Administering Movement Assessments via Markerless Motion Capture Provides New Normative Values Over Clinical Tests

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Abstract

**Background:** Advances in markerless motion capture (MMC) provide an opportunity to improve clinical assessments of neuromuscular health. Conventional tests are generally subjective and/or coarse, making it difficult to identify subtle deficits and track progress. As part of a larger project, we leveraged MMC to create a quantitative motor assessment informed by several commonly used evaluations. The purpose of this research was to 1) seed a normative database for the MMC-mediated assessment and 2) to compare modified test results to analogous conventional tests.

**Methods:** The modified assessment consisted of five tests: finger oscillation, tremor, visually guided movement, reaction time, and balance. We administered it to 132 healthy individuals (64 females) between 18 and 50 years old.

**Results:** Descriptive statistics for measures on the MMC-mediated movement assessment from a healthy population are presented. Correlations between the modified and conventional tests were weak but followed similar trends, namely finger oscillation results depended on age and sex; reaction and movement time slowed with age; and balance sway was greatest on a soft surface with eyes closed.

**Conclusions:** A user-friendly, inexpensive, quantitative motor assessment is feasible with MMC; however, a new set of normative values is required for MMC-mediated tests.

1. Introduction

There is a recognized need for clinical measurements of neuromuscular health that are quantitative, accurate, relatively simple to administer, and cost-effective. Such exams could improve the evaluation, diagnosis, and treatment of movement disorders. Motor deficits are often subtle and complex and generally progress slowly with time, making it difficult to target the primary issue, track progress, and update rehabilitation prescriptions to an individual’s current needs. Although a variety of test batteries exist to evaluate motor deficits, they are generally lacking in one or more of these criteria (quantitative, accurate, and cost-effective). For example, clinical rating scales are cost-effective but are generally only semi-quantitative in that they require subjective scoring, generally based on a course scale from 0 to 4 [1, 2]. Traditional motion capture systems, such as optoelectronic systems, electromagnetic systems, inertial measurement units, and electrogoniometers are quantitative and highly accurate and can be used to identify movement impairments [3, 4], but they require placement of markers/sensors and calibration, making them time- and cost-prohibitive for routine clinical use. Robotic systems are also quantitative and highly accurate [5, 6], and in some cases require little setup time; however, such sophisticated technology can be cost prohibitive.

In contrast, advances in gaming technology provide an opportunity to develop motor batteries that are quantitative, cost-effective, and sufficiently accurate for clinical evaluation. Compared to traditional motion capture, markerless motion capture (MMC) systems, such as the X-box Kinect, Organic Motion, and Leap Motion Controller (LMC), are relatively low-cost and do not require any markers/sensors on the body, so movements can be recorded with little to no setup time. Although not as accurate as traditional motion capture systems, the accuracy of some MMC systems is approaching a level sufficient for clinical use. For example, the LMC, which tracks the movement of hands and fingers, has a static and dynamic accuracy below 0.5 mm and 1.2 mm, respectively [7, 8], and samples around 100 Hz.
However, just because MMC are sufficiently accurate does not make them ready for deployment to administer motor tests. One necessary step is to create clinically meaningful tests that can be administered via MMC. To this end MMC-mediated tests are emerging. For example, researchers have investigated the feasibility of using MMC to assess posture and movement in patients during at-home rehabilitation exercises [9] and in workers and athletes during lifting, squatting, and jump landings [10–12]. Their studies illustrate the potential for MMC as a remote form of movement evaluation. Other studies have compared MMC to marker-based motion capture systems in tests of fine motor movements [13] and visually guided movements [14]. They determined that the MMC is comparable in many aspects to motion capture with markers, and tests that utilize MMC are capable of distinguishing between healthy and diseased states. Similarly, we recently modified four of the most common conventional motor tests (visually guided movements, finger tapping, postural tremor, and reaction time) so they could be administered via the LMC, and we presented the successes and challenges encountered in administering those tests [15].

Another necessary step in preparing MMC-mediated motor batteries for clinical use is to establish test norms (the range of test results of neurotypical, healthy participants against which the results of impaired subjects can be evaluated) and compare these norms to those of similar conventional tests. The purpose of this study was to establish test norms for our recently developed MMC-mediated tests [15] as well as an additional MMC-mediated balance test, and to compare these norms to those of the conventional tests on which the MMC-mediated tests were based.

2. Methods

2.1 Participants

One hundred thirty-two healthy individuals (64 females) 18–50 years old (M = 29.9, SD = 9.7 years) participated in this study. All participants were right-handed and declared themselves free of any movement disorder or medications that interfere with movement or alertness. All procedures were in accordance with the Federal Policy for the Protection of Human Subjects, also known as the Common Rule. All participants provided informed consent, which was approved by the institutional review board for human research at Brigham Young University.

