# Robotic Assessment of Sensorimotor Deficits After Traumatic Brain Injury

*Chantel T. Debert, MD, MSc, Troy M. Herter, PhD, Stephen H. Scott, PhD, and Sean Dukelow, MD, PhD*

**Background and Purpose:** Robotic technology is commonly used to quantify aspects of typical sensorimotor function. We evaluated the feasibility of using robotic technology to assess visuomotor and position sense impairments following traumatic brain injury (TBI). We present results of robotic sensorimotor function testing in 12 subjects with TBI, who had a range of initial severities (9 severe, 2 moderate, 1 mild), and contrast these results with those of clinical tests. We also compared these with robotic test outcomes in persons without disability.
**Methods:** For each subject with TBI, a review of the initial injury and neuroradiologic findings was conducted. Following this, each subject completed a number of standardized clinical measures (Fugl-Meyer Assessment, Purdue Peg Board, Montreal Cognitive Assessment, Rancho Los Amigos Scale), followed by two robotic tasks. A visually guided reaching task was performed to assess visuomotor control of the upper limb. An arm position-matching task was used to assess position sense. Robotic task performance in the subjects with TBI was compared with findings in a cohort of 170 person without disabilities.
**Results:** Subjects with TBI demonstrated a broad range of sensory and motor deficits on robotic testing. Notably, several subjects with TBI displayed significant deficits in one or both of the robotic tasks, despite normal scores on traditional clinical motor and cognitive assessment measures.
**Discussion and Conclusions:** The findings demonstrate the potential of robotic assessments for identifying deficits in visuomotor control and position sense following TBI. Improved identification of neurologic impairments following TBI may ultimately enhance rehabilitation.

**Key words:** *proprioception, reaching, rehabilitation, robotics, traumatic brain injury*

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The Hotchkiss Brain Institute, Division of Physical Medicine and Rehabilitation, Department of Clinical Neurosciences, University of Calgary, Calgary, Alberta, Canada (C.T.D., T.M.H., S.D.); and Department of Anatomy and Cell Biology, Queen's University, Kingston, Ontario, Canada (T.M.H., S.H.S.)

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**Correspondence**: Sean Dukelow, E-mail: sean.dukelow@albertahealthservices.ca



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## INTRODUCTION

Traumatic Brain Injury (TBI) is a health problem that transcends gender, age, and race. Incidence of TBI ranges from 250 to 300 per 100,000 people in developed Western countries[1,2] and is approximately 1.7 million annually in the United States.[3-5] Traumatic brain injury can produce complex and heterogeneous neurologic deficits. In clinical studies, tasks such as the Purdue Pegboard test, Fugl-Meyer Assessment tool, finger-tapping test, go/no-go test, alertness test, and physical performance measures (eg, strength testing and gait analysis) have demonstrated that motor impairments in individuals with mild to severe TBI often persist long after the initial injury.[6-13] Some of these assessments rely on observer-based ordinal scales, which may miss subtle but potentially clinically important changes. Others provide little insight into why an individual has difficulty with a task.[14] Furthermore, to our knowledge, no study has rigorously assessed proprioceptive impairment following TBI.

Deficits in sensory, motor, or cognitive function may play a role, individually or in combination, in the inability to perform daily activities. Identifying deficits, and the magnitude of these deficits, should represent one of the first steps in developing a rehabilitation treatment plan. In clinical practice, the detection and quantification of abnormalities, even if small, may be useful when advocating for rehabilitation resources for individuals with TBI. Furthermore, the development of better assessment tools has been identified as a key step in improving clinical trials in rehabilitation.[15] Finally, better assessment tools should help provide insight into the neurophysiologic basis of deficits and thereby help guide development of novel therapeutic approaches.

For many years, basic scientific research on human motor performance has used robotic technology to assess sensorimotor function.[16-18] Robotic technology combined with virtual reality offers obvious value for quantifying sensorimotor impairments, because of the ability to measure a subject's performance during a variety of behaviors in a highly controlled sensory and motor environment.[14] Robotic assessments are inherently objective and may allow for detection of small changes in function not visible to the human examiner. The purpose of this study was to explore the feasibility of using robot-based assessments to detect and quantify arm sensory and motor deficits in a series of individuals with TBI. Here, we present the results of the robotic assessments, accompanied by a number of traditional clinical assessments.

## METHODS

### Subjects

Subjects with TBI were recruited as inpatients and outpatients at the Foothills Medical Centre in Calgary, Alberta, Canada. Subjects with TBI were included in the study if they were 18 years of age or older and were able to understand the instructions required to complete the assessments. They were excluded from the study if they had ongoing acute medical issues (eg, active cardiac disease), history of a prior TBI, other neurologic disorders, or ongoing musculoskeletal problems of the upper extremity. For comparison, persons without disabilities (comparison subjects) were recruited from the communities of Calgary and Kingston (Ontario, Canada). Contact was made through posted flyers, advertisements in local newspapers, and direct communication with families of inpatients at the Foothills Medical Centre and St Mary's of the Lake Hospital (Kingston). Recruitment was tailored to obtain a roughly uniform distribution of subjects aged between 20 and 85 years and equal representation of both sexes. Comparison subjects were excluded from the study if they had any history of neurologic disorders or ongoing musculoskeletal problems of the upper extremity. All subjects provided informed consent before participating in the study. This study was approved by the research ethics boards at the University of Calgary, Queen's University, and Providence Care.

