked to grasp with a pinch grip and transport each of the 11 Virtual Eggs (VEs) from one side to the other of the platform for seven times. To account for the effect of the dominant hand, we balanced the two movement directions. In the first repetition, the participant starts on the dominant-hand side and moves the block to the opposite side of the barrier. In the second repetition, the direction reverses, moving from the non-dominant side back to the dominant side. This alternating pattern continues until a total of seven repetitions are completed. The procedure starts with the most robust VE (VE #11) and ends with the most fragile (VE #1). Before starting the test, the participant is allowed to re-familiarize with the fragility of each new VE, by manipulating and breaking it on purpose (phase 1 in Fig. 2). For each of the seven repetitions, the participant, using the tested hand (the prosthesis and contralateral hand for the target group, or the dominant hand for the control population), presses the button to start the timer, transports the VE (from one side to the other) and presses again the button to stop the timer (phase 2 in Fig. 2). The software records the duration for each repetition. The examinator takes note of the occurrences of broken VEs using the GUI and supervises the execution.

3) Metrics: Two indexes were identified for assessing the participant performance: the Fine Dexterity Index (FDI) and the Gross Dexterity Index (GDI). These indexes were computed starting from the best transport time for each VE and features extracted from the Weibull psychometric function fitting the probability of successfully transporting the VEs, p.

More in detail, for each participant, the probability p of successfully transporting the VEs, is calculated across the seven repetitions, for each different VE ($0 \leq p(\o) \leq 1$). We chose to describe the fragility of the VE using the breaking force normalized to its weight, assuming that manipulation difficulty (for a given coefficient of friction) depends on this parameter. p is then fitted using a Weibull psychometric function [30], [31], [32] (guessing rate γ and slope β being fixed at 0 and 2 respectively). From this function, two outcome measures of the VET, Λ and α are extracted. Λ is the upper asymptote of the psychometric fitting, depends on the ability of transporting robust VEs (the higher the better), and corresponds to 1-λ, where λ is the lapse rate of the Weibull

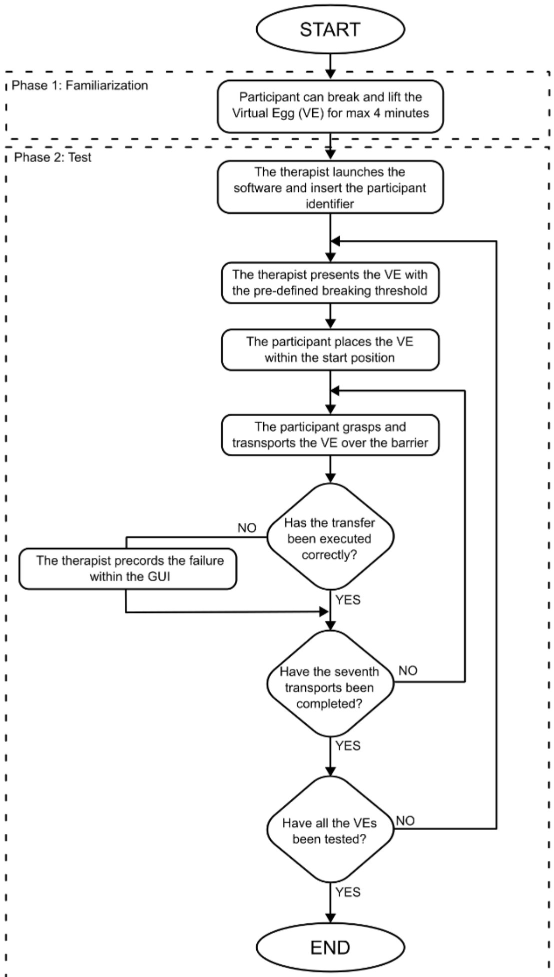

Fig. 2. Flow chart describing the protocol of execution of the Virtual Eggs Test (VET).

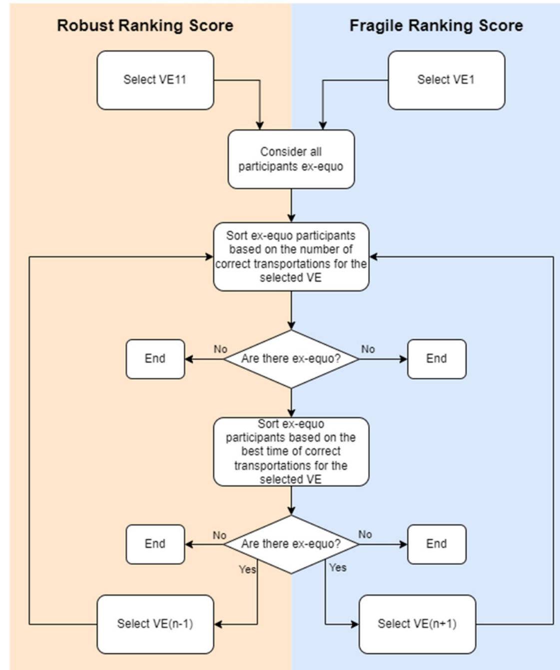

Fig. 3. Method for assigning the Robust and Fragile Ranking Scores based on the performances of the participant in successfully transfer the Virtual Eggs.

psychometric function [31], [32] ($0 \le \Lambda \le 1$). α is the value of the abscissa at 63% of Λ. It depends on the performance of the participant in transporting fragile VEs (the lower the better). α coincides with the FDI (Fine Dexterity Index):

$$FDI = \alpha. \tag{1}$$

For each participant, the best time t for successfully transporting the VEs, is extracted across the seven repetitions, for each different VE. The mean across the t of the robust VEs defines the outcome measure b (the lower the b, the better ability in transporting the robust VEs).

The GDI (Gross Dexterity Index) combines the measures associated to the robust VEs, b and Λ, as follows:

$$GDI = \left(1 - \frac{b}{20}\right) \times \Lambda. \tag{2}$$

GDI ranges between 0 to 1. The higher GDI, the better the gross dexterity performance both including the speed and accuracy of transports.

D. Robust and Fragile Ranking Score of Amputees

An a priori hypotheses to rank the amputees based on their proficiency in transporting the VEs was used as an additional way to assess the validity of the construct. Coherently with the requirement of the test – i.e., transport the VE first without break it and then as fast as possible – we hypothesized that the more you break the VE or the slower you move it the worst you are in term of dexterity. Following the method depicted in the flow chart in Fig. 3, we assigned to each amputee a Robust Ranking Score and a Fragile Ranking Score.