2.2 Modified and conventional tests

Complete details of the development of the MMC-mediated tests are described in Kincaid, Johnson & Charles (2023) [15]. Briefly, we scrutinized a variety of motor assessments associated with various movement-related disorders and identified the motor tests that were 1) most widely used, 2) most adaptable to LMC technology, and 3) most easily administered via the LMC. While adapting the tests, our goal was to modify the conventional tests as little as possible, only making changes where necessary to enable LMC administration. These tests necessarily exclude tests requiring the application or sensing of force (e.g. strength and muscle tone). The result was a battery of four modified movement tests: finger oscillation (FO), visually guided movement activity (VGM), postural tremor (PT), and simple reaction time (SRT). For this study, we added a fifth MMC-mediated test: standing balance. In addition, for comparison, we included corresponding conventional tests for three of the five modified exams: Halstead-Reitan Finger Tapping Test (HRFTT), a non-MMC simple reaction time test available online [16], and the NIH Toolbox balance tests [17]. We excluded conventional tests corresponding to PT and VGM because rating scales for such measures are zero for an unimpaired population. A summary of each test and its measures is provided in Table 1.
Table 1
Modified and conventional (non-MMC) motor assessment tests and measures.

<table>
<thead>
<tr>
<th>Modified Test</th>
<th>Attributes</th>
<th>Measures</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finger Oscillation</td>
<td>Movement speed, regularity, and efficiency</td>
<td>Number of complete finger oscillations</td>
<td>Count</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Variance of the period of the taps</td>
<td>ms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Variance of the amplitude of the taps</td>
<td>mm</td>
</tr>
<tr>
<td>Postural Tremor</td>
<td>Upper limb postural control</td>
<td>Power spectrum area</td>
<td>mm²</td>
</tr>
<tr>
<td>Visually Guided Movement</td>
<td>Movement accuracy and efficiency; Visuomotor control</td>
<td>Dysmetria—distance between the cursor and the target at the end of the movement, normalized by the direct path length</td>
<td>% of path length (unitless)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Path ratio—path length of movement to the direct path length</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximal speed</td>
<td>mm/s</td>
</tr>
<tr>
<td>Simple Reaction Time</td>
<td>Processing time</td>
<td>Reaction time—time between visual cue and arm movement</td>
<td>seconds</td>
</tr>
<tr>
<td>Balance</td>
<td>Postural control</td>
<td>Sway—normalized mean path of the crown of the head in five conditions: with feet together; feet tandem; hard surface; soft surface; eyes opened; eyes closed</td>
<td>mm/s</td>
</tr>
<tr>
<td>Conventional Tests</td>
<td>Attribute</td>
<td>Measures</td>
<td>units</td>
</tr>
<tr>
<td>Halstead-Reitan Finger Tapping Test (HRFTT)</td>
<td>Motor speed</td>
<td>Number of lever presses on a mechanical counter</td>
<td>count</td>
</tr>
<tr>
<td>Simple Reaction Time</td>
<td>Processing time</td>
<td>Reaction time—time between visual cue and keyboard press</td>
<td>Time (s)</td>
</tr>
<tr>
<td>NIH Toolbox Balance Test</td>
<td>Postural control</td>
<td>Sway—normalized mean Anterior-Posterior path length at the hips in five conditions: with feet together; feet tandem; hard surface; soft surface; eyes opened; eyes closed</td>
<td>Sway (m/s)</td>
</tr>
</tbody>
</table>

2.3 Experimental setup

Prior to each subject’s arrival, the LMC was calibrated for the ambient lighting and its relative position to the computer screen. For all but the balance tests, participants sat at a table in front of a computer screen. The LMC sat on the table, face up in front of the computer screen. Participants were introduced to the LMC and while watching the results of their hand movements on a screen, were instructed to keep their hand within the sensor’s field of view, which is approximately 150° deep and 120° wide and extends upward roughly 600 mm from the surface of the sensor for optimum tracking (Fig. 1). During each test, position and velocity of the fingertips and palm were recorded in three dimensions by the LMC at approximately 100 samples per second. For the balance test, the LMC was mounted on a tripod to record the movement of two wooden dowels attached to a helmet worn by the participant. An iPod used for the NIH balance tests was attached to a belt around the participant’s waist, so data for both balance tests were collected simultaneously. Upper-limb movements were performed on each side. The entire assessment lasted no more than two hours.
2.4 Experiment protocol

The tests were performed in random order, except the balance test, which was administered last to avoid upsetting the LMC-screen calibration for the other tasks. Administration of the modified and conventional tests were conducted according to established protocols. Each modified test is described fully in previous work [15] and condensed in Table 1, but we also provide a brief summary of each test here.

