A normative database for quantitative motor assessment

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Abstract: We created a Quantitative Motor Assessment (QMA) to assess neuromuscular health and to identify motor deficits that affect human performance. Using custom software and an inexpensive novel motion capture sensor, we adapted and automated traditional subjective motor assessments in an integrated system that is quick, low-cost, and highly sensitive. We administered the QMA to 104 (53 males and 51 females) healthy individuals 18-50 years old in order to establish a normative database of unimpaired motor behavior. We expect that the sensitivity, objectivity, low cost, portability, and ease of use make the QMA a beneficial and accessible tool to clinicians as well as researchers.

Introduction

Conventional exams to assess neuromuscular health and human performance rely on subjective observations of the clinician conducting the assessment, and often fail to detect subtle damage. Correctly identifying movement impairments that result from injury or physiological disruptions is critical for diagnosing movement disorders and prescribing an appropriate rehabilitation program. Developments in gaming technology make is possible to accurately capture finger and hand movements [1] providing an elegant solution for recording movement during a motor assessment resulting in data for in-depth movement analyses. Almost equally impressive is that this technology is inexpensive and commercially available. The purpose of our research is to 1) leverage this technology to develop a quantitative motor assessment (QMA) that is clinically relevant, user-friendly, low-cost, and highly sensitive, and 2) establish a normative database for each of the test measures to allow comparisons relative to a healthy norm.

To this end, we developed an integrated system that automates conventional movement exams performed by doctors, physical therapists, and other clinicians. Our system consists of an $80 Leap Motion sensor (Leap Motion, San Francisco) (Figure 1B) integrated with customized software. As the person being tested performs each movement in the assessment, the system records their hand and finger position with a resolution of 0.01mm and a sampling frequency of 100Hz. We have seeded a normative database by administering this QMA to 104 control subjects.

Methods

Determining Motor Tests

To determine which tests to include in the QMA, we consulted the literature [2], [3] that defines and describes motor assessments commonly used in clinical settings, especially for patients who have suffered a neuromuscular disorder, traumatic brain injury or stroke. There was no standard test battery, however the literature indicated that a complete clinical evaluation of the motor systems should include assessments of strength, muscle stiffness, reflexes, movement efficiency and speed, postural control and abnormal movement. This information, coupled with advice from highly regarded resident experts, made it possible for us to define a list of motor assessments that would lend themselves best to motion capture and collectively have great utility to the clinician. In all, we defined five tests from which we would draw eight measures that directly address movement efficiency and speed, postural control, and abnormal movement. We also included a conventional test to determine strength, another for visuomotor integration, and also one for comparison to our motion capture finger oscillation test.

Developing the Quantitative Motor Assessment

To develop the QMA, we first thoughtfully defined the test protocols and parameters for the chosen assessments given the definitions of the measures we required. We also needed to consider the limitations of the motion capture device, which were its cone of field of view the orientation of the device. Then using Python, we programmed the assessments as part of an integrated system with a graphical user interface (GUI) (Figure 3) and the Leap Motion sensor connected via USB to a desktop computer. Our customized software not only defined the behavior of the test protocol and GUI, but also captured and stored the hand and finger measures. The tests and measures that comprise the QMA and the conventional tests included in this study are shown in Table 1.

Table 1: Quantitative Motor Assessment and Conventional Motor Assessment Tests and Measures

QMA Test	Behavioral Attributes	Measures
Balance	• postural control	• normalized mean path of the crown of the head
Finger Oscillation	• motor speed • movement efficiency	• number of taps • regularity/σ Amplitude and frequency of taps
Postural Tremor	• upper limb postural control	• power spectrum area
Reaction Time	• processing time	• reaction time
Visually Guided Movements	• visuomotor control • abnormal movement • intention and kinetic tremor	• dysmetria • power spectrum area
Conventional Tests	**Behavioral Attribute**	**Measures**
Grip Strength	• strength	• strength
Beery VMI	• visual-motor integration	• a raw score based on defined criteria
Halstead-Reitan Finger Tapping Test	• motor speed	• number of taps

Administering the QMA and establishing a normative database

Participants

One hundred four healthy subjects (51 females and 53 males in the age range of

18-50 years) participated in this study. To be included, participants were required to be right-handed, free of any movement disorder or medications that interfere with movement or alertness, and not pregnant.