E. Statistical Analysis

Statistical analyses were performed using IBM® SPSS®. Data distributions were tested for normality using the Kolmogorov-Smirnov test, and the homogeneity of variances using the Levene test. When the data proved normally distributed (Kolmogorov-Smirnov test, $p > 0.05$), we performed a parametric test according to the output of the homogeneity test of the variance (Levene test). Otherwise, we performed a non-parametric test. The results of these tests are reported in appendix (Tables V and VI). The statistical significance of all the tests performed was defined by $p < 0.05$. Concerning the assessment of correlation, we selected Perason correlation coefficient when the data proved normally distributed, and Spearman correlation coefficient when they are not. We considered large for $p > 0.5$, moderate for $0.3 \le p \le 0.5$, and small correlation for $0.1 < p < 0.3$ as suggested by Resnik et al. [3]. First, we tested the sensitivity to the level of amputation and laterality of amputation separately. We divided the target population according to the laterality (dominant or not dominant hand) and we selected as parametric test the T-test for unpaired data. Similarly, we clustered the target population in three groups based on the level of amputation (proximal, medium, distal), we selected as parametric test the one-way ANOVA test and as non-parametric test the Kruskal-Wallis test. Then, we evaluated the characteristics of the VET according to Resnik et al. [3]. In particular, we assessed the

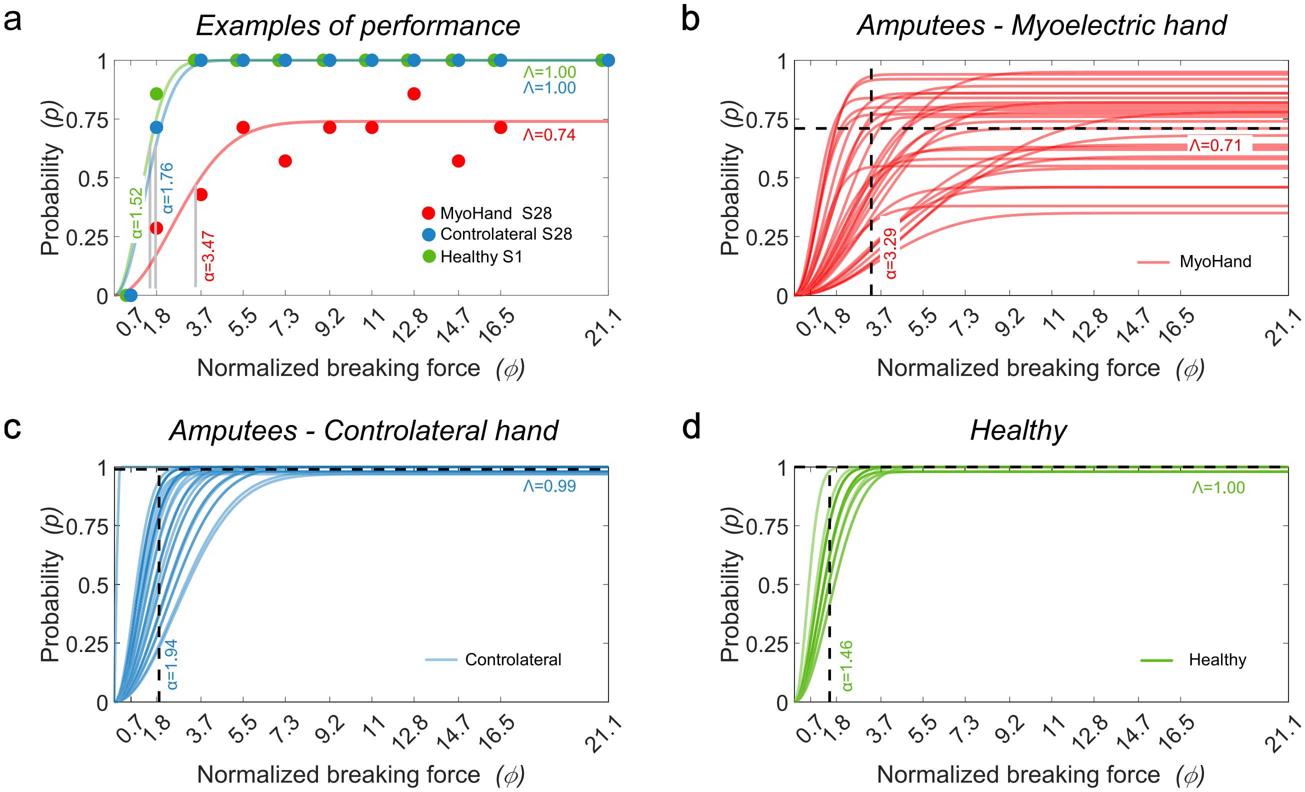

Fig. 4. Ability to transport the Virtual Egg without breaking it. The performances are plotted as probability $p(\emptyset)$ for each normalized force required to break the VEs. Examples of performance of the VET executed by a healthy participant (S1), and a participant using the prosthesis or the contralateral hand (S28), fitted using psychometric curves (a). Trans-radial amputees (30 participants) using a myoelectric hand (b), their contralateral healthy limb (30 participants) (c), and healthy participants (35 participants) using their dominant hand (d).

concurrent validity, construct validity and test-retest reliability as follows.

1) Concurrent Validity: We tested the correlation between the VET and the MDDT and ABILHAND tests (exhibiting a similar construct) on amputees while using their myoelectric hand prosthesis.

2) Construct Validity: Following the know-group method, we assessed the ability of the VET to discriminate between different groups. We compared the target population performing the VET with the prosthetic hand with the control population at T1. Also, we compared the target population performing the VET with the healthy hand, with the control population at T1. We performed as parametric test the T-test for unpaired data and as non-parametric test the U-Mann Whitney. In addition, we calculated the correlation between the results of the VET performed by the target population using the prosthetic hand with the Fragile Ranking Score and the Robust Ranking Score defined by means of the a-priori hypothesis.

3) Test-Retest Reliability: We verified the reliability of the VET on the control population performing four trials divided in two different sessions two weeks apart (S1: T1 and T2, S2: T3 and T4). We compared the first trial and the second trial of each session separately (i.e., T1 vs T3 and T2 vs T4). We selected T-test for paired data as parametric test and the Wilcoxon Signed Ranks test as non-parametric test.

