Linking Quantitative Motor Assessments to the Underlying Brain Injury: A Preliminary Report

[1]Paula Johnson, [2]Clay Kincaid, [3]Nathan Muncy, and [1,2]Steven K. Charles

[1]Neuroscience, [2]Mechanical Engineering, [3]Psychology, Brigham Young University, Provo, UT

Abstract: Using custom software and an inexpensive novel motion capture controller, we adapted and automated traditional subjective motor assessments in an integrated system to develop a quantitative motor assessment (QMA) that is low-cost, and highly sensitive. Twelve participants who have suffered a traumatic brain injury performed the QMA and had MRI scans of their brain. We compared the individual QMA results from the TBI group to normative standards (developed in an earlier work). We also compared the QMA results to measures of damage found in MRI results. Preliminary analysis of a subset of data are reported here.

Introduction

There is a recognized need for sensitive, cost- and time-effective, quantitative exams that assess neuromuscular health following a traumatic brain injury (TBI). Conventional exams to tend rely on subjective observations of the clinician conducting the assessment, and often fail to detect subtle damage. Assessment tools that are sensitive and objective, such as optoelectric and electromagnetic systems, require precise and time-consuming marker placement, and are cost prohibitive for many clinicians. Yet, 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 computer gaming technology in the past decade have provided a means to address these needs. Small, USB-connected, motion capture controllers (Figure 1C) have been designed for interaction with computers via hand gestures, replacing the need to move and click a mouse or press arrows on a keyboard while playing computer games. The IR camera technology in the device is akin to Microsoft Kinect's markerless motion capture. However, instead of detecting gross whole body movement in a large space, it recognizes fine finger and hand movements in a small space. The controller captures the movement of any finger-like object within 1 m distance from the face of the device with accuracy of 0.7 mm and sampling frequency of 100 Hz [1]. Almost equally impressive is the low-cost of the controller—80 USD—that makes it accessible to most anyone.

We leveraged this 3D markerless motion capture technology to develop a quantitative motor assessment (QMA) that is sensitive and inexpensive. Our QMA is a system consisting of a Leap Motion controller (San Francisco, CA) integrated with a computer

by way of customized software. We programmed the controller to record position and velocity of the hands and fingers of patients as they perform movements similar to those done in clinical evaluations [2], [3] to detect movement impairments. We also established normative data for each of the QMA measures to allow comparisons relative to a healthy norm based on seventy 18-40 year-old participants free of movement issues. Results from that work are currently being prepared for peer review.

Presented here are preliminary results that associate QMA data from TBI patients with their MRI data in an effort to link motor deficits with underlying brain damage.

Methods

Participants

Twelve individuals (18-37 years old) who have suffered a mechanical injury to the head have participated in this study to date. The participants are stratified in two levels according to the severity of their injury: 1) mild, which includes concussion, and 2) moderate to severe. (See Table 1)
There are two parts to the study, QMA testing and MRI scanning. Total time to complete both tasks was no more than three hours.

Quantitative Motor Assessment

A complete QMA battery is comprised of five motor tests resulting in 15 measures. A summary of the tests and the measures included in this study are shown in Table 2. In two of the three tests, participants sat square at a table in front of a computer screen. The motion capture sensor sat on the table, face up, so that the participant's outstretch hand was directly over it (Figure 1A). For the third test, which was a balance test, the controller was mounted on a tripod and the participant wore a helmet with dowels that are positioned over the controller (Figure 1B). For each test the participant was presented with a graphic user interface specific to a given QMA task. As the participant performed each QMA task, position in three dimensions and velocity of the finger tips and palm of the hand (or wooden dowels) were recorded by the Leap Motion sensor at approximately 100 samples per second. Movements were performed by both hands. The tasks were performed in random order.