In four of the five QMA tests, participants were asked to sit square at a table in front of a computer screen (Figure 1A) and were presented with a GUI specific to the given QMA task. The motion capture sensor sat on the table, face up, in front of the computer screen so that participant's outstretch hand was directly over it. Position in three dimensions and velocity of the finger tips and palm (or wooden dowels, in one case) were recorded by the Leap Motion sensor at approximately 100 samples per second. The entire assessment required 1 hour 45 minutes. The tasks were performed in random order. Movements were performed by both hands.

Each subject performed the following QMA and conventional tests:

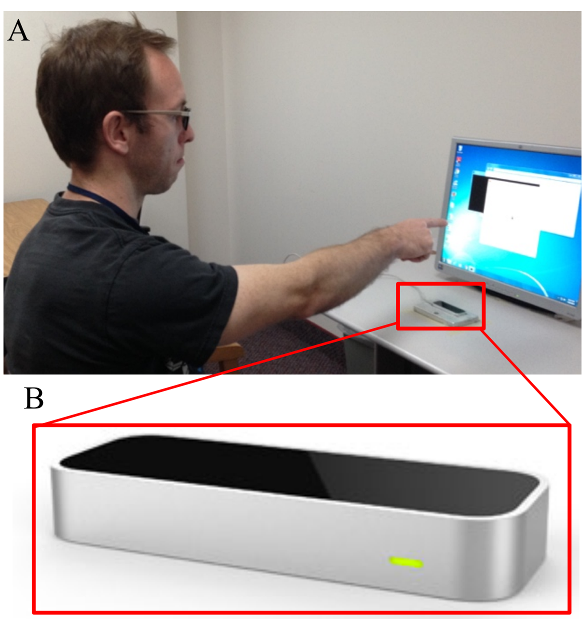

Figure 1: Test Setup (A) Participant sits squarely to the desk, computer screen and motion capture sensor with his hand over the top of the sensor. (B) Leap Motion Sensor

Balance

The sensor was mounted on a tripod and participants wore a helmet with two dowels, which were the thickness of fingers, attached on the front. Participants stood with feet together and hands across the chest by the tripod so that the dowels extended over the sensor (Figure 2). They held that position in each of five different conditions for 30s each while the movement of the dowels was recorded. The five conditions were:

- Standing on a hard surface with their eyes open
- Standing on a hard surface with their eyes closed
- Standing on a soft surface with their eyes open
- Standing on a soft surface with their eyes closed
- Standing on a hard surface in a tandem stance, preferred foot in front, with their eyes open

Figure 2: Setup for Balance Test- Eyes Open Soft Surface

Finger Oscillation Test

Participants started by sitting square to the table and computer screen. The GUI on the screen for the finger oscillation task (Figure 3A) contained two parallel lines, spaced 15mm apart, a black ball representing the user's finger, and a set of crosshairs marking the starting point. While pointing at the GUI with their index finger over the sensor, participants were instructed to "tap" in the air as fast as possible so that the black ball on the screen moved below and then above the two parallel lines. They were to move only at the metacarpal-phalangeal joint, keeping their wrist and shoulder stationary. Each trial lasted 10s, with a 10-90s rest between trials. Our system tallied the number of taps during each trial. Movements in which the ball did not cross both the bottom and top lines were not included. The assessment was complete when the subject performed 5 trials within 5 oscillations of each other. In the event that this requirement was not met, the number of taps in ten trials were averaged. The participant was given as many practice trials as desired. The test was performed with each hand.

Postural Tremor

Sitting square to the table and computer screen, participants were instructed to position their hand so that the corresponding virtual hand in the GUI was over a set of crosshairs in the center of a rectanlge on the screen. (Figure 3C). In this location the hand was approximately 20cm over the motion capture sensor. They held their hand at that location with the palm down and fingers spread for 30s while the sensor captured their palm and finger movements. Two trials were performed with each hand to assess postural tremor.

Reaction Time

Participants held their hand 20cm over the sensor, centering it over a set of crosshairs in a gray-colored circle on the screen. When the hand was properly aligned the background color changed form gray to white. At a random time between 0.5s - 5s from the time the participants hand aligned with the crosshairs, a smaller 25mm circle appeared around the virtual hand and the background color on the screen changed from white to green (figure 3D). Participants were instructed to remove their hand out of the circle as quickly as possible when background color changed to green. Ten trials were performed with each hand. The reaction time was defined as the average over the ten trials.