III. Results

Following Resnik's et al. methodology [3], for each of the outcome measures retrieved from the VET, we analysed: (i) the mean and standard deviation or the median and interquartile range, (ii) the sensitivity to the level and laterality of the amputation, (iii) the concurrent validity by means of the correlation with other tests having the same construct, (iv) the construct validity through the ability to discriminate among the different populations and the correlation with a priori hypotheses, (v) the test-retest reliability (i.e., the consistency over time). Demographics and outcome measures of all amputees and healthy participants are reported as appendix in Table V and Table VI, respectively.

A. Probability of Correct Transports

Λ and α, extracted from the Weibull' psychometric curve fitting p for each participant, provided direct measures of the ability of successfully transporting the robust and fragile VEs, respectively (representative cases in Fig. 4a). The average Λ across the amputee population proved 0.71 using the myoelectric hand and 0.99 using the contralateral healthy hand (Table II, Fig. 4b-c). Similarly, the average α proved 3.29 using the myoelectric hand and 1.94 using the contralateral healthy hand (Table II, Fig. 4b-c). Although the performance in using the myoelectric prosthesis exhibited a large variability (Fig. 4b), both Λ and α proved insensitive to the level of amputation (ANOVA $p = 0.958$, $p = 0.331$, Table III) and laterality of amputation (T-test unpaired data $p = 0.783$, $p = 0.535$, Table III).

No correlation was found between Λ and MMDT (Pearson's correlation, $p = 0.807$) neither between Λ and ABILHAND (Pearson's correlation, $p = 0.065$). Λ proved statistically correlated with the Robust Ranking Score (Spearman's correlation $p < 0.001$, $\rho_S = -0.772$, Table IV), confirming the hypothesis

TABLE II

OUTCOME MEASURES OF THE VIRTUAL EGGS TEST (VET), THE MINNESOTA MANUAL DEXTERITY TEST (MMDT), AND THE ABILHAND QUESTIONNAIRE FOR THE DIFFERENT GROUPS AND TRIALS. NORMALLY DISTRIBUTED VARIABLES ARE REPORTED AS MEAN AND STANDARD DEVIATION; NOT NORMALLY DISTRIBUTED VARIABLES (IN BOLDFACE) ARE REPORTED AS MEDIAN AND INTERQUARTILE RANGE OF PROBABILITY DISTRIBUTION

		Myoelectric hand	Contralateral healthy hand	Healthy			
	N	30	30	35			
	Trial	T1	T1	T1	T2	T3	T4
VET	α (FDI)	3.29 ± 1.66	1.94 ± 0.81	**1.52 ± 0.26**	1.40 ± 0.22	1.46 ± 0.32	1.40 ± 0.24
	Λ	0.71 ± 0.16	0.99 ± 0.01	**1.00 ± 0.00**	**1.00 ± 0.00**	**1.00 ± 0.00**	**1.00 ± 0.00**
	b (s)	4.99 ± 1.46	2.00 ± 0.42	1.93 ± 0.39	1.78 ± 0.29	1.76 ± 0.30	1.74 ± 0.29
	GDI	0.54 ± 0.14	0.89 ± 0.21	0.90 ± 0.02	0.91 ± 0.01	0.91 ± 0.01	0.91 ± 0.01
MMDT	Time (s)	489.1 ± 120.4					
ABILHAND	Score	36.93 ± 5.39					

TABLE III

STATISTICS OF SENSITIVITY, CONSTRUCT VALIDITY AND TEST-RETEST RELIABILITY. SENSITIVITY TO THE LEVEL OF AMPUTATION: COMPARISON OF THE THREE GROUPS WITH ANOVA TESTS (F) OR KRUSKAL-WALLIS TEST (χ2); SENSITIVITY TO THE LATERALITY OF AMPUTATION: COMPARISON BETWEEN TWO UNPAIRED GROUPS WITH T-TEST (T). CONSTRUCT VALIDITY (I.E. ABILITY OF DISCRIMINATION ANALYSIS AMONG THE DIFFERENT POPULATIONS): COMPARISON BETWEEN TWO UNPAIRED GROUPS WITH T-TEST (T) OR U-MANN WHITNEY (U). TEST-RETEST RELIABILITY: COMPARISON BETWEEN TWO PAIRED GROUPS WITH SIGN TEST AND T-WILCOXON SITAB6

Property and Method	Group	α (FDI)	Λ	b	GDI
Sensitivity	Level of amputation: Proximal N = 8, Medium N = 14, and Distal N = 8	*p* = 0.331 F = 1.152	p = 0.958 F = 0.043	p = 0.728 χ^2 = 0.636	p = 0.798 F = 0.228
	Laterality of the amputation: Dominant N = 19, and Non-Dominant N = 11	p = 0.535 t = -0.628	p = 0.783 t = 0.278	p = 0.414 t = -0.829	p = 0.573 t = 0.570
Construct Validity	Target population using myoelectric hand *vs* control at T1	**p < 0.001** **U = 154.000**	**p < 0.001** **U = 0.000**	**p < 0.001** **t = 11.128**	**p < 0.001** **t = -13.710**
	Target population using contralateral hand *vs* control at T1	**p = 0.009** **U = 332.000**	p = 0.305 U = 472.500	p = 0.484 t = 0.704	p = 0.241 t = -1.184
Test-Retest reliability	Control at T1 *vs* control at T3 (N = 35)	p = 0.818 Z = -0.230	p = 1.000 Z = 0.000	**p = 0.002** **t = 3.317**	**p = 0.002** **t = -3.319**
	Control at T2 *vs* control at T4 (N = 35)	p = 0.905 t = 0.121	p = 0.102 Z = -1.633	p = 0.381 t = -0.887	p = 0.183 t = -1.360

that Λ (and thus the VET) assessed the gross dexterity of myoelectric hand users (Fig. 5a).

The degree of correlation between the Fragile Ranking Score and α (Fig. 5b) proved statistically significant (Spearman's correlation, $p < 0.001$, $\rho_S = 0.814$, Table IV), and confirmed the hypothesis that α evaluated the fine dexterity of myoelectric hand users.

The metrics Λ and α confirmed capable of discriminating the group of healthy individuals from the group of myoelectric hand users (U Mann-Whitney non-parametric test, $p < 0.001$ for all comparisons, Table III). When comparing the performance achieved by the healthy individuals and the healthy hand of the amputees, while α proved statistically different (U-Mann Whitney, $p = 0.009$), Λ did not (U-Mann Whitney, $p = 0.305$), suggesting the two groups have the same capability in terms of gross dexterity but not in terms of fine dexterity.