2.4.1 Modified Finger Oscillation Test

The finger oscillation test had a graphical user interface that contained two parallel lines, spaced 15 mm apart, a black ball controlled by the user’s finger, and a set of crosshairs marking the starting point (Fig. 2A). While pointing at the graphical user interface with their index finger over the LMC, participants were instructed to “tap” in the air, waving their finger up and down as fast as possible so that the black ball on the screen moved below the lower line, then above the upper line, repeatedly. They were also instructed to keep their wrist and shoulder stationary and move only at the finger joint. Each trial lasted 10 s, with a rest up to 90 s between trials. The assessment was complete when the subject performed five trials that were within five 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.

2.4.2 Modified Visually Guided Movement Test

The visually guided movement test involved moving a cursor from target to target. The graphical user interface for the test consisted of a small red ball-shaped cursor and black targets that appeared one at a time in the corners of the screen (Fig. 2B). The cursor was controlled by the user’s index fingertip. Participants were instructed to move the cursor to the black target as quickly and accurately as possible. After holding the cursor on the target for 500 ms, the target disappeared and a new target appeared, and the process repeated. Sixty targets were presented pseudo-randomly so that the 12 possible finger paths from corner to corner were travelled five times in each of two trials, for a total of 120 paths for each hand.

2.4.3 Modified Postural Tremor Test

Participants were instructed to position their hand above the LMC, with the palm down, so that the center of their “virtual hand” was in the center of a rectangle on the screen (Fig. 2C). In this location the hand was approximately 20 cm over the LMC. They held their hand at that location with the palm down and fingers spread for 30 s while the sensor captured their palm and finger movements. Two trials were performed with each hand.

2.4.4 Modified Simple Reaction Time Test

Participants held their hand approximately 20 cm over the LMC, centering a hand-shaped cursor over crosshairs in a large, gray-colored circle on the graphical user interface. When the hand was properly aligned, the background color changed from gray to white. At a random time no greater than 8 s, a smaller 15-mm diameter circle appeared centered on the palm of the virtual hand, and simultaneously the background color on the screen changed from white to green (Fig. 2D). Participants were instructed to remove their hand from the circle (referring neither to the smaller nor larger circle) as quickly as possible when the background color changed to green. Ten trials were performed with each hand.

2.4.5 Modified Balance Test
Participants wore a helmet modified with two dowels that protruded from the front of the helmet (Fig. 3A). Participants stood with feet together and hands across the chest so that the dowels extended over the LMC, which was mounted on a tripod. They held that position in five different conditions for 30 s each: 1) Standing feet together on a hard surface with eyes open, 2) standing feet together on a hard surface with eyes closed, 3) standing feet together on a soft surface with eyes open, 4) standing feet together on a soft surface with eyes closed, and 5) standing on a hard surface in a tandem stance, preferred foot in front, with eyes open. The participant was instructed to look forward at the wall during the tasks and was otherwise given no instruction. The LMC recorded the movement of the dowels, from which the movement of the crown of the hand was calculated.

2.4.6 Conventional Finger Oscillation Test: Halstead-Reitan Finger Tapping Test (HRFTT)

To provide a comparison for the Finger Oscillation test, participants also performed the Halstead-Reitan Finger Tapping test (HRFTT) [18]. The HRFTT is administered using an instrument consisting of a board with a mechanical counter attached. Participants started 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 (Fig. 3B). Participants were instructed to tap the lever as quickly as possible for 10 s. The administrator initiated the trial by saying, "Go", and kept time with a hand-held stopwatch. Similar to the Finger Oscillation test, the HRFTT test is complete when the total number of taps over five trials is within five taps of each other. 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 rests up to 90 s were given between trials.

2.4.7 Conventional Reaction Time Test: Key-Press Simple Reaction Time Test

To provide a comparison for the modified reaction time test, participants completed the Red Light – Green Light key-press reaction time test [16]. They were instructed to place any digit of the hand being tested on the space bar of a standard external keyboard and press it when the stoplight in the figure changed from red to green. The average time of five trials was recorded for each hand.

2.4.8 Conventional Balance Test: NIH Toolbox Standing Balance Test

For comparison with the MMC mediated balance test, participants also completed the NIH Toolbox standing balance test [17]. Participants wore a gait belt with an accelerometer synced to an iPad running the NIH toolbox balance test software. Since the instrumentation and protocol of the NIH Toolbox were compatible with those of the MMC mediated balance test (see above), the two tests were performed simultaneously. MMC mediated balance test trials finished 20 s before NIH toolbox test trials, so the participant was instructed to hold the pose until both tests were complete. After each of the five poses (described previously for the MMC mediated balance test), data were transferred from the accelerometer to the iPad.