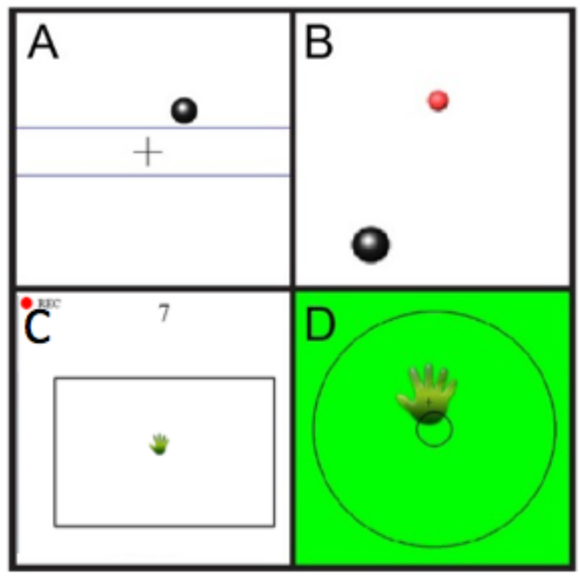

Figure 3: Graphical User Interface (A) Finger Oscillation Test (B) Visually Guided Movement (C) Tremor Test (D) Reaction Time Test

Visually Guided Movement

Participants started sitting square to the table and computer screen. The GUI for the visually guided movement assessment (Figure 3B) consisted of a red ball that represented the user's index finger tip and a black target that initially appeared in one of the corners of the screen. The participant was instructed to move their finger as fast as possible so that the red ball sat on top of the black target. They were to hold it there until they saw the next target appear in another corner, and then move to it as quickly as possible. The subsequent target appeared after the finger had rested on the target for 500ms. Sixty targets were presented randomly so that the 12 possible finger paths from corner to corner were performed and recorded five times in each of two trials, for a total of 120 paths for each hand.

<u>Grip Strength</u>
Grip strength was measured with a hand dynamometer (Stoelting, Wood Dale, IL). After adjusting the grip distance for the participant's hand size, the participant was instructed to stand straight with the working hand down at their side and squeeze as hard as possible for about roughly 3s. One measure was taken for each hand.

<u>Beery Visual Motor Integration (VMI)</u>
The Beery VMI test is a developmental sequence of geometric forms to be copied with paper and pen. It was designed to assess the extent to which individuals can integrate their visual and motor abilities. We adhered to the instructions for individual administration, instructing the participant to keep the test booklet and their body squared and centered to the desk, and to copy the form in each section in the box below it. There were 30 forms in all, starting with a straight horizontal line and getting progressively more complex.

<u>Halstead-Reitan Finger Tapping Test (HRFTT)</u>
The HRFTT is administered using an instrument consisting of a board with a mechanical counter attached. Participants start with the heel of their hand resting on the board, their index finger on the lever of the counter, and the remaining fingers extended and resting on the board. The participant is instructed to tap the lever as quickly as possible for 10s. The test is complete when five trials within five taps of each other are performed. In the event that this is not accomplished, the average of ten trials is used. The participant is given as many practice taps as necessary and 10s - 90s rests were given between trials. The test was performed with each hand.

Analysis

<u>Measurement Definitions</u>
Using Matlab 2013b (Mathworks, Inc), we automated the extraction of test-specific measures (Table 1) from the raw position and time data captured by the motion sensor. The code included analyzing the data for motion tracking errors.
Careful thought and review of the literature were employed to calculate the measures. To assess balance, the path of the crown of the head was extrapolated from the position of the two tools on the helmet (Figure 4). After accounting for time gaps and tracking losses, the normalized path for the crown of the head was calculated by:

$$Normalized\ Path = \frac{1}{t}\sum_{j=1}^{N-1}\left|p_{j+1} - p_j\right|$$

where t is time duration, N is the number of samples, and p is the three dimensional motion capture data at time sample j.

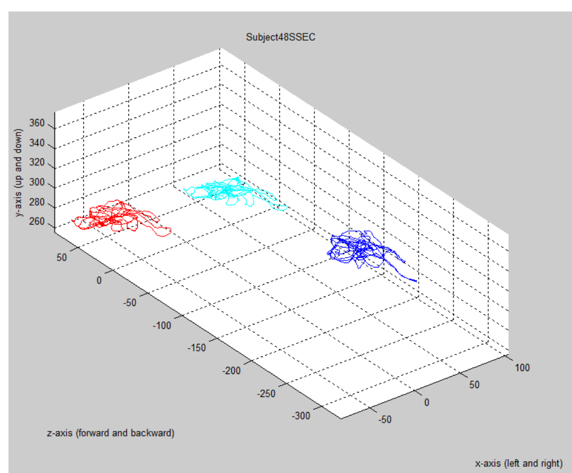

Figure 4 Path of Sway- Red: left tool; Cyan: Right tool; Blue: Crown of head

The finger oscillation assessment included an average number of finger taps for each hand, calculated for the number of valid taps over the five trials, or in the case where five trials within five taps of each other were not performed, the average was calculated for 10 trials. The regularity was determined by calculating the standard deviation of both the amplitude and frequency of the oscillations. Larger standard deviations indicate greater irregularity.