The healthy individuals proved generally very proficient in performing the VET (Table II). The test-retest procedure demonstrated the reliability of the VET as the performance did not statistically differ between the first trial of each session (T1 and T3) (Wilcoxon Signed Ranks test, $p = 1.00$ and $p = 0.818$ for Λ and α respectively Table III and Fig. 6), as well as the second trial of each session (T2 and T4) (Λ: Wilcoxon Signed Ranks test, $p = 0.102$; α: T-test paired data, $p = 0.905$, Table III and Fig. 6).

B. Transport Time

Among the amputees, the average b proved 4.99 s using the myoelectric hand and 2.00 s using the contralateral healthy hand (Table II). b proved insensitive to the level of the amputation (Kruskal-Wallis $p = 0.728$, Table III) and the laterality of the amputation (T-test unpaired data $p = 0.414$, Table III).

TABLE IV

CORRELATION FOR TESTING THE CONSTRUCT AND CONCURRENT VALIDITY. WE ANALYSED THE CORRELATION EXPLOITING THE PEARSON'S CORRELATION COEFFICIENT (ρ_P) AND THE SPEARMAN'S CORRELATION COEFFICIENT (ρ_S). WE CONSIDERED: P > 0.5 LARGE CORRELATION, 0.3 < P < 0.5 MODERATE CORRELATION, 0.1 < P < 0.3 SMALL CORRELATION. STATISTICALLY SIGNIFICANT RESULTS (P < 0.05) IN BOLDFACE

Property	Outcome measure	α (FDI)	Λ	b	GDI
Construct validity	Fragile Ranking Score	**p < 0.001 ρs = 0.814**	-	-	-
	Robust Ranking Score	-	**p < 0.001 ρs = -0.772**	**p = 0.010 ρs = 0.463**	**p < 0.001 ρs = -0.804**
Concurrent validity	MMDT	p = 0.314 ρP = 0.190	p = 0.807 ρP = 0.047	**p = 0.009 ρP = 0.470**	p = 0.635 ρP = -0.090
	ABILHAND	p = 0.759 ρP = -0.058	p = 0.065 ρP = -0.341	p = 0.067 ρP = -0.339	p = 0.349 ρP = -0.177

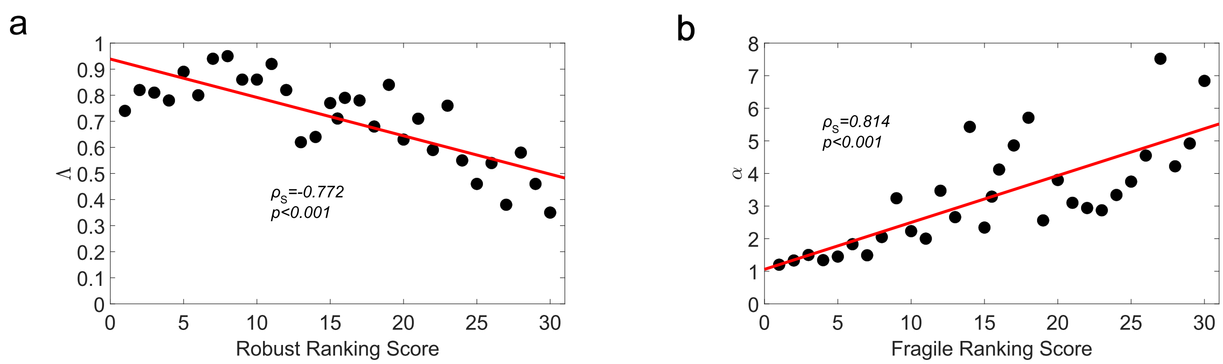

Fig. 5. Correlations between the outcome measure Λ and the Robust Ranking Score (a) and between α and the Fragile Ranking Score of the amputees using the myoelectric prosthetic hand (b).

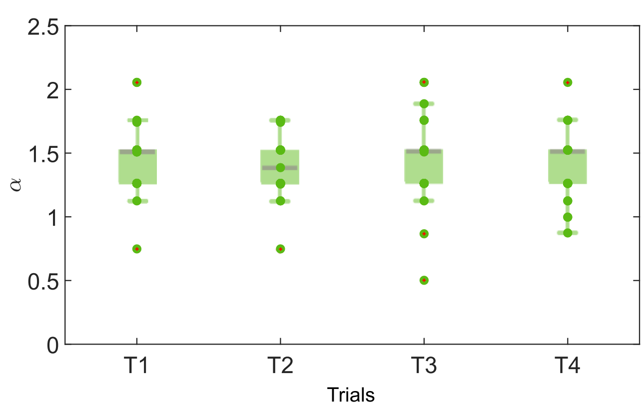

Fig. 6. Outcome measure α computed on the healthy individuals over four trials, two weeks apart (Session 1: T1-T2 in week 1, and session 2: T3-T4 two weeks later).

b and MMDT proved moderately correlated (Pearson's correlation test p = 0.009, $\rho_P = 0.470$, Fig. 8b, Table IV), suggesting that b can assess the gross dexterity of myoelectric hand users. On the contrary, we did not find a correlation between b and the ABILHAND score (Pearson's correlation test p = 0.067, Table IV), suggesting that the pace at which rigid VEs are transported does not correlate with the perceived difficulty of amputees in performing daily activities as assessed by the ABILHAND. b proved to moderately correlate with the Robust Ranking Score (Spearman's correlation p = 0.010, $\rho_S = 0.463$, Table IV). b discriminated the group of healthy individuals from the myoelectric hand users (T-test unpaired data, p < 0.001, Table III). On the contrary, b did not yield statistical differences between healthy participants and the healthy hand of the amputees (T-test unpaired data, p = 0.484, Table III).

The healthy individuals proved fast in transferring robust VEs (Fig. 8). b significantly differed between the first trial of each session (T1 and T3) (T-test paired data p = 0.002 Table III and Fig. 8c), while it did not between the second trials (T2 and T4) (T-test paired data p = 0.381, Table III).

C. Gross Dexterity Index

The compound GDI proved on average 0.54 for myoelectric hand users and 0.89 for the amputees when using the contralateral healthy hand (Table II). The GDI proved insensitive to the level of amputation (ANOVA, p = 0.798, Table III) and laterality of amputation (T-test unpaired data p = 0.573, Table III).