### Clinical History

Subject demographics and histories were obtained from charts. We report Glasgow Coma Scale (GCS) scores determined on arrival at the emergency department. TBI was defined on the basis of GCS scores, as follows: a score $>12$, mild; 9 to 12, moderate; and $\leq 8$, severe.[19] Durations of posttraumatic amnesia (PTA) and loss of consciousness (LOC) were obtained from patients' clinical charts but were self-reported when such information was otherwise unavailable. Radiologic characteristics of each TBI were documented from computed tomography scans reviewed by a neuroradiologist.

### Clinical Assessment

The clinical assessment took 60 to 90 minutes to complete and was done prior to the robotic assessment.

#### TBI Subjects

A brief medical history was taken. Neurologic examination of the upper extremities included muscle power and reflexes.[20] A Modified Ashworth Scale was used to assess spasticity.[21] Range of motion was evaluated to ensure that it was adequate for subjects to complete both robotic tasks. Visual acuity was tested with a Snellen eye chart to ensure adequate vision to complete the tasks. Visual fields were tested by the confrontation technique.[20] Clinical assessments included the Edinburgh Handedness Inventory,[22] upper-extremity portion of the Fugl-Meyer Assessment (FMA),[23] Purdue Pegboard (PPB),[24] Ranchos Los Amigos Scale,[25] Montreal Cognitive Assessment (MoCA),[26] and Behavioral Inattention Test.[27] These were performed because they represent a mix of assessments used in standard clinical care of patients with TBI and those historically used to assess sensorimotor function after TBI. All assessments were performed by either a trained study physician or a physical therapist.

#### Comparison Subjects

Before performing the robotic assessment, comparison subjects completed a simplified clinical assessment, including the Edinburgh Handedness Inventory and tests for muscle power, dexterity (PPB), visual acuity, and visual fields.

### Robotic Assessment

#### Apparatus

Robotic assessment was performed with the KINARM exoskeleton robot (BKIN Technologies Ltd, Kingston) (Figures 1A and 1B).[28-30] Subjects sat in a modified wheelchair seat with their arms placed in exoskeletal supports that were adjusted to fit each individual. The exoskeleton provided gravitational support of the upper limbs and permitted movements in the horizontal plane. Subjects viewed a virtual reality display that projected visual targets in the same plane as the arms and hands. During robotic tasks, direct vision of the arms and hands was occluded. Identical robots and procedures were used at the Foothills Medical Centre, St Mary's of the Lake Hospital, and Queen's University testing sites.

#### Visually Guided Reaching Task

This task was used to assess visuomotor control of the upper extremity (Figures 2A and 2B).[28] Subjects were instructed to reach as "quickly and accurately" as possible from a central target (1.0-cm radius) to one of eight peripheral targets

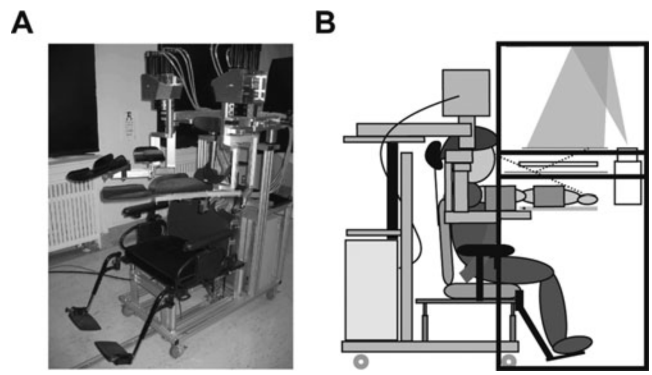


**Figure 1.** Apparatus. A, Photograph of the KINARM exoskeleton robot, showing the modified wheelchair base and exoskeletal arm troughs linked to motors mounted up top. B, Schematic diagram illustrating the KINARM exoskeleton robot docked to the augmented reality workstation in which subjects view targets projected through a semitransparent mirror onto the same plan as their arms and hands.

 

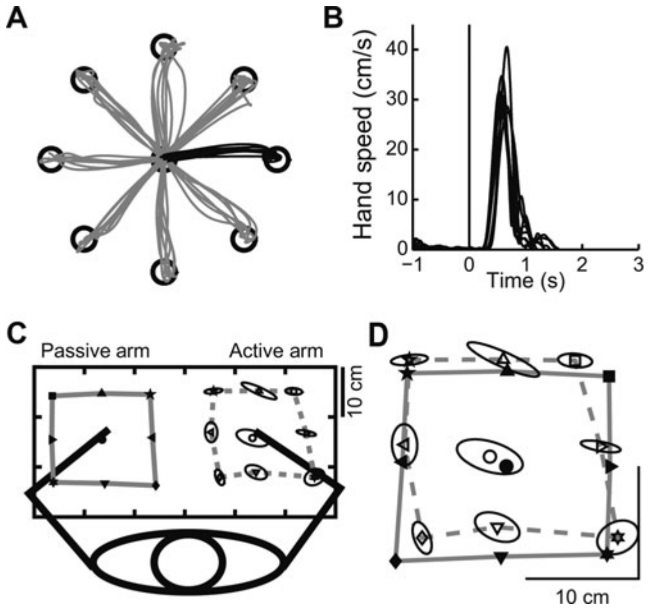


**Figure 2.** Robotic assessment tasks. A, Hand paths (reaching trajectories) of a subject without disability performing the visually guided reaching task with the right arm. B, Hand-speed profiles of reaching movements to the target on right in A (shown in black). C, Workspace view of the same subject without disability performing the arm position-matching task, using the right hand to actively match the passively moved left hand. Mean hand positions of the passive (closed symbols) and active (open symbols) hands are shown for each of the nine target locations. Mean positions of the eight peripheral targets are joined by solid (passive hand) and dashed (active hand) gray lines. Variability of the active hand is illustrated with the ellipses (1 SD) centered on each open symbol. D, Illustration of the matching performance in C, with the passive left hand superimposed on the active right hand. Symbols are the same as in C.