Table 1: Participant demographics

ID	sex	Age (years) Avg=26.2 SD=5.81	Age of Injury (mos)	Severity
1	M	24	0.75	mild
2	F	19	3	mild
3	M	22	7	mild
4	F	32	7	mild
5	F	19	8	mild
6	M	22	8	mild
7	M	22	12	mild
8	F	18	24	mild
9	M	37	16	moderate
10	F	31	7	severe
11	M	19	46	severe
12	M	25	67	severe

Figure 1 Test setup. for most tests (A), subjects pointed to objects on a screen while a Leap Motion sensor (C) captured their movements. In the balance test (B), subjects' head sway was extracted from the motion of dowels attached to a helmet.

Table 2: 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 for five poses
Reaction Time	processing time	reaction time
Visually Guided Movements	visuomotor control	dysmetria

Each subject performed the following QMA subtests:

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 1B). 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

Reaction Time
Participants set their hand over the sensor

centering the hand on the screen in a circle as in the Tremor assessment (Figure 2C). 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. Participants were instructed to remove their hand out of the circle as quickly as possible when background color changed to green (Figure 2D). Ten trials were performed with each hand. The reaction time was defined as the average over the ten trials.
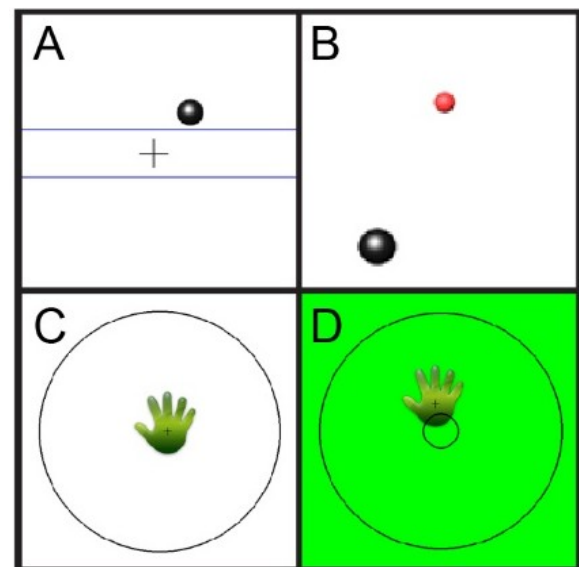

Figure 2 Graphical User Interface for QMA tests: finger oscillation (A), visually guided movements (B), postural tremor (C), and reaction time (C-D).

Visually Guided Movement
Participants started sitting square to the table and computer screen. The GUI for the visually guided movement assessment (Figure 2B) consisted of a red ball that represented the user's finger 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.

MRI Acquisition

The MRI data were acquired using a 3T Siemens TIM-Trio (Siemens Medical Inc., Erlangern, Germany). Scans included 3D T1-weighted structural images and diffusion tensor images (DTI).

The scanning session starts with high resolution T1-weighted scans for structural imaging. These are acquired using a 160-slice 3D MPRAGE (Magnetization Prepared Rapid Gradient Echo) volume scan with TR (Repetition Time) = 1900 ms, TE (Echo Time) = 2.26 ms, flip angle = 9 degree, FOV (Field of View) = 250 mm, 256 X 215 matrix size, and 1 mm slice thickness.

DTI images are acquired using a single-shot, spin-echo, EPI (Echoplanar Imaging) sequence with 30 orthogonal directions with TR = 6600 ms, TE = 90 ms, FOV = 230mm, and matrix size = 128x 128. Fifty 4-mm thick slices are imaged (no slice gap).

T2-weighted anatomical as well as susceptibility weighted images, fluid attenuated inversion recovery images were also acquired during the scanning session, but data have yet to be processed.