The GDI did not correlate neither with the MMDT (Pearson's correlation test p = 0.635, Table IV), nor with the ABILHAND (Pearson's correlation test p = 0.349, Table IV). Instead, the GDI proved statistically correlated with the Robust Ranking Score (Spearman's correlation p < 0.001, $\rho_S = -0.804$, Table IV). The GDI discriminated between the target group using myoelectric hand and the healthy individuals (T-test unpaired data p < 0.001, Table III). The GDI did not discriminate between the contralateral hand of myoelectric hand users and the healthy individuals (T-test unpaired

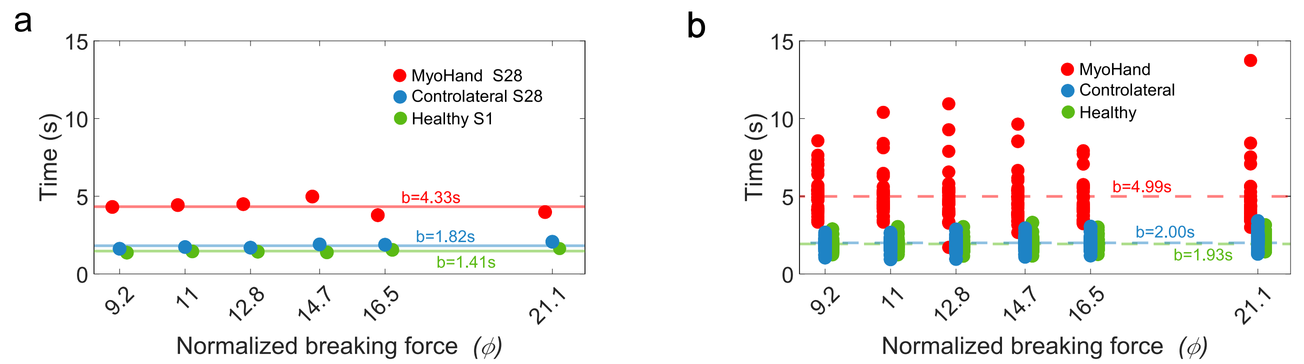

Fig. 7. Performance of the trans-radial amputees and healthy individuals (green dots) in terms of transport time, using the myoelectric prosthesis (red dots) and the contralateral hand (blue dots). Examples of participants (a), and all groups (b). Dots are the best transport time over seven repetitions associated to robust VEs for each individual.

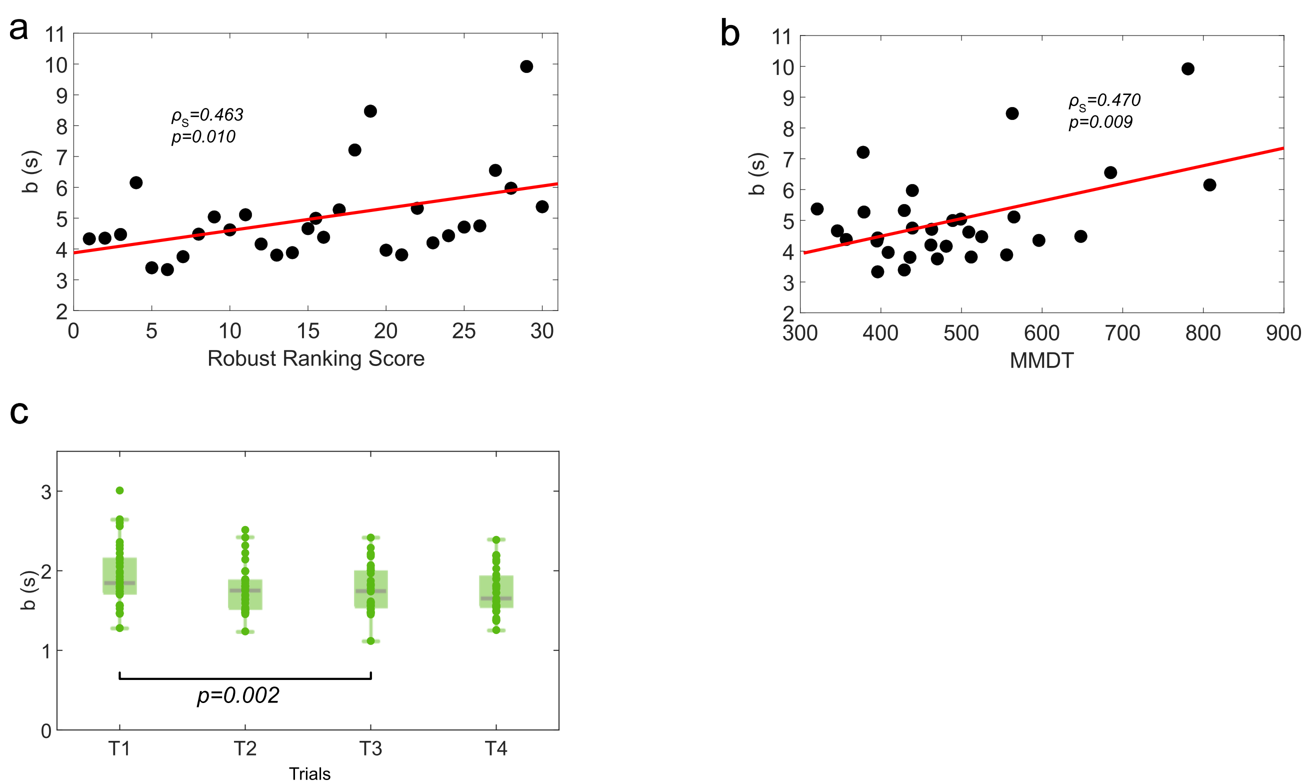

Fig. 8. Correlation between the outcome measure b of the Virtual Eggs Test (VET) and the Robust Ranking Score (a), and the score of the MMDT (b). Outcome measure b computed on the healthy individuals over four trials, two weeks apart (Session 1: T1-T2 in week 1, and session 2: T3-T4 two weeks apart) (c).