(1.0-cm radius) distributed uniformly 10 cm from the center. The central target was located near the center of the workspace for each arm. The position of the index finger was presented as a white dot (0.5-cm radius) by means of the virtual reality system. Subjects started each trial by holding their index finger at the center target for 1250 to 1750 ms before the peripheral target was illuminated. Each peripheral target was presented once in a randomized block, which also included two "catch" trials in which a peripheral target was not presented. Eight blocks were obtained, for a total of 80 trials. All subjects completed the task twice, once with each arm, in random order (total time ≈ 12 minutes).

### Arm Position-Matching Task

This task was used to assess accuracy of upper extremity position sense (Figures 2C and 2D).[30] The robot moved one arm (passive arm) to one of nine different target locations. After the robot completed the movement, subjects actively moved the opposite arm (active arm) to the mirror location in space. Each of the nine target locations was presented once in a randomized block. Six different blocks were obtained, for a total of 54 trials. Subjects completed the task twice, once with each arm, in random order (total time ≈ 7 minutes).

### Data Analysis

For the reaching task, data are reported for nine parameters.[28] Descriptions/definitions of these parameters are given in Table 1. Most measures were characterized by computing median values across all trials and targets (posture speed, reaction time, initial direction error, initial distance ratio, movement time, and maximum speed), whereas highly nonlinear parameters (initial speed ratio, number of speed peaks, and minimum–maximum speed difference) were defined on the basis of a mean (see Coderre et al[28]). For the arm position-matching task, data are reported for three measures of underlying position sense[30]: (1) variability, (2) spatial contraction/expansion, and (3) systematic shifts (Table 1).

Statistical analyses were performed in MATLAB (Mathworks, Inc, *Natick*, Massachusetts, USA). Performance by the comparison group (subjects without disability) was used to identify normative ranges for each parameter that spanned 95% of the group. In most cases, the 95% range was one-sided, reflecting the fact that abnormal values would be expected to be larger or smaller than the comparison sample (ie, movement time would be expected to be longer in individuals with TBI; see Table 1 for ranges). These normative ranges reflected the influence of age, sex, and handedness (see Supplemental Digital Content 1, http://links.lww.com/JNPT/A25, which gives detailed methods describing the regression analysis and normalized scores). For visualization purposes, values for each parameter were transformed into a normalized score, akin to a *z* score, by using the median, 5th, and 95th percentiles (p50, p5, and p95, respectively).

## RESULTS

### Participant Pool

Demographic data, initial clinical history, time between injury and assessment (delay), and clinical assessment scores for individual subjects with TBI are shown in Table 2. Subjects are organized on the basis of initial GCS scores. Nine subjects had severe TBI, whereas relatively few had moderate (n = 2) or mild (n = 1) TBI. Neuroradiologic assessment of initial CT scans indicated eight subjects had focal lesions and diffuse axonal injury, whereas four subjects had focal lesions only.

The subjects without disabilities included 81 men and 89 women, ranging from 20 to 83 years of age (median age = 49). Although most comparison subjects were right-hand dominant, nine were left-hand dominant and five were ambidextrous.

### Comparison Subject Performance

Example hand paths (A) and speed profiles (B) during reaching for a comparison subject (a 23-year-old female) are illustrated in Figure 2. Hand position remained fairly constant during the postural hold period preceding onset of the peripheral target (vertical line at 0 s). Movements were initiated with similar reaction times and were fairly straight, with bell-shaped velocity profiles and only minor corrective movements to attain to the peripheral target. The performance of this same subject

**Table 1. Attributes and Parameters of the Visually Guided Reaching and Arm Position-Matching Tasks**

| Task | Behavioral Attribute | Submetric | Parameter | Abbreviation | Normative range, % | Definition |
|---|---|---|---|---|---|---|
| Visually guided reaching | Postural control | | Posture speed | PS | 0–95 | Mean hand speed during the 500 ms preceding peripheral target onset |
| | Visuomotor reaction | | Reaction time | RT | 0–95 | Time from peripheral target onset to movement onset |
| | Movement control | Total movement metrics | Movement time | MT | 0–95 | Total time elapsed from movement onset to end |
| | | | Maximum speed | MS | 5–100 | Global maximum hand speed |
| | | Initial movement | Initial direction error | IDE | 0–95 | Angular error between (i) straight line from hand position to the peripheral target at movement onset and (ii) straight line from hand position at movement onset to hand position after the initial phase of movement (first hand speed minimum) |
| | | | Initial distance ratio | IDR | 5–100 | Ratio of (i) distance the hand traveled during the initial phase of movement to (ii) distance the hand traveled between movement onset and offset |
| | | | Initial speed ratio | ISR | 5–100 | Ratio of (i) maximum hand speed during the initial phase of movement to (ii) global maximum hand speed |
| | | Corrective movements | Number of speed peaks | NSP | 0–95 | Number of hand speed maxima between movement onset and offset |
| | | | Minimum-maximum speed difference | MSD | 0–95 | Differences between hand speed maxima and minima |
| Arm position matching | Position sense | | Variability | Var | 0–95 | Trial by trial variability of the active hand |
| | | | Spatial contraction/expansion | C/E | 2.5–97.5 | Ratio of (i) spatial area enclosed by the active hand to (ii) spatial area of enclosed by the passive hand |
| | | | Spatial shifts | Shift | 0–95 | Systematic shifts between the active and passive hands |