Analysis

QMA Data

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 3). After accounting for time gaps and tracking losses, the normalized path for the crown of the head was calculated by:

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

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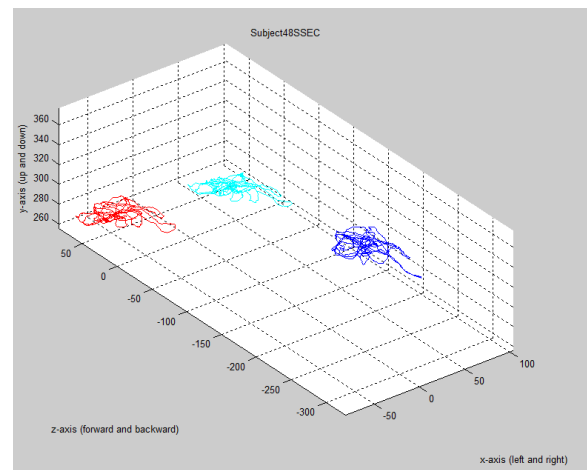

Figure 3   Path of Sway- Red: left tool; Cyan: Right tool; Blue: Crown of head

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 50 ms during capture we excluded and then the mean path length between each of the targets were calculated. The participants path was reported as a percent of the path from target to target. Kinetic tremor was also calculated, which was done in a manner similar to that of the postural

tremor.

Statistical Analysis

TBI Group vs. Normative Data
We compared the QMA results from individual TBI patients to the normative standard to determine the extent of each patient's motor deficits. Note that the normative standard is based on median and 10th to 90th percentile QMA results from 70 healthy individuals (18-40 years old), which was determined in a work currently being prepared for peer review.

MRI Data
2D diffusion weighted (DW) DICOM data were combined to produce a 3D structural file in the NIfTI file format, b-value weightings, and vector gradients. The 3D structural file was then pre-processed via alignment to and averaging of B0, rigid-body alignment of the DW images to the B0 which corrects for motion (eddy current), alignment of the DW data to a T1-weighted structural file, resampling of the DW voxel dimensions into isotropic 2mm dimensions (for use with the template), and finally fitting the vector data and tensors.

Pre-processed DW data was then segmented via a tractography-based approach, producing individual white-matter tracts in participant space. This analysis involved constraining the definition of tract to probabilistic pathways that occur at 2 differing endpoints defined *a priori* in a template space. Upon rendition of the tracts, and according to anatomic factors (e.g. crossing fibers of different tracts), each tract was then divided into 100 equal parts, and diffusion tensor scalars, such as fractional anisotropy (FA), for each section of the tract was calculated. This division increases sensitivity of the tractography-based approach, being able to localize discrete regions of variation between groups. As such, FA values for regions of the corticospinal pathway which discriminated between mild and severe TBI groups were used in subsequent statistical analyses. Specifically, the FA values were used in a multiple regression with a Bonferroni correction to determine if and how damage in those areas of the neural circuitry contributed to the motor deficits seen in QMA results.

Results

TBI results vs Normative data

The extent of motor damage varied across individuals and tests. Results indicating how individuals that are representative of each TBI group (mild, moderate and severe) compared to the normative data are shown for balance (Figure 4), dysmetria (Figure 5) and reaction time (Figure 6). Generally, the QMA results for the individuals with TBI fell outside of the 25th-75th quartiles.

TBI results relative to MRI results

Results of DTI tractography of the corpus callosum are shown in Figure 7. There is a difference in FA values between the mild and moderate to severe groups for indicated the areas of the motor portion of the corpus callosum and left and right cortical spinal tracks shown in Figure 8. However, there was no statistical relationship between damage seen in these three areas and QMA results.