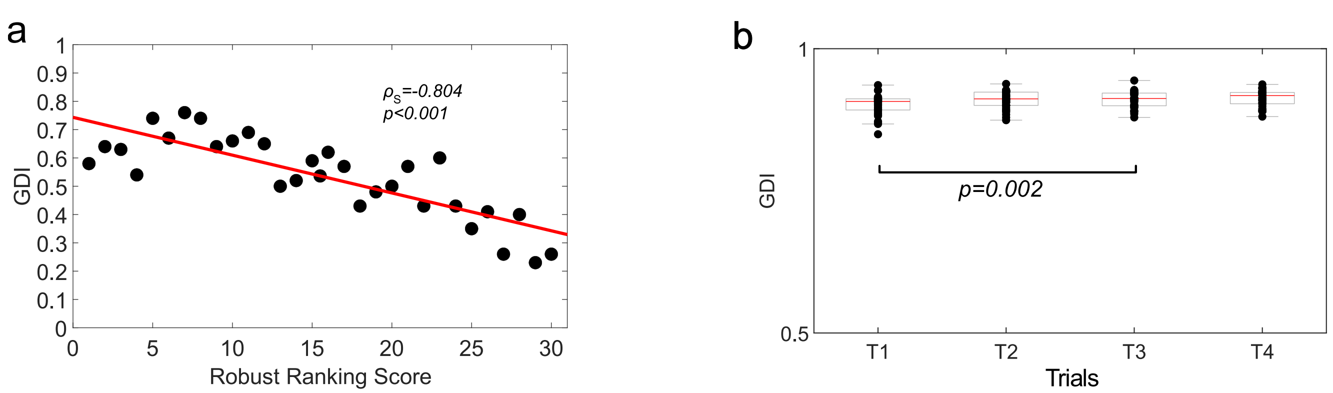

Fig. 9. Correlation between the Gross Dexterity Index (GDI) and the Robust Ranking Score (a), and GDI computed on the healthy individuals over four trials, two weeks apart (Session 1: T1-T2 in week 1, and session 2: T3-T4 two weeks later).

data p = 0.241, Table III). The average GDI of the healthy individuals proved 0.90 during the first trial (T1). The GDI significantly differed between the first trials of each session (T1 and T3) but not between the second ones (T2 and T4) (T-test paired data p = 0.002 for T1-T3 and p = 0.183 for T2-T4, Table III and Fig. 9b).

IV. Discussion

Prosthetic hands can partially restore hand function, but the loss of dexterity is significant, resulting in a substantial upper-limb related disability for amputees [19]. Myoelectric signals can be difficult to control and deploy precisely, leading to limited dexterity and difficulty with fine motor tasks and in general, long training times [33], [34]. In addition, the lack of sensory feedback reduces manual dexterity, especially for tasks that require fine motor skills [35], [36], [37]. Standard clinical measures, developed in times in which clinical prostheses exhibited limited mechanical dexterity and essential controllability, fail in uncovering more detailed aspects like the fine dexterity, potentially endowed by new technologies. However, this lack of sensibility curtails the assessment of potential significant functional improvements gained by prosthetic device users, thus preventing the evidence-based adoption of such devices by healthcare payers (universal systems or insurances).

In this study, we present an attempt to systematize and validate the Virtual Eggs Test (VET), a test already used in several studies from our group [26], [27], [29], but in different forms. The test requires the participant to transport fragile objects with different degrees of fragility over a barrier, while avoiding breaking them by squeezing them too much (hence, Virtual Eggs VEs). The performance is based on the ability to regulate the grip force (by counting the number of unbroken transferred VEs) and on the speed (by measuring the transport time of the unbroken transferred VEs), which are two factors considered essential to grasp proficiency and are primary deficits in amputees [38]. The number of successfully transferred VEs and the transport time are used to retrieve three outcome measures: α, Λ, and b, with the latter two combined in a unique Gross Dexterity Index (GDI) and α used for the definition of the Fine Dexterity Index (FDI).

The performance of a target population of 30 trans-radial amputees using a myoelectric hand, measured by the VET, showed higher variability compared to other groups (Table II, Table V, Table VI). The high variability of the performance of the amputees is also highlighted by ABILHAND and MMDT. This can be explained by the age and the time of daily use/training of the prosthesis, the rehabilitation efforts, or the engagement. Our findings align with the recent results of Resnik et al. [19], which indicate that measures of dexterity in amputees vary by age group and (hypothesized) engagement.

On the contrary, all outcome measures and the indexes derived from the VET proved consistent within the target population, with different levels of amputation and laterality (Table III, Table V). Our results can be considered coherent with the observation that the ability of transradial amputees in controlling their prostheses primarily relies on the ability to produce reliable electromyographic signals -which were not assessed in this study- rather than the level of amputation or the laterality [39]. The lack of significance of laterality on the ability to manipulate fragile objects is aligned with Valero-Cuevas et al. [20] proving that this skill is unaffected by laterality. However, since handedness was not formally assessed in our study, we cannot determine the impact of this factor with certainty.

The outcome measure derived from the robust VEs Λ did not prove correlated with both control tests (ABILHAND and MMDT), while b correlated only with MMDT (Table IV). The correlation between b and MMDT proved moderate and positive, and this might be explained by the similarity of the two outcome measures since both measure the execution time of gross movements while using the prosthesis. For the same reason, the lack of correlation between Λ and MMDT was indeed expected as the first assesses the ability of the transport of robust objects without breaking them, whereas MMDT assesses the execution time. Λ and b did not prove correlated with ABILHAND (Table IV). This lack of correlation is coherent with observations made for other pathologies [40] and it had to be expected considering that the two tests measure different aspects of prosthetic device usage. The VET (akin to the MMDT) measures the index in a functional test while directly using the prosthetic hand. On the contrary, ABILHAND, more generally, evaluates the subjective ability in executing activities of daily living (ADLs) notwithstanding whether such activities are carried out using the prosthetic/pathologic hand or not. Hence, only limited or indirect information on the actual use of the prosthetic/pathologic hand is given by ABILHAND.

The correlation between VET and MMDT is lost when the outcome measures Λ and b are combined to obtain the GDI, that considers both the accuracy in regulating the grasp force (by means of Λ) and the speed of transport (by means of b). Accuracy and speed are trade-off factors [41], [42]: the faster you move the VE, the more likely you are to break it. In the VET, the amputee is compelled first not to break the VE and secondly to quickly transport it over the barrier. However, the emphasis of humans on accuracy over speed in a motor task cannot be controlled. In this regard, the GDI, by combining the two outcome measures, can assess the overall capacity of the participant in transporting robust objects. This discrepancy suggests that the VET differs from other dexterity assessments, as it specifically evaluates the ability to manipulate objects that can break. This may explain the lack of correlation of the GDI with the other tests, while also encouraging further exploration of new methods for computing the GDI.