**Table 2. Demographics, Initial Clinical History, and Clinical Assessment Scores of Subjects with TBI at the Time of Their Robotic Assessment[a]**

| | Demographics | | | Initial Clinical History | | | | Clinical Assessments at Time of Robotic Testing | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subject | Age | Sex | EHI | GCS | PTA | LOC | Brain Injury | Delay | FMA (L/R) | PPB (L/R) | Power (L/R) | MAS (L/R) | RLA | MoCA | BIT | Vis Field Defects |
| 1 | 58 | M | R | 13 | 14[b] | 0 | Focal | 169 | 66/63 | 10/11 | 20/20 | 0/0 | VI | 26 | 145 | No |
| 2 | 53 | M | A(R) | 10 | 28[b] | 3 | DAI/focal | 45 | 66/66 | 10/9 | 20/20 | 0/0 | VII | 24 | 144 | No |
| 3 | 23 | M | R | 9 | 23 | <1 h | DAI/focal | 41 | 66/66 | 9/10 | 20/20 | 0/0 | VIII | 28 | 141 | No |
| 4 | 19 | M | A(L) | 8 | 8[b] | 7 | DAI/focal | 553 | 66/66 | 13/11 | 20/20 | 0/0 | VIII | 24 | 145 | No |
| 5 | 37 | M | L | 7 | 5 | <1 h | DAI/focal | 165 | 58/65 | 7/14 | 18/20 | 0/0 | VIII | 25 | 142 | No |
| 6 | 24 | M | R | 7 | 6[b] | 3 | DAI/focal | 23 | 66/66 | 8/9 | 16/20 | 0/0 | VII | 27 | 144 | No |
| 7 | 25 | M | R | 7 | 13[b] | 3 | Focal | 43 | 66/62 | 12/10 | 20/16 | 0/0 | VI | 8 | 142 | No |
| 8 | 46 | F | R | 7 | 12 | 3 | DAI/focal | 26 | 66/66 | 15/15 | 20/15[c] | 0/0 | VIII | 28 | 145 | No |
| 9 | 20 | M | A(R) | 6 | 3[b] | 9 h | Focal | 106 | 66/66 | 14/13 | 20/20 | 0/0 | VIII | 29 | 146 | No |
| 10 | 21 | F | R | 6 | 9 | 3 | DAI/focal | 31 | 66/66 | 14/14 | 20/20 | 0/0 | VII | 30 | 144 | No |
| 11 | 21 | F | R | 5 | 37[b] | ... | Focal | 193 | 65/65 | 11/12 | 20/20 | 0/0 | VI | 23 | 139 | No |
| 12 | 20 | F | R | 3 | 150 | 90 | DAI/focal | 1636 | 61/37 | 7/1 | 20/17 | 2/2 | VI | 14 | 141 | L-HH |

Abbreviations: BIT, Behavioral Inattention Test; DAI, diffuse axonal injury; EHI, Edinburgh Handedness Inventory; FMA, Fugl-Meyer Assessment tool; GCS, Glasgow Coma Scale; HH, homonomous hemianopsia; LOC, loss of consciousness; L/R/A, left/right/ambidextrous; MAS, Modified Ashworth Scale; MoCA, Montreal Cognitive Assessment; PPB, Purdue Peg Board; PTA, posttraumatic amnesia; RLA, Rancho Los Amigos Scale.

[a]Subjects are sorted by their GCS score, recorded at the hospital within the first 24 hours following their accident. Subjects with mild (1), moderate (2, 3), and severe (4 to 12) TBI are separated by thin horizontal lines. Unless indicated otherwise, PTA, LOC, and delay (from time of injury to time of robotic testing) are shown in days. PPB scores are given in seconds. Muscle power is a cumulative score out of 20 for shoulder flexion, shoulder extension, elbow flexion, and elbow extension.

[b]Subjects with self-reported PTA.

[c]This score is out of 15 rather than 20 because shoulder flexion power was not tested in this subject.

in the position-matching task is illustrated in Figures 2C and 2D. In this example, the robot passively moved the left arm and the subject actively moved the right arm to mirror-match the position of the left arm at each target (Figure 2C). When the active and passive arms are superimposed (Figure 2D), it is evident that the end positions of the active arm are generally located near the corresponding end positions of the passive arm. Across all targets, the area subtended by the active arm is similar to that of the passive arm, and there is no obvious systematic shift between the end positions of the active and passive arms. The variability ellipses demonstrate that the trial-to-trial position of the active arm about each end position was small (<6 cm).

The normative ranges in real units for each of the parameters measured in the matching and reaching tasks for a 23-year-old female comparison subject are given in Table 3. The normalized scores of the same subject in the reaching and position-matching tasks are illustrated in Figure 3. The gray shaded area denotes the normative range, based on the subject's age and sex, and the adjacent black vertical bar denotes the direction in which deficits would be expected. The posture speed and reaction time exhibit normalized scores less than −1, indicating excellent performance (top 5% of comparison subjects). The icons for these parameters are unfilled because the statistical test is one-sided, with abnormalities being larger than for 95% of comparison subjects (>1).

The reaching and matching tasks generated 24 parameters across the two limbs. By definition, values for 5% of comparison subjects will fall outside the normative range for each parameter. Thus, it is important to identify the number of parameters identified as being outside the normative range for comparison subjects within and across tasks. Less than 5% of all control subjects were outside the normative range in three or more parameters for visually guided reaching across both arms, two or more parameters for the position-matching task for a given limb, or four or more parameters across both tasks and both arms. Thus, for subjects with TBI, we operationally defined failure on the reaching, matching, or both tasks on the basis of these thresholds.