2.5 Data processing

Raw position data from the LMC (position/orientation of the fingertips/palm/dowels) were processed as follows (for details, see Kincaid et al. [15]). Since the raw data were sampled at a variable sampling rate, raw data from all tests (except the reaction time test) were resampled at a constant rate of 100 samples per second. Motion capture
errors, including loss of tracking, were identified and removed in an automated fashion. More specifically, gaps in time greater than 50ms, jumps in position of more than 30 mm, and movements less than 20 samples long were flagged as invalid and excluded from the analysis. These threshold values were chosen after a thorough visual inspection of the data [15]. After this processing, we extracted a number of measures for each test (Table 2). Most measures reflect those included in the conventional tests from which each modified test was adapted.

### 2.5.1 Modified Finger Oscillation Test

Measures calculated for the finger oscillation assessment include the average number of up and down finger oscillations for each hand and the regularity of the movement. The average number was calculated over the five trials that were within five oscillations of each other. If the participant was not able to complete five trials within five oscillations of each other, the average was calculated for all 10 trials. Variation in period and amplitude was defined as the standard deviation of the period and amplitude of oscillations. Therefore, larger standard deviations indicate greater irregularity of movement.

### 2.5.2 Modified Postural Tremor

Tremor most commonly manifests in the tremor band, defined here as the frequency range from 4 to 12 Hz [19]. Without compensation, the bandwidth of the LMC is too low to track tremor accurately, so we passed the output of the LMC through an inverse filter designed to compensate for the low bandwidth [20]. The amount of postural tremor was defined as the power in the tremor band, computed as the area under the power spectral density (PSD) curve between 4 and 12 Hz. We integrated the PSD by trapezoidal integration over the tremor band, resulting in a measure of power for each repetition, axis (x, y, and z), and hand. Measures were averaged across repetitions and summed across axes, resulting in one measure of total power per hand.

### 2.5.3 Modified Visually Guided Movement Test

The Visually Guided Movement task provides measures of dysmetria, path ratio, and maximum speed. Dysmetria was defined as the distance between the center of the cursor at the end of the movement and the edge of the target, normalized by the distance between the cursor at the onset of the movement and the edge of the target. We normalized to account for differences in distance between targets, which were located at the corners of a square. Therefore, dysmetria is reported as a percent of the path length. Path ratio is the ratio of the path length to the direct distance between the onset position and the position at the end of movement. Maximum speed is the maximum speed between the onset and end of each movement. The onset and end of a movement were defined based on 5% of the maximum velocity, which was calculated by numerical differentiation with subsequent low-pass filtering (for details, see Kincaid et al. [15]).

### 2.5.4 Modified Simple Reaction Time

Reaction time was defined as the time between the appearance of the visual stimulus (the change of the background from white to green) and the moment the center of the palm exited the 30 mm (diameter) circle. The center of the circle followed the center of the palm of the hand during the waiting period, allowing subjects to drift. The reported measure is the average of ten trials for each hand.

### 2.5.5 Modified and Conventional Balance Tests

The LMC recorded the position and orientation of the dowels while the subject performed each of the five tasks. During some trials, the dowels drifted outside the sensory range of the LMC, or facial features obstructed the
recognition of the dowels, causing erroneous spatial jumps between successive samples. To adjust for this, we eliminated successive samples with a jump distance of more than 5 mm from each other. The temporary loss of dowels also caused a larger time gap, so we removed any successive samples spaced more than 50ms in time. The normalized path length (NPL) was defined as the 3-dimensional path length of the crown of the head divided by the duration over which the path was measured:

$$NormalizedPath = \frac{\sum \Delta p_i}{\sum \Delta t_i} = \frac{\sum_i \|\vec{p}_{i+1} - \vec{p}_i\|}{\sum_i (t_{i+1} - t_i)}$$

where $\Delta p$ is the distance between the position of the crown of the head at one sample ($\vec{p}_i$) and the position at the next sample ($\vec{p}_{i+1}$), $\|\|$ represent the length of the vector inside the brackets, and $\Delta t$ is the time between samples. Measures from the NIH toolbox balance test are similarly calculated [21].

2.6 Data analysis

Two primary goals drove the data analyses: 1) Provide descriptive statistics for each of the modified tests, and 2) Compare modified test norms and trends to those of the corresponding conventional tests.

Trials with values greater than three standard deviations from the mean were considered outliers and excluded from the analysis. Roughly two percent of more than 2500 values were excluded in this manner. To establish each measure's normative range, the dataset was tested for normality using normal quantile plots. Measures not normally distributed were transformed with a log transform and the transformed data were verified for normality. Regressions were performed to determine the effect of age and gender on each measure. Pearson correlation tests and ANOVAs with a Bonferroni correction were used to quantify relationships between measures from the modified and conventional tests and identify trends in the modified test data. Statistical tests were performed using JMP Pro 13.0 (SAS Institute, Cary, NC).

3. Results

3.1 Normative data of modified tests

All participants performed the tasks without incident, resulting in the measures listed in Table 2. Where normative values for conventional test are stratified by age and sex, we similarly stratified the analogous modified versions.
Table 2
Summary of descriptive data from modified tests.