Postural tremor was assessed by determining the area under the power spectrum curve between 4Hz -12Hz, the bandwidth for tremor[4].

Reaction time was defined as the time between the appearance of the visual stimulus, which is flagged in the data at the time of the test, and the exit of the palm of the hand outside of the 25mm circle, which was centered on the palm vector at the time of the visual stimulus.

Visual motor integration was assessed by a measure of dysmetria, the distance away from the target at the end of the movement. Paths with time gaps greater than 50ms during capture were excluded and then the mean path length between each of the targets were calculated. Dysmetria was calculated as the percent difference between the length of the participant's path and the direct path from target to target. Kinetic or intention tremor was also calculated, which was done in a manner similar to that of the postural tremor.

Grip strength was a straight forward reading from the hand dynamometer in kilograms. Normative values are well-defined and provided by the manufacturer.

The Beery VMI is based on Score and No Score criteria that is well-defined and based on examples of thousands of tests results. Standardized norms are provided for the raw scores in the Beery VMI test kit.

The average number of taps on the HRFTT were calculated for each hand. Normative data is available for comparison [5].

Results

Being normative data from healthy subjects, the QMA results were generally stereotyped with expected differences between men and women in grip strength ($p<.0001$ for both the dominant and non-dominant hand) and the finger oscillation test ($p=.007$ for the dominant hand and $p=.002$ for the non-dominant hand.). There were significant differences between dominant and non-dominant hands on the visually guided movement test for dysmetria ($p<0.001$) (Figure 5).

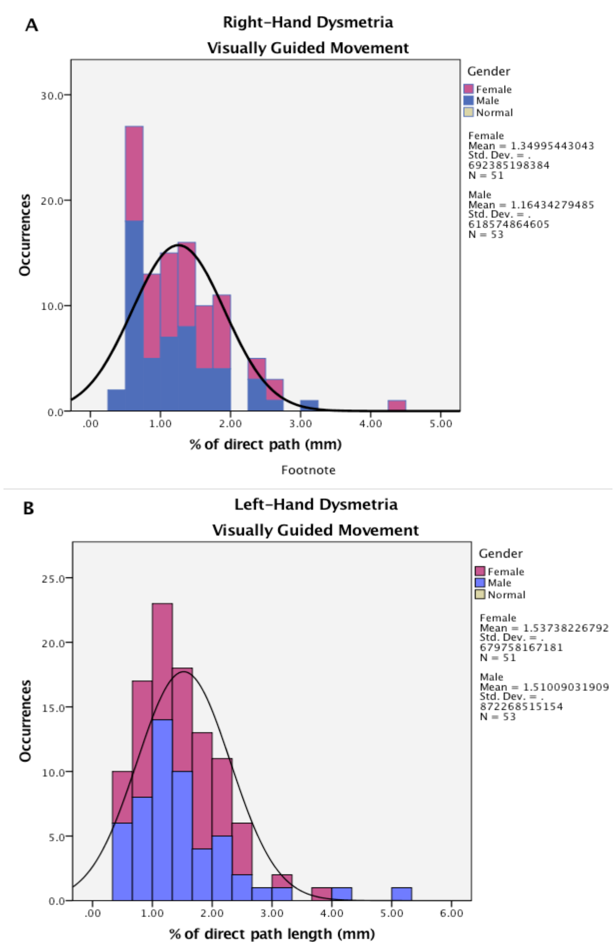

Figure 5: Distribution of Dysmetria on the Visually Guided Movement Test (A) Right Hand (B)Left hand