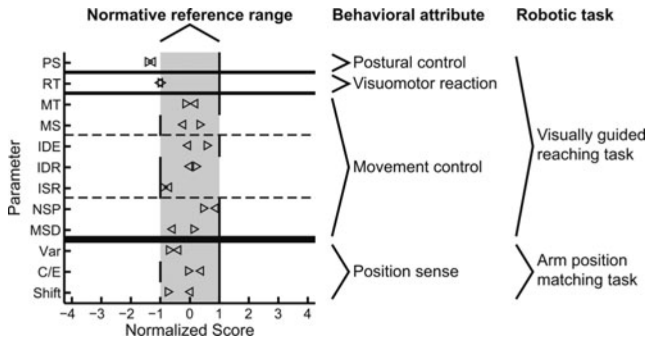


**Figure 3.** Normalized scores and normative reference range. Normalized scores of the comparison subject shown in Figure 2 are illustrated for the visually guided reaching and arm position-matching tasks. Normalized scores for reaching and matching with the right and left arms (active arm) are shown with rightward and leftward facing triangles, respectively. Filled triangles represent values that deviate significantly from normal. The normative reference range (gray shaded area) for each reaching and matching parameter spans normalized scores of −1 (p5) to 1 (p95), with median values (p50) obtaining a normalized score of 0. The nine reaching parameters are located above the three matching parameters and separated by a thick horizontal line. Reaching parameters are further subdivided by medium-thick horizontal lines into their behavioral attributes: postural control at the top, visuomotor reaction in the middle, and movement control at the bottom. Movement control is further divided by thin dashed lines into its submetrics: total movement metrics at the top, initial movement metrics in the middle, and corrective movement metrics at the bottom. Vertical black lines at the edges of the normative reference range serve to denote the direction(s) in which performance outside the range is considered clinically significant. PS, posture speed; RT, reaction time; MT, movement time; MS, maximum speed; IDE, initial direction error; IDR, initial distance ratio; ISR, initial speed ratio; NSP, number of speed peaks; MSD, minimum–maximum speed difference; Var, variability; C/E, spatial contraction/expansion; Shift, spatial shifts.

**Table 3. Normative Reference Range Values of Robotic Parameters for a 23 year-old Comparison Subject**

| | Significant Effects | | | | | | |
|---|---|---|---|---|---|---|---|
| Parameter | Age | Sex | Test Arm | Median | Interquartile Range | Outside Normative Range | Exemplar Control Subject (Left, Right) |
| PS, cm/s | X | ... | ... | 0.281 | 0.145 | 0.497 | 0.133, 0.110 |
| RT, s | X | ... | ... | 0.313 | 0.054 | 0.400 | 0.256, 0.256 |
| MT, s | ... | X | ... | 1.099 | 0.222 | 1.380 | 1.154, 1.052 |
| MS, cm/s | X | X | ... | 25.08 | 7.491 | <17.42 | 23.46, 29.02 |
| IDE, deg | X | ... | ... | 2.143 | 0.722 | 3.33 | 2.107, 2.813 |
| IDR | X | X | ... | 0.907 | 0.077 | <0.752 | 0.908, 0.920 |
| ISR | ... | ... | ... | 0.989 | 0.022 | <0.951 | 0.963, 0.959 |
| NSP | X | X | ... | 2.195 | 0.492 | 2.845 | 2.937, 2.484 |
| MSD, cm/s | X | X | ... | 1.528 | 0.968 | 2.805 | 1.060, 1.677 |
| Var, cm | X | ... | ... | 2.964 | 0.861 | 4.544 | 2.606, 2.283 |
| C/E | X | ... | ... | 0.873 | 0.305 | <0.495 >1.345 | 1.019, 0.852 |
| Spatial shifts, cm | ... | ... | ... | 3.784 | 3.258 | 9.207 | 3.930, 1.722 |

Abbreviations: C/E, spatial contraction/expansion; IDE, initial direction error; IDR, initial distance ratio; ISR, initial speed ratio; MS, maximum speed; MSD, minimum–maximum speed difference; MT, movement time; NSP, number of speed peaks; PS, posture speed; RT, reaction time; Var, variability; X indicates a significant effect ($P < 0.05$) of age, sex, or test arm was observed in the normative reference data for this parameter.

## Mild TBI

Subject 1 (a 58-year-old man; case of mild TBI) experienced a TBI defined as mild on the basis of initial GCS scores. Duration of PTA was unavailable from the medical chart, and thus the self-reported PTA of 14 days was used (Table 2). At the time of robotic testing, our clinical assessments did not reveal large motor deficits on the FMA (L/R = 66/63). The PPB scores were lower than the published norms (L/R = 10/11).[24] Some residual cognitive issues were identified (Ranchos Los Amigos Scale = VI; MoCA = 26). The performance of this subject is illustrated in Figure 4 for the reaching (A and B) and position-matching (C) tasks. Hand paths (Figure 4A) and hand speed profiles (Figure 4B) were qualitatively similar to those of the exemplar control subject except for one trial, in which a delayed reaction time is obvious in the hand speed profile. All scores for reaching were within the normative range for this right-handed man (Figure 4D). In the position-matching task, the only significant deviation from the normative range was a systematic shift with the active right hand.