A. Hard - Eyes Open   B. Hard - Eyes Closed
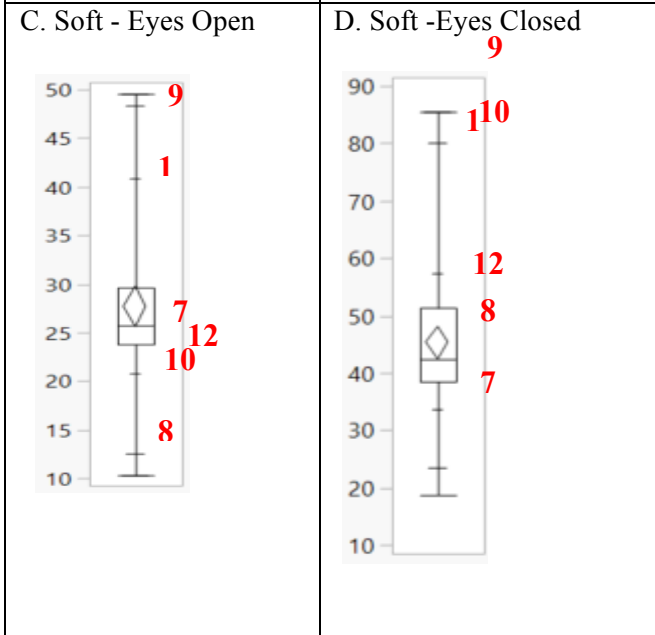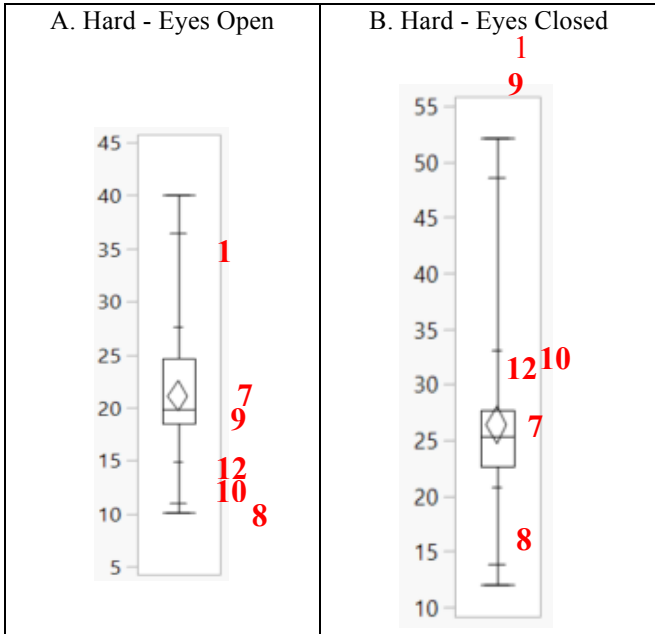
C. Soft - Eyes Open   D. Soft -Eyes Closed

Figure 4: Normative data for balance tests are shown as a measure of the path length of the crown of the head (mm). The median is shown in the center of the box, with the 75% and 25% quartiles at the top and bottom edges respectively. The next hash above and below the box are the 90th and 10th percentiles respectively.

The ID numbers of individual TBI patients representative of each group (mild, moderate, and severe) are shown in red. The location next to the scale shows where their QMA balance measure would fit.

The four conditions are standing on A. hard surface with eyes closed, B. hard surface with eyes open, C. soft surface with eyes open and D. soft surface with eyes closed.