<table>
<thead>
<tr>
<th>Name</th>
<th>Test Measure (units)</th>
<th>N</th>
<th>Mean Age ± SD years</th>
<th>Median</th>
<th>Q1</th>
<th>Q3</th>
<th>Mean</th>
<th>SD</th>
<th>Upper 95%</th>
<th>Lower 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finger Oscillation (FO)</td>
<td></td>
<td></td>
<td>25</td>
<td>38 ± 7</td>
<td>44.6</td>
<td>36.2</td>
<td>51.6</td>
<td>43.3</td>
<td>9.4</td>
<td>47.1</td>
</tr>
<tr>
<td></td>
<td>Count -r Male ≥ 30 yr</td>
<td></td>
<td></td>
<td>38 ± 7</td>
<td>40.2</td>
<td>33.3</td>
<td>44.0</td>
<td>39.2</td>
<td>8.3</td>
<td>42.6</td>
</tr>
<tr>
<td>FO count-l</td>
<td></td>
<td></td>
<td>25</td>
<td>38 ± 7</td>
<td>44.6</td>
<td>36.2</td>
<td>51.6</td>
<td>43.3</td>
<td>9.4</td>
<td>47.1</td>
</tr>
<tr>
<td></td>
<td>Male ≥ 30 yo</td>
<td></td>
<td></td>
<td>38 ± 7</td>
<td>40.2</td>
<td>33.3</td>
<td>44.0</td>
<td>39.2</td>
<td>8.3</td>
<td>42.6</td>
</tr>
<tr>
<td>FO-R</td>
<td></td>
<td></td>
<td>27</td>
<td>24 ± 2</td>
<td>57.6</td>
<td>55.0</td>
<td>59.4</td>
<td>56.8</td>
<td>5.1</td>
<td>58.8</td>
</tr>
<tr>
<td></td>
<td>Male &lt; 30 yo</td>
<td></td>
<td></td>
<td>24 ± 2</td>
<td>57.6</td>
<td>55.0</td>
<td>59.4</td>
<td>56.8</td>
<td>5.1</td>
<td>58.8</td>
</tr>
<tr>
<td>FO Count-r</td>
<td></td>
<td></td>
<td>27</td>
<td>24 ± 2</td>
<td>51.6</td>
<td>49.0</td>
<td>55.0</td>
<td>51.5</td>
<td>5.0</td>
<td>53.5</td>
</tr>
<tr>
<td></td>
<td>Male &lt; 30 yo</td>
<td></td>
<td></td>
<td>24 ± 2</td>
<td>51.6</td>
<td>49.0</td>
<td>55.0</td>
<td>51.5</td>
<td>5.0</td>
<td>53.5</td>
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<tr>
<td>FO Count-r</td>
<td></td>
<td></td>
<td>26</td>
<td>42 ± 6</td>
<td>38.3</td>
<td>30.7</td>
<td>44.1</td>
<td>37.4</td>
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<td>41.0</td>
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<td>44.1</td>
<td>37.4</td>
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<td>41.0</td>
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<td>42 ± 6</td>
<td>35.8</td>
<td>29.2</td>
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<tr>
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<td></td>
<td></td>
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<td>22 ± 3</td>
<td>54.0</td>
<td>50.8</td>
<td>56.4</td>
<td>52.6</td>
<td>6.2</td>
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<tr>
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<td></td>
<td>22 ± 3</td>
<td>54.0</td>
<td>50.8</td>
<td>56.4</td>
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<td>FO Count-l</td>
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<td></td>
<td>23</td>
<td>22 ± 3</td>
<td>45.4</td>
<td>42.2</td>
<td>51.8</td>
<td>45.8</td>
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<td>9.0</td>
</tr>
<tr>
<td></td>
<td>Female &lt; 30 yo</td>
<td></td>
<td></td>
<td>22 ± 3</td>
<td>45.4</td>
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<td>51.8</td>
<td>45.8</td>
<td>7.6</td>
<td>9.0</td>
</tr>
<tr>
<td>Per-Var-r (ms)</td>
<td>99</td>
<td></td>
<td>31 ± 10</td>
<td>16.2</td>
<td>12.7</td>
<td>19.5</td>
<td>17.6*</td>
<td>10.3*</td>
<td>19.2*</td>
<td>16.2*</td>
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<tr>
<td>Per-Var-l (ms)</td>
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<td></td>
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<td>24.3*</td>
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<td>5.5</td>
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<td>1.5</td>
<td>5.0</td>
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<tr>
<td>Amp-Var-l (mm)</td>
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### Table 1: Descriptive Statistics for Modified Balance Measures

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*Indicates back-transformed values

List of abbreviations: Finger Oscillation (FO); Period Variance (Per-Var); Amplitude Variance (Amp-Var); Postural Tremor (PT); Visually Guided Movement (VGM); Dysmetria (Dys); Path Ratio (PR); Maximum Speed (MxS); Simple Reaction Time (SRT). Balance poses: Feet together (tgthr); Feet tandem (tndm); Hard surface (hrd); Soft surface (sft); Eyes open (opn); Eyes closed (clsd).