## Moderate TBI

Subjects 2 and 3 (cases of moderate TBI), both had normal FMA scores, whereas PPB scores (10/9 and 9/10) were below published norms (Table 2).[24] The performance of subject 3 is illustrated in Figure 5 for the reaching (A and B) and position-matching (C) tasks. This subject exhibited numerous large lateral deviations relative to the target during reaching (Figure 5A) and multiple peaks in the hand-speed profiles (Figure 5B). These features highlight that this subject required multiple movements to attain the target (measured by the parameter number of speed peaks, Figure 5B). Subject 3 also displayed a substantial amount of variability (Var) with both arms in the position-matching task (Figure 5C). Both subjects with moderate TBI displayed a broad range of abnormalities in both tasks and with both limbs (Figures 5D and 5E).

## Severe TBI

The majority of cases (n = 9) were of severe TBI (Table 2). These subjects exhibited a broad range of values on their GCS (3 to 8), PTA (3 to 150 days), and LOC (0 to 90 days). They also exhibited a broad range of assessment scores on the FMA (58 to 66, except subject 12), PPB (7/1 to 15/15), and MoCA (8 to 30).

The performance of subject 12 (a 20-year-old female; case of severe TBI) is illustrated in Figure 6 for the reaching (A and B) and position-matching (C) tasks. The hand paths of subject 12 exhibited substantial jitter, particularly with the right hand (Figure 6A). Furthermore, subject 12 was often unable to generate movements to the upper-left quadrant with the right arm. Hand-speed profiles showed multiple peaks, and reaction times were long and variable (Figure 6B). In position matching, subject 12 showed dramatic deficits, including greater variability, spatial contraction, and systematic shifts with both arms (Figure 6C). Given that this subject had difficulty reaching to and maintaining posture at targets with the right hand, the matching results with use of the active right hand may be influenced by motor deficits. However, she was consistently able to reach to and maintain hand posture at pe-

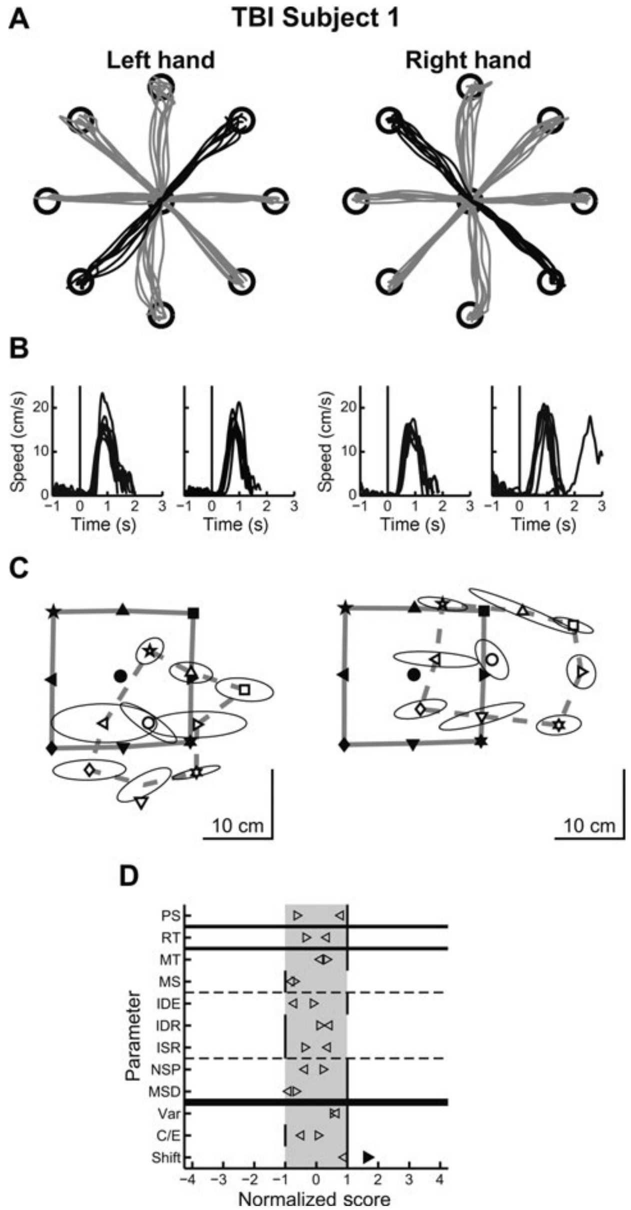


**Figure 4.** Profiles of a subject with mild TBI. A, Hand paths (reaching trajectories) of a subject with mild TBI (subject 1) performing the visually guided reaching task with the left and right arms. B, Hand-speed profiles of multijoint reaching movements with the left and right arms (shown in black in A). C, Superimposed view of performance in the arm position-matching task, using the left hand to actively match the position of the passive right hand (left) and the right hand to actively match the position of the passive left hand (right). D, Normalized scores of TBI subject 1, plotted relative to the normative reference range for age- and sex-matched normative data (gray-shaded area). Symbols for the arm position-matching task (C) and normalized scores (D) are the same as in Figures 2 and 3, respectively. PS, posture speed; RT, reaction time; MT, movement time; MS, maximum speed; IDE, initial direction error; IDR, initial distance ratio; ISR, initial speed ratio; NSP, number of speed peaks; MSD, minimum–maximum speed difference; Var, variability; C/E, spatial contraction/expansion; Shift, spatial shifts.