Right Hand   Left Hand
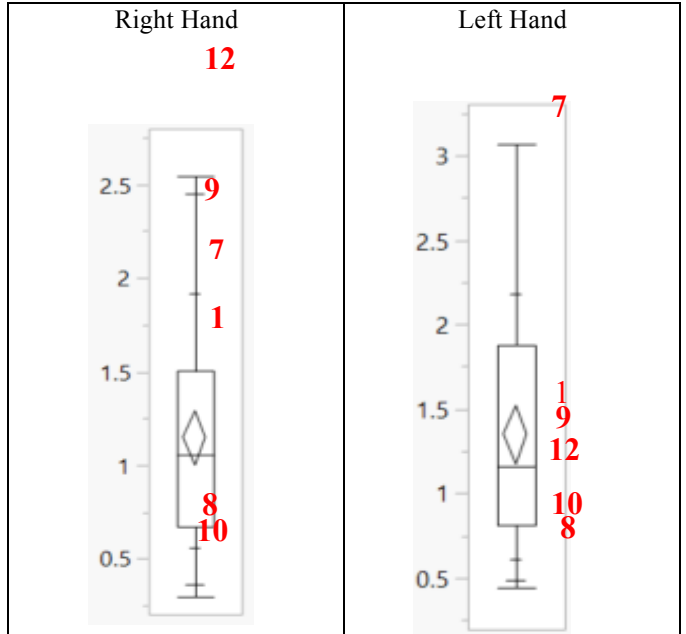
Figure 5: Dystmetria normative measures shown as a % of finger path length. Median and 25%-75% quartiles are indicated by the center and edges of the box.
Red numbers are subject IDs and indicate where representative TBI subjects fall within norms.
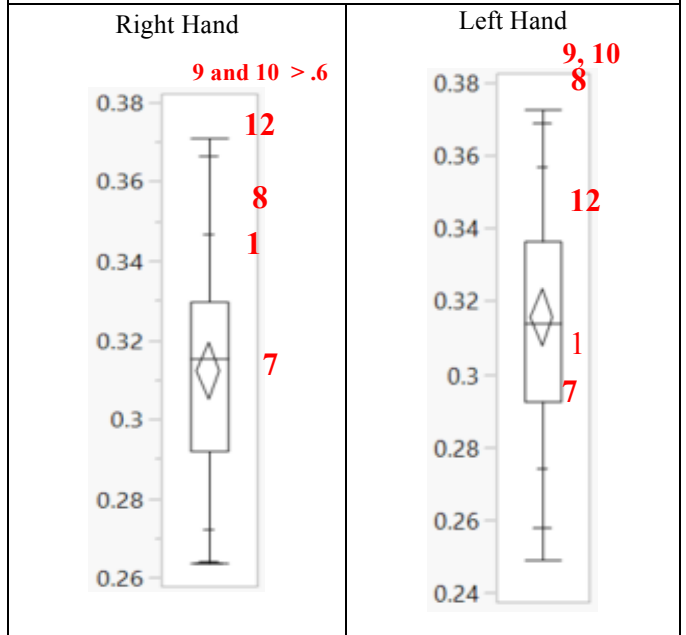

Right Hand   Left Hand

Figure 6: Reaction time (ms) normative data. Median and 25th – 75th quartiles are indicated by the center and edges of the box.
Red numbers are subject IDs and indicate where representative of TBI QMA data fit within the norms.
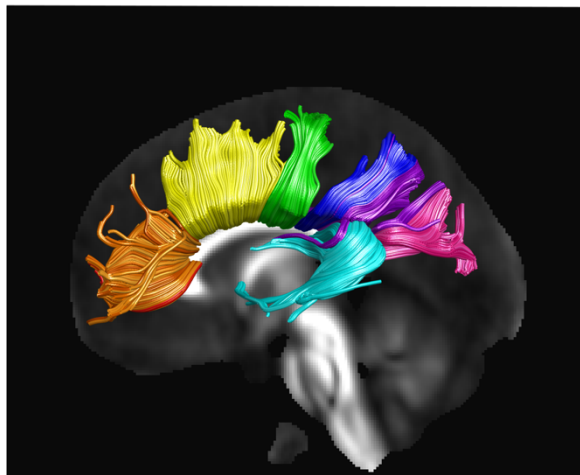
expect for regions of the left corticospinal tract. This finding requires further investigation. One possible explanation is there is low power in this group of four moderate to severe TBI patients.

Figure 7- Corpus callosum white matter tracks based on FA

Discussion

We used novel markerless motion capture technology to develop a quantitative motor assessment (QMA) and gather and analyze movement information from individuals who suffered a traumatic brain injury. We compared their results to normative standards to determine motor deficits. We also used advanced imaging techniques and MRI data analysis to determine the location and extent of neurological damage.