The outcome measure α was retrieved from the performance in transporting the fragile VEs, i.e. those with lower breaking thresholds. For this reason, α is hypothesized to measure fine dexterity and it corresponds to the FDI. In this study, α (FDI) did not correlate neither with MMDT nor with ABILHAND (Table IV). This had to be expected since MMDT evaluates gross dexterity while ABILHAND evaluates the subjective ability in executing activities of daily living. In analogy with Resnik et al. [19], we computed the ratio between the α (FDI) of the healthy population and the amputees using their myoelectric hand to evaluate the magnitude of outcome of impairment. The value retrieved in our study (0.46) is aligned

TABLE V
TARGET POPULATION – AMPUTEES DEMOGRAPHICS, AMPUTATION CHARACTERISTICS AND OUTCOMES USING THE MYOELECTRIC PROSTHESIS AND THE CONTRALATERAL HAND

Amputees population							Myoeletric Prosthesis								Contralateral hand			
ID	Sex	Age	Amputation level	Dominant hand	Amputated hand	Years since amputation	α	Λ	b	ABILHAND	MDDT	GDI	FRS	RRS	α	Λ	b	GDI
02	male	50	proximal	right	left	30	3,75	0,71	3,81	45	512	0,57	25	21	1,37	0,98	1,43	0,90993
03	male	57	proximal	right	left	44	4,55	0,82	4,16	34	481	0,65	26	12	1,26	1	1,93	0,9035
05	male	58	distal	right	left	40	2,56	0,38	6,55	42	685	0,26	19	27	3,67	0,97	2,54	0,84681
06	male	60	proximal	right	right	3	3,1	0,46	9,92	30	781	0,23	21	29	1,52	1	2,25	0,8875
07	male	51	medium	right	right	34	4,86	0,54	4,75	40	439	0,41	17	26	1,52	1	1,97	0,9015
08	male	33	medium	left	left	6	3,24	0,82	4,35	30	596	0,64	9	2	1,61	1	2,36	0,882
09	male	55	medium	right	right	27	1,34	0,8	3,33	38	396	0,67	4	6	2,77	1	2,07	0,8965
10	male	41	distal	right	right	6	5,71	0,59	5,32	42	429	0,43	18	22	1,75	0,98	1,68	0,89768
11	male	21	distal	right	right	5	2,94	0,63	3,96	35	409	0,5	22	20	1,46	0,98	1,1	0,9261
12	male	48	distal	right	right	19	1,5	0,94	3,75	32	470	0,76	3	7	2,06	1	2,26	0,887
13	male	48	medium	right	left	5	5,43	0,64	3,88	37	556	0,52	14	14	2,23	1	1,58	0,921
14	male	53	medium	right	right	22	1,33	0,77	4,66	36	346	0,59	2	15	2,4	1	1,41	0,9295
17	female	51	medium	right	right	31	3,8	0,78	5,27	43	379	0,57	20	17	1,26	0,97	2,05	0,870575
18	female	40	medium	right	left	18	2	0,79	4,38	34	357	0,62	11	16	1,52	1	1,48	0,926
20	female	27	proximal	left	right	28	1,49	0,55	4,43	42	396	0,43	7	24	1,52	1	2,21	0,8895
22	male	50	distal	right	left	5	1,45	0,92	5,11	37	565	0,69	5	11	1,26	1	2,28	0,886
23	male	45	proximal	right	left	24	2,34	0,58	5,97	36	439	0,4	15	28	1,26	1	1,98	0,901
24	male	34	medium	right	right	12	1,83	0,86	5,04	30	499	0,64	6	9	1,13	1	2,12	0,894
25	male	52	medium	right	right	32	4,92	0,35	5,37	41	321	0,26	29	30	0,11	1	2,25	0,8875
26	male	57	medium	right	right	37	6,84	0,68	7,21	31	378	0,43	30	18	2,82	1	2,89	0,8555
28	male	62	medium	right	right	45	4,22	0,46	4,71	46	463	0,35	28	25	3,15	1	1,75	0,9125
30	male	28	distal	right	right	3	2,05	0,76	4,2	36	462	0,6	8	23	2,06	1	1,39	0,9305
31	male	38	proximal	right	right	4	1,2	0,84	8,47	31	563	0,48	1	19	1,52	1	2,39	0,8805
32	male	32	medium	right	left	8	2,23	0,86	4,62	42	509	0,66	10	10	1,26	1	2,05	0,8975
33	male	46	distal	right	right	27	2,66	0,62	3,8	38	436	0,5	13	13	2	0,98	2,11	0,87661
34	male	59	distal	right	left	44	4,12	0,95	4,48	40	648	0,74	16	8	3,58	0,98	1,78	0,89278
35	male	52	proximal	right	right	41	2,87	0,89	3,39	35	429	0,74	23	5	2,77	1	1,77	0,9115
36	female	29	proximal	right	left	30	3,47	0,74	4,33	46	395	0,58	12	1	1,76	1	1,82	0,909
37	male	33	medium	left	left	9	3,34	0,81	4,47	35	525	0,63	24	3	3,15	1	2,38	0,881
38	male	58	medium	right	right	12	7,52	0,78	6,15	24	808	0,54	27	4	2,4	1	2,79	0,8605

with the ratio between the Southampton Hand Assessment Procedure outcome [43] of unpaired males and unilateral amputees (0.44) reported in [19]. This similarity suggests that VET can estimate the magnitude of outcome of impairment in activities of daily living and suggest further investigation on the correlation between the two tests.

We assessed the validity of the construct first by comparing different groups and then by formulating a priori hypotheses on the gross and fine dexterity abilities. All outcome measures and the indexes derived from the VET proved to discriminate between the amputees using the myoelectric hand and the healthy participants (Table III), supporting the construct validity. Only α differs between the healthy hand of the target population and the control population (Table III). This might be explained by the differences between the two groups that here is reflected on the fine dexterity, while seems not affecting the gross dexterity contrary to [44]. One difference pertains to age: the control population was aged between 21 and 45 years, instead, the target population was between 21 and 62 years old. This suggests the need for normative data stratified by group age. Another difference is associated with the hand used during the test: the control population executed the test using their dominant hand, while the target population used the healthy hand regardless their dominance. Hand dominance is proved influencing hand dexterity in precise motions according to [45] and since amputation frequently occurs on the dominant hand, the difference between α of the healthy hand of the two populations is expected.

The correlation (between moderate and high) of Robust and Fragile Ranking Score to the outcome measures of the VET (Table IV) suggests the validity of the VET in evaluating both gross and fine dexterity. For all outcome measures of the VET, the test-retest reliability, evaluated healthy participants, is verified only between the second trials of the two sessions. This suggests that, at least for healthy participants, the consistency of the results of the VET performance is achieved after a familiarization that lasts for the VET duration. The property must be further investigated on amputees using the myoelectric hand.