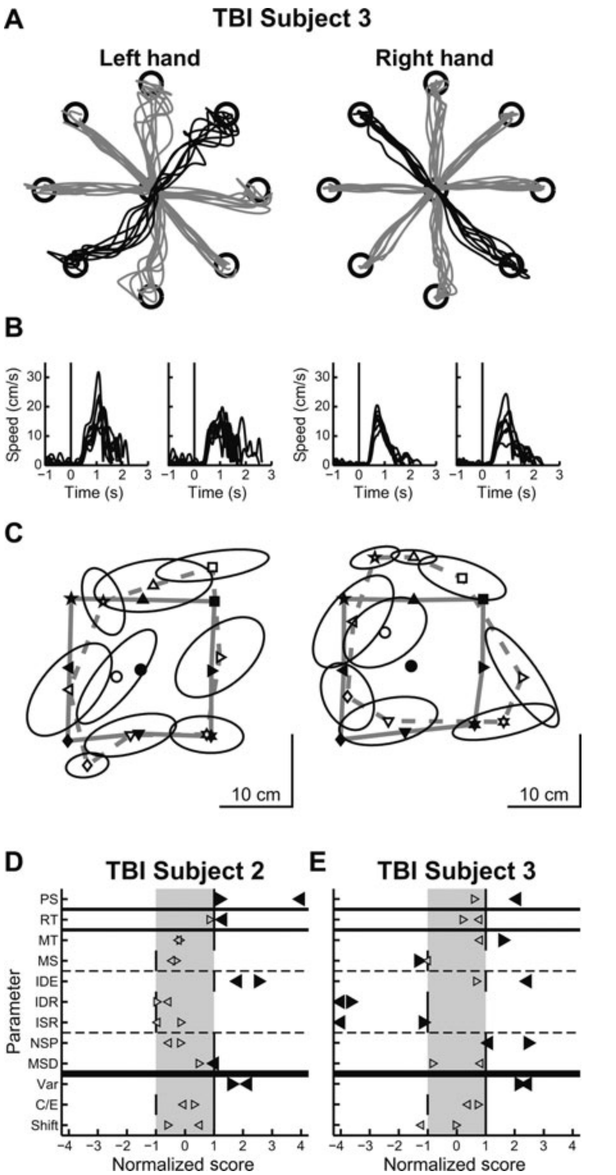


**Figure 5.** Profiles of subjects with moderate TBI. A, Hand paths (reaching trajectories) of a subject with moderate TBI (subject 3) performing the visually guided reaching task with the left and right arms. B, Hand-speed profiles of multijoint reaching movements with the left and right arms (shown in black in A). C, Superimposed view of performance in the arm position-matching task, using the left hand to actively match the position of the passive right hand (left) and the right hand to actively match the position of the passive left hand (right). D, E, Normalized scores of TBI subjects 2 and 3 (moderate TBI), plotted relative to the normative reference range for age- and sex-matched normative data (gray-shaded area). Symbols for the arm position-matching task (C) and normalized scores (D) are the same as in Figures 2 and 3, respectively. PS, posture speed; RT, reaction time; MT, movement time; MS, maximum speed; IDE, initial direction error; IDR, initial distance ratio; ISR, initial speed ratio; NSP, number of speed peaks; MSD, minimum–maximum speed difference; Var, variability; C/E, spatial contraction/expansion; Shift, spatial shifts.

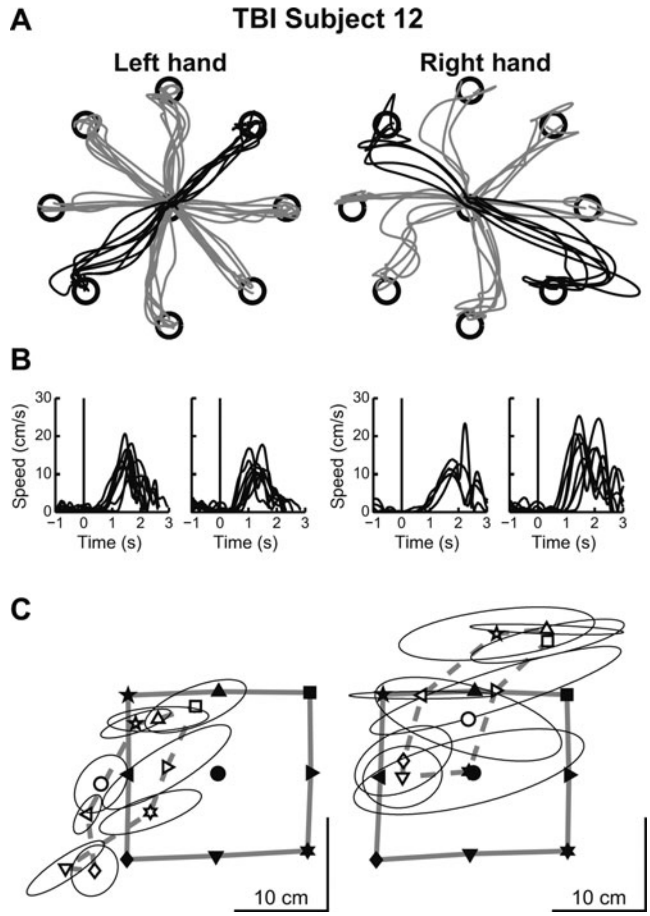


**Figure 6.** Profiles of a subject with severe TBI. A, Hand paths (reaching trajectories) of subject 12, performing the visually guided reaching task with the left and right arms. B, Hand-speed profiles of multijoint reaching movements with the left and right arms (shown in black in A). C, Superimposed view of performance in the arm position-matching task, using the left hand to actively match the position of the passive right hand (left) and the right hand to actively match the position of the passive left hand (right). Symbols for the arm position-matching task are the same as in Figure 2.

ripheral targets with the left hand; thus, the deficits in matching arm positions with use of the active left hand should not be due to motor deficits. Every other subject with severe TBI had sufficient motor control in both arms to eventually reach the end target on the reaching task, which allowed assessment of position sense by using the arm position-matching task.