When we compared the results of the QMA test to normative data form healthy subjects, we found that though the results varied across individuals and tests, they generally fell outside of the established norms. This is indicative of the sensitivity of the QMA.

Analysis of fractional anisotropy (FA) within the motor tracts of the corpus callosum and the left and right corticospinal tracts indicate a difference between mild TBI and moderate to severe TBI groups. FA values are a measure of the diffusion process along axons. Values closer to zero indicate increased isotropic diffusion, indicative of damage to the axon. The expectation is that those with more severe TBI would have lower FA values. This is true of our results,
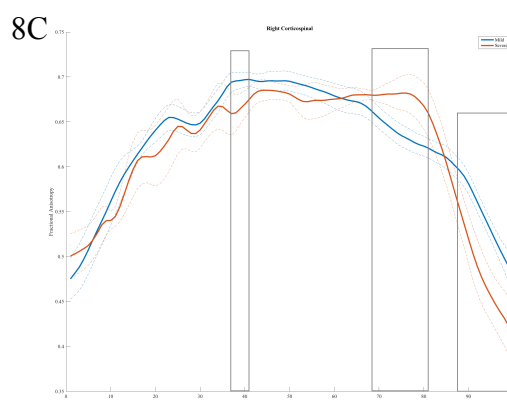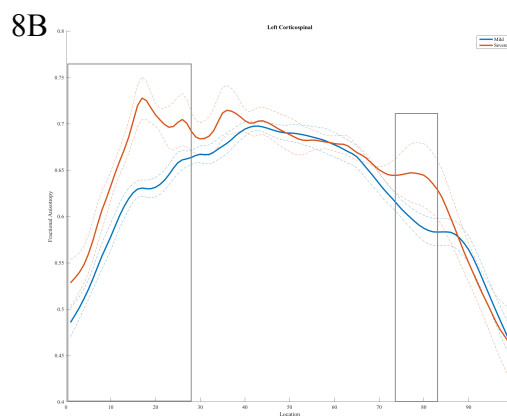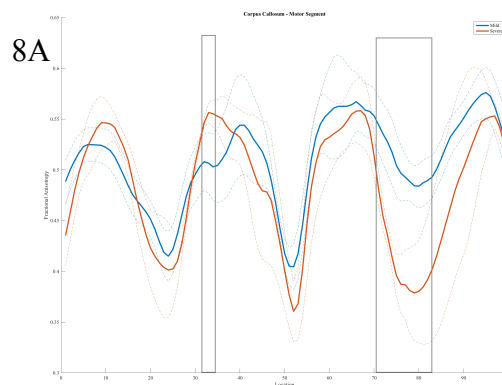

Figure 8: FA values for A. motor portion of corpus callosum. B. Left corticospinal tract. C. Right Corticospinal tract. Red: moderate to severe TBI; Blue: mild TBI

We compared the results of QMA tests to FA values found in three areas of the white

matter tracts, but found no strong statistically significant relationships. However, this does not mean that the QMA cannot be related to underlying damage. We will continue in this research direction expecting promising results with additional data from a larger number of TBI patients. Also, the data presented here are but a subset of the information gathered. There are additional QMA measures and white matter areas that we intend to analyze.

Conclusions

The QMA is an effective tool for identifying movement problems following a head injury. Not only is it sensitive and quantitative, it is portable and affordable. With data from additional TBI patients and complete analysis of all of the available QMA and MRI measures, we expect to determine associations between motor deficits identified by the QMA and the underlying neural issue. As such, the QMA will not only be a sensitive, low-cost test for identifying motor impairment, but also provide additional insights into the underlying damage causing those impairments. This new tool will lead to more accurate and detailed diagnosis and more informed rehabilitation prescriptions not only for TBI patients but in a wide variety of cases involving neural-based movement issues.

References

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