### 3.2 Comparison of modified tests to conventional tests

Three modified tests were compared to their corresponding conventional clinical tests: 1) the finger oscillation test to the Halstead-Reitan finger tapping test, 2) the modified simple reaction time test to the Key-press simple reaction time test, and 3) the MMC-mediated balance tests to the NIH toolbox balance tests. As previously mentioned, we did not administer conventional analogues of the modified tremor or visually guided movement tests because they dictate zero values for an unimpaired population.

#### 3.2.1 Correlations

The finger oscillation tests for each hand were weakly correlated to the HRFTT for the corresponding hand (right hand $r = 0.23$, $p = .023$; left hand $r = 0.33$, $p < .001$). There were no significant correlations between the measures of the modified and conventional reaction-time tests, nor between the measures of the modified and conventional balance tests.

#### 3.2.2 Behavioral Trends
The behavioural trends of the modified tests generally matched those of the conventional tests assessed in this study and/or past studies.

### 3.2.2.1 Finger Tapping/Oscillation

The finger oscillation test showed similar trends as the HRFTT (Fig. 4). Specifically, there was a main effect for gender on both hands in the finger oscillation test (right: \(F(1,100) = 7.62, p = .007\); left: \(F(1, 100) = 11.53, p = .001\)) as well as the HRFTT (right: \(F(1, 100) = 37.37, p < .0001\); left: \(F(1,100) = 31.64, p < .0001\)). Men made more finger oscillations than women, with a mean difference of 5.72 oscillations on the right (95% CI [1.61, 9.83]) and 6.13 oscillations on the left (95% CI [2.54, 9.71]). Similarly, males made more taps on the HRFTT than females on both hands (p < .0001 for both), with a mean difference of 6.12 taps (95% CI [4.13, 8.11]) on the right and 6.08 taps (95% CI [3.93, 8.22]) on the left. There was a significant decline in the number of finger oscillations with age (0.76 oscillations/year on the right, p < .0001; 0.63 oscillations/year on the left, p < .0001); however, not with the HRFTT (Fig. 4B). For the finger oscillation test, we also analyzed the regularity of finger oscillations but did not find any effect of age or sex.

### 3.2.2.2 Reaction Time and Movement Speed

Visualization of changes in reaction time and maximum speed with age in our tests are shown in Fig. 5B. The modified simple reaction test showed a slowing of reaction time with age (right \(F(1,98) = 10.29, p = .0002\); left \(F(1,98) = 13.79, p = .0003\)); however, the small increase in reaction time was not meaningful (less than 0.01%). No significant change in reaction time on the key press was observed with age even though reaction time has been shown to increase with age [22, 23]. The effect of aging on maximum speed in our visually guided movement tests are visualized in Fig. 6. As expected, the maximum speed on the visually guided movement test declined with age on both hands (right \(F(1, 96) = 36.05, p < .0001\); left \(F(1,96) = 28.3, p < .0001\)). However, there were no significant differences between males and females on any of these tests (Fig. 5A and Fig. 6A) despite past evidence of a gap in reaction time between the sexes [24] though this gap has significantly narrowed over the past decade [25].

### 3.2.2.3 Balance

Sway measured at the head in MMC-mediated balance tests was greater with eyes closed on both hard and soft surfaces (Fig. 7) (p < .0001 in both cases). Head sway was also greater on the less stable soft surface (compared to the hard surface) with eyes open or closed (p < .0001 in both cases). Similarly, the sway measured at the hip in the NIH toolbox balance test was greater with eyes closed on both hard and soft surfaces, and greater on the soft surface with eyes open or closed (p < .0001 in all four cases). In both the MMC-mediated balance and NIH toolbox tests, the greatest mean difference in the amount of sway was between the stable hard surface with eyes open and the less stable soft surface without the benefit of visual cues (p < .0001 for both tests).

### 4. Discussion

The aim of this research was to establish test norms for our four recently developed MMC-mediated tests [15] and an additional MMC-mediated test (the balance test), and to compare these norms to those of the conventional tests on which the MMC-mediated tests were based. To this end, we administered the modified tests to 132 unimpaired subjects. The modified tests provided movement data with relatively high accuracy (~1mm) and sampling rate (~100 samples/s) using a setup that is portable, inexpensive, and user-friendly.
The modified tests results did not correlate well with the conventional tests results. However, the measured trends of the MMC-modified tests generally aligned with their traditional counterparts, as well as with their published norms. According to the Handbook of Normative Data for Neuropsychological Assessment [26], sex and age exert powerful effects on tapping speed, with men consistently tapping faster than women, and slowing on the tap test occurring with age. Additionally, slower movement and reaction time occur with age [18]. Trends in the MMC mediated balance tests were similar to those on force-platform tests [27, 28], computerized posturography [29, 30], and Romberg tests [31], which exhibit more sway in standing postures with the eyes closed on unstable surfaces (compared to eyes open and stable surfaces).