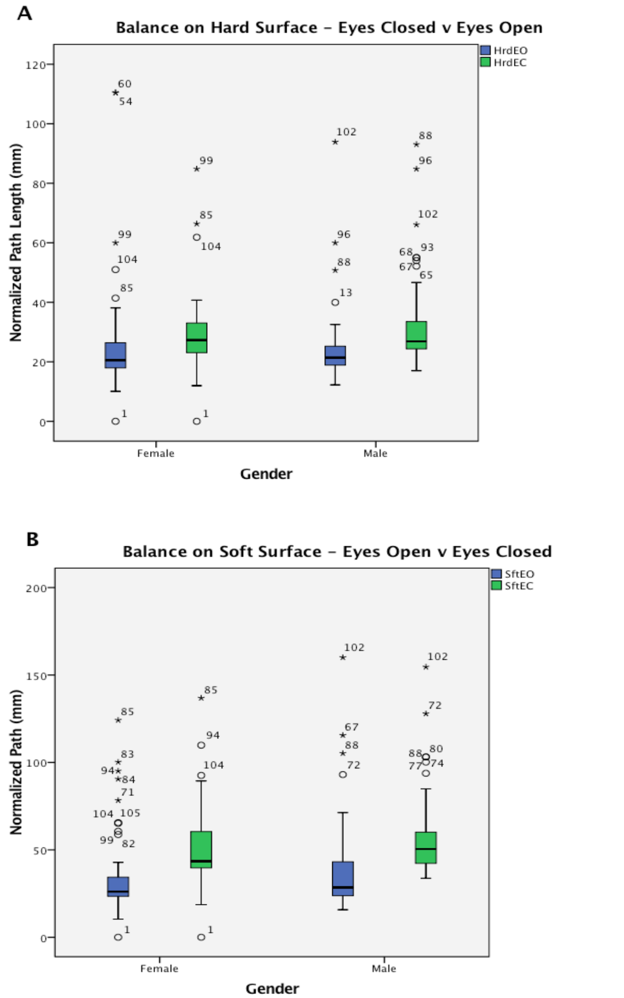

Figure 6: Normalized path of the head during balance with eyes open and eyes closed on (A) a hard surface and (B) a soft balance pad.

In the balance assessment (Figure 6), there was a significant difference between the Eyes Open vs. Eyes Closed conditions on both Hard Surface ($p<.001$) and Soft Surface ($p<.001$), and the Hard Surface vs. Soft Surface conditions during both Eyes Closed ($p<.001$) and Eyes Open ($p<.001$) trials. It should be noted that outliers in the balance test belonged to the older age group.

The mean and standard deviation of the Reaction Time test are shown in Table 2. There was no significant difference between genders or dominant vs. non-dominant hand.

Table 2: Reaction Time

	Gender	N	Mean	Std. Deviation	Std. Error Mean
RRxn	Female	51	.333383602	.046755342	.006547057
	Male	53	.319470224	.033944432	.004662626
LRxn	Female	51	.334129368	.051595793	.007224856
	Male	53	.323213610	.034741851	.004772160

When comparing the QMA finger oscillation test to conventional HRFTT, there was no correlation with values of $r = 0.23$ and 0.36 for right and left respectively. However, there was no significant difference between our HRFTT results and the published norms.

The "Standard Deviation of Period" and "Standard Deviation of Amplitude" are highly positively correlated and appear to be redundant for both right and left ($r = 0.69$ and $r = 0.63$ respectively).

There is a negative correlation between the mean number of finger oscillation and the standard deviation of the frequency for both right and left hands ($r = -0.72$).

Together these measures will form a normative database against which patients' QMA results can be compared to evaluate the degree of their impairment.

Discussion

Additional analysis needs to be completed to determine the complete normative database of measures, and to determine if all the tests and measures are in fact necessary, or if some are redundant. However, that the difference between genders in the QMA finger oscillation test is consistent with results of both computer keyboard press and mechanical finger tap tests [5], and the measures of differences in our balance measures agree with posturography results [6], provide a level of confidence in the validity of the QMA.

The results from the QMA finger oscillation test provide some new insights. The lack of correlation between the QMA finger oscillation test and the HRFTT is unexpected, but indicates that the QMA test is measuring something different than the HRFTT. The high correlation between the standard deviations of both amplitude and frequency mean that a person with a more regular amplitude also have a more regular frequency. The negative correlation between the number of finger oscillations and the standard deviation of the frequency indicate that people who have more regular oscillations also have more oscillations. This information was not available in the HRFTT version of the test.

The outliers in the balance data are all due to participants in the 30- to 50-year-old age category. This information may indicate the need to stratify the normative database according to age as well as gender.

Novel markerless motion capture technology allows for collection of an abundance of quantitative movement information. Using this technology and the associated normative databases will allow for quick, low-cost, and highly sensitive motor assessment in clinical settings, which we expect will result in improved diagnosis, prognosis, and rehabilitation following TBI or stroke. Additionally, it may be useful in any setting in which neuromuscular health and human performance are suspected to be compromised. Because of the demands within the gaming industry, motion capture technology is likely to continue to improve, creating even more sensitive instruments.

This QMA and its normative database will be available on the BYU Neuromechanics Research Group website. We invite others to take advantage of it and contribute to the database.

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