TABLE VI
HEALTHY POPULATION DEMOGRAPHICS AND OUTCOMES OF VIRTUAL EGGS TESTS

Healthy population			Dominant hand															
			T1				T2				T3				T4			
ID	**Sex**	**Age**	**α**	**Λ**	**b**	**GDI**	**α**	**Λ**	**b**	**GDI**	**α**	**Λ**	**b**	**GDI**	**α**	**Λ**	**b**	**GDI**
H1	female	25	1,52	1	1,47	0,93	1,26	1	1,48	0,93	1,26	1	1,52	0,92	1,26	1	1,49	0,93
H2	male	32	1,26	1	2,22	0,89	1,52	1	1,8	0,91	1,52	1	1,81	0,91	1,26	1	1,9	0,91
H3	female	25	1,26	1	3,01	0,85	1,39	1	1,47	0,93	1,52	1	1,59	0,92	1,52	1	1,57	0,92
H4	male	30	1,26	1	1,28	0,94	1,13	1	1,24	0,94	1,76	1	1,12	0,94	1,26	1	1,26	0,94
H5	female	26	1,26	1	1,77	0,91	1,26	1	1,69	0,92	1,52	1	1,62	0,92	1,26	1	1,62	0,92
H6	male	30	1,51	0,98	1,56	0,9	1,76	1	1,46	0,93	1,52	0,98	1,75	0,89	1,52	1	1,73	0,91
H7	female	24	1,52	1	1,81	0,91	1,52	1	1,64	0,92	1,52	1	1,56	0,92	1,13	1	1,49	0,93
H8	male	26	2,06	1	1,79	0,91	1,74	0,98	1,89	0,89	1,76	1	1,58	0,92	2,06	1	1,57	0,92
H9	female	29	1,52	1	1,74	0,91	1,52	1	1,78	0,91	1,89	1	1,47	0,93	1,52	1	1,39	0,93
H10	female	26	1,52	1	1,93	0,9	1,26	0,99	1,81	0,9	1,52	1	1,48	0,93	1,52	1	1,37	0,93
H11	male	29	1,13	1	2,14	0,89	1,52	1	1,84	0,91	1,26	1	1,82	0,91	1,52	1	1,61	0,92
H12	female	26	1,26	1	2,05	0,9	1,26	1	1,89	0,91	1,52	1	1,6	0,92	1,52	1	1,65	0,92
H13	male	44	1,51	0,98	1,53	0,91	1,52	1	1,65	0,92	2,06	0,98	1,57	0,9	1,52	1	1,56	0,92
H14	male	29	2,06	1	1,71	0,91	1,52	1	1,51	0,92	0,87	1	1,47	0,93	1	1	1,4	0,93
H15	female	26	1,26	1	1,8	0,91	1,26	1	1,54	0,92	1,52	1	1,49	0,93	1,52	1	1,38	0,93
H16	female	27	1,26	1	2,56	0,87	1,26	1	2,22	0,89	1,52	1	2,06	0,9	1,26	1	2,03	0,9
H17	female	27	1,26	1	1,99	0,9	1,26	1	2	0,9	1,26	1	2,22	0,89	1,13	1	2,11	0,89
H18	male	27	1,52	1	1,86	0,91	1,26	1	1,52	0,92	2,06	1	1,78	0,91	1,52	1	1,78	0,91
H19	male	35	1,52	1	1,74	0,91	1,26	1	1,81	0,91	1,26	1	1,61	0,92	1,52	1	1,5	0,93
H20	male	29	1,76	1	1,71	0,91	1,52	1	1,75	0,91	1,26	1	1,87	0,91	1,26	1	1,8	0,91
H21	male	28	1,52	1	1,89	0,91	1,52	1	1,75	0,91	1,52	1	1,97	0,9	1,26	1	1,95	0,9
H22	female	26	1,74	0,98	1,47	0,91	1,75	0,98	1,47	0,91	1,26	0,98	1,45	0,91	1,76	1	1,55	0,92
H23	male	25	1,52	1	2,36	0,88	1,52	1	1,99	0,9	1,76	1	2,18	0,89	1,52	1	2,19	0,89
H24	female	27	1,75	0,98	1,56	0,9	1,76	1	1,5	0,93	1,51	0,98	1,47	0,91	1,26	1	1,54	0,92
H25	male	27	1,26	1	2,1	0,9	1,26	1	1,87	0,91	1,52	1	2,07	0,9	1,26	1	2,14	0,89
H26	male	25	1,52	1	2,6	0,87	1,26	1	2,51	0,87	1,13	1	2,2	0,89	1,52	1	2,19	0,89
H27	female	30	1,52	1	1,97	0,9	1,26	1	1,89	0,91	1,26	1	2,01	0,9	1,26	1	2,19	0,89
H28	female	28	1,26	1	1,7	0,92	1,52	1	1,51	0,92	1,26	1	2,01	0,9	1	1	1,72	0,91
H29	male	30	1,52	1	2,16	0,89	1,52	1	2,14	0,89	1,52	1	1,83	0,91	1,76	1	1,82	0,91
H30	female	21	0,75	1	2,32	0,88	0,75	1	2,32	0,88	0,5	1	2,03	0,9	0,87	1	1,9	0,91
H31	female	55	1,52	1	2,28	0,89	1,52	1	1,7	0,92	1,26	1	2,29	0,89	1,52	1	2,2	0,89
H32	female	24	1,51	0,98	1,57	0,9	1,76	1	1,59	0,92	1,52	0,98	1,52	0,91	1,52	1	1,54	0,92
H33	male	27	1,52	1	2,65	0,87	1,26	1	2,42	0,88	1,26	1	2,42	0,88	1,26	1	2,39	0,88
H34	male	26	1,52	1	1,46	0,93	1,13	1	1,48	0,93	1,26	1	1,55	0,92	1,26	1	1,56	0,92
H35	female	25	1,52	1	1,85	0,91	1,26	1	2	0,9	2,06	1	1,74	0,91	1,76	1	1,81	0,91

In conclusion, the results suggest that VET can evaluate both gross and fine dexterity providing two distinct indexes. Results also suggest that future efforts are needed to investigate the correlation of the VET to tests with other constructs (such as the Nine Peg Hole), verifying test-retest reliability on amputees wearing myoelectric prostheses, and also the impact of handedness on the outcome measures of the VET. It is also our aim to extend the use of VET to people with other impairments to make the VET a standard procedure regardless of the type of pathology.

APPENDIX
PARTICIPANTS DATA AND DEXTERITY OUTCOMES

See Tables V and VI.

Acknowledgment

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