Although the MMC-mediated test results followed the trends of the traditional tests, there were clear differences. These differences in results were likely caused by differences in the tests, most of which were dictated by constraints of the LMC (despite our efforts to make the modified tests as close as possible to the conventional test). The consequences to the subjects included differences in visual and haptic feedback (and perhaps fatigue), which may have contributed to the lack of correlation between the sets of batteries.

Although the LMC accurately measures low-frequency oscillatory movements (less than approximately 3 Hz), the limited bandwidth reduces the accuracy for movements of a higher frequency[20]. Consequently, the visual feedback for the graphical user interface was incongruent in two ways. First, the cursor representing the subject’s fingertip moved with less amplitude than their actual fingertip. At the frequency of the finger oscillations (around 5 Hz), the amplitude of cursor movement was about 80% of the amplitude of finger movement. Second, the cursor lagged behind the subject's fingertip. At the frequency of finger oscillations, this phase shift was roughly 90°. The combination of incongruent feedback on amplitude and timing likely reduced subjects’ ability to make finger oscillations as quickly as possible without ignoring the graphical interface. In addition, because the cursor moved less than the finger, the software likely failed to record some successful oscillations.

An important difference between the modified finger oscillation test and the conventional HRFTT is that the HRFTT involved haptic feedback as the participant pressed the lever and the lever bounced back to the starting position. In contrast, the finger oscillation test required the participant to hold their hand over the sensor and oscillate their index finger in the air with purely visual and proprioceptive feedback as a guide to the movement. There was also a haptic element in the reaction time test with a quick keyboard press of the finger vs. movement at the wrist and elbow over the LMC in the modified test.

Because all of the movements were performed in the field of view over the LMC, upper limb weakness was more of a factor in the modified tests than their counterparts. A number of the tests required subjects to perform actions in rapid succession or while resisting gravity, so it’s likely that the results introduce fatigue with continued trials despite the provided rest periods. The modified reaction time test and the visually guided movement tests required subjects to have their arm extended while awaiting the stimulus. The participant’s arm was also extended over time in the finger oscillation test while simultaneously performing the up-and-down finger movement as quickly as possible. Fatigue may be an even greater factor when conducting assessments on individuals with impairments.

The LMC constraints also lead to notable differences in the balance assessments. The modified balance tests measured the path of the crown of the head where we could mount finger-like extensions that the LCM would recognize, whereas the NIH toolbox balance tests measured movement at the hips.
4.2 Advantages and disadvantages of sensor-based movement assessments

This study exposed strengths and weaknesses of using MMC in general to evaluate movement deficits. Compared to conventional clinical tests, MMC provide greatly increased accuracy, sampling rate, number of samples, and number of potential measures (Wren 2023, Pottorf, Vapne, Ghilgiarelli, Haase, 2023; Lam, Tang, Fong 2023, Drazan 2021). Furthermore, MMC-mediated tests can provide measures of movement previously unavailable in clinical practice. In tandem with careful observation from the test administrator, these measures could yield deeper insight into the causes underlying deficits. For example, poor performance on the finger oscillation test may be caused by weakness or irregularity. The data captured by MMC allow one to easily calculate measures relating to these causes, such as movement speed vs. variability in frequency or amplitude. However, MMC is not a practical solution for all situations. Some tests are more easily or robustly administered using other technology [15]. For example, the NIH toolbox balance test, which uses a hip-worn accelerometer, is simpler to administer and interpret than the MMC-mediated balance test used in the current study. Also, patients may be unfamiliar with (or even intimidated by) MMC systems and find it difficult to relate to visual feedback on a computer monitor, which usually requires at least some degree of visuomotor transformation. Also, any automated test focuses only on the aspects for which the test was designed and may miss subtle or even obvious aspects observable by a trained clinician. In light of these strengths and limitations, MMC systems may be most valuable in the following situations: 1) automated pre-screening, 2) regular evaluations to determine effect of interventions or progression of disorder (as opposed to diagnosis), 3) evaluations at home or in care centers with little access to movement-disorder expertise, and 4) for individuals whose movement deficits are not well-captured by conventional clinical tests, including subjects with mild deficits where conventional tests often fail to pick up anything, or very severe deficits where conventional scales often run into a ceiling effect.

4.3 Limitations

The purpose of this study was to establish test norms for our MMC-mediated tests and to compare these norms to those of the conventional tests on which the MMC-mediated tests were based. However, the normative data were collected from a college community where the majority of the participants have more than 12 years of education. Some motor test results, such as reaction time, are known to be influenced by participants’ level of education [18]. Thus, some of the normative data may not be representative of populations with less education.

5. Conclusions

This study provides normative values from a healthy population for a battery of MMC-mediated movement tests. The MMC-mediated normative values are different from their traditional clinical counterparts, likely due to differences in the tests dictated by constraints of the MMC device; however, both traditional clinical and MMC-mediated tests followed similar expected performance patterns. The MMC-mediated tests are easy to set up and provide objective and quantitative measures, including information about the variance in frequency and amplitude of finger oscillation and dysmetria not available from traditional clinical tests. The modified tests with their normative values set the foundation for quantitative assessment of motor impairments. As MMC systems continue to advance, especially in the area of whole-body motion capture, the possibilities for more tests, such as gait analysis, become more practical in the clinical setting. Such assessments, however, will require their own set of normative data.
Declarations

6.1 Ethics approval and consent to participate

The study was approved by the Brigham Young University Institutional Review Board for Human Research Ethics and conducted in compliance with U.S. Department of Health and Human Services Code of Federal Regulations (45 CFR 46) Subpart A, also known as the Common Rule. All participants gave their written informed consent prior to entering the study.

6.2 Consent for publication

The authors confirm that any aspect of the work covered in this manuscript (including individual details and images) that has involved human participants has been obtained with the consent for publication from all relevant bodies.

6.3 Availability of data and materials

Interested parties can contact the corresponding author with reasonable requests to access the datasets collected and analyzed for this study.

6.3 Competing interests

The author affirm that there are no competing interests associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

6.4 Funding

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6.5 Authors' contributions

Paula K. Johnson: conceptualization, methodology, software, formal analysis, resources, data curation, writing (draft, reviewing, and editing), visualization, project administration, funding acquisition.

Clay J. Kincaid: methodology, software, formal analysis, data curation, writing (reviewing and editing)

Nicholas L. Lush: software, data curation, writing (reviewing, and editing)

Stephen J. Jackson: writing (reviewing and editing)

Dennis Eggett: formal analysis, writing (reviewing and editing)

J. Brent Feland: conceptualization, methodology, writing (reviewing and editing)

Erin D. Bigler: conceptualization, methodology, resources, writing (reviewing and editing)

Steven K. Charles: conceptualization, methodology, resources, writing (reviewing and editing), supervision

6.6. Acknowledgements
The authors would like to thank and acknowledge the participants in the study for their time and willingness to contribute to the scientific process.

References


Figures
Figure 1

Experiment Setup for most tasks. Participants (A) use their index finger to move a cursor or (B) hold their palm over the Leap Motion Controller (LMC) while it recorded their movement.

Figure 2

Graphical User Interface for modified tests: (A) finger oscillation, (B) visually guided movements, (C) postural tremor, (D) and reaction time.
Figure 3

(A) Balance test setup on the soft surface. The Leap Motion Controller (LMC) is mounted on the tripod and tracks the dowels on the helmet. (B) The Halstead-Reitan Finger Tapping Test (HRFTT) setup.
Figure 4

(A) Number of finger oscillations/taps in the MMC-mediated Finger Oscillation Test and the Halstead-Reitan Finger Tap Test (HRFTT) for males and females. The first box of each pair is the dominant hand, the second is the non-dominant hand. Each box shows the median and 1st and 3rd quantiles. The whiskers indicate the min and max. The diamond shows the mean and 95% CI. The dots are outliers. The red line indicates the shortest half (i.e. the smallest interval that contains 50% of the data). (B) Spline curves of the HRFTT (top pair) and Finger Oscillation Test (bottom pair) results by age. The uppermost of each pair represents the dominant hand.

Figure 5

(A) Reaction time (s) from the MMC-Mediated and online key press reaction tests, respectively, for females and males. The first box of each pair is the dominant hand, the second is the non-dominant hand. Each box shows the
Figure 6

(A) Maximum speed (mm/s) for Visually Guided Movement (VGM) tests grouped by sex. The first box of each pair is the dominant hand. The box shows the median and 1st and 3rd quantiles. The whiskers indicate the min and max. The diamond shows the mean and 95% CI. The dots are outliers. The red line indicates the shortest half (i.e. the smallest interval that contains 50% of the data). (B) Spline curves of the MMC-mediated reaction time test (top pair) and online computer key press reaction time (bottom pair) results by age. The uppermost of each pair represents the dominant hand.
MMC-Mediated and NIH Toolbox balance tests have similar qualitative results; sway is least on a hard surface with eyes open and greatest on a soft surface with eyes closed.