Our sample of nine subjects with severe TBI demonstrated a broad range of deficits across both robotic tasks (Figures 7A to 7I). Subjects 7 and 9 displayed deficits in two parameters related to reaching, and this is less than the three required to fail the task. Subjects 8 and 10 were outside the normal range on three parameters in the reaching and matching tasks, respectively, signifying failure in these tasks. The remainder of the subjects fell outside the normal range on four or more parameters.

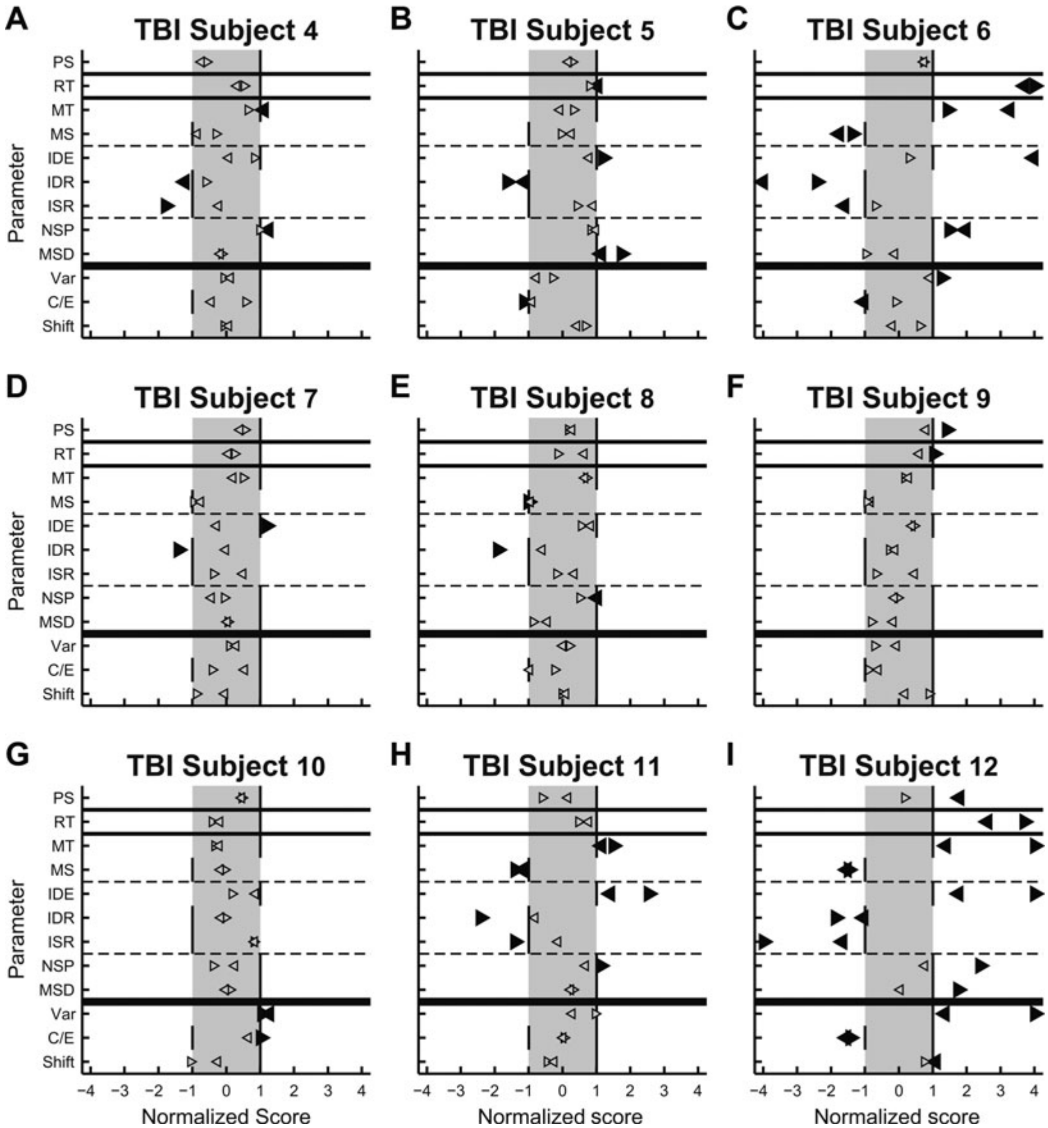


**Figure 7.** Normalized scores of all subjects with severe TBI. A–I, Normalized scores sorted by TBI severity (highest to lowest Glasgow Coma Scale scores). For each subject, normalized scores are plotted relative to the normative reference range for age- and sex-matched normative data (gray-shaded area). Symbols are the same as in Figure 3. PS, posture speed; RT, reaction time; MT, movement time; MS, maximum speed; IDE, initial direction error; IDR, initial distance ratio; ISR, initial speed ratio; NSP, number of speed peaks; MSD, minimum–maximum speed difference; Var, variability; C/E, spatial contraction/expansion; Shift, spatial shifts.

## DISCUSSION

This study highlights some of the potential strengths of using robotic technology to perform assessments of sensorimotor function for individuals with TBI. Robotic technology offers the promise of objectivity and the ability to quantify many different aspects of subject performance related to a given behavior. Given that this was a feasibility study focused on assessment rather than treatment, it was fundamentally important to include a wide variety of cases from inpatient and outpatient clinics, some acute and some more chronic in nature. The subjects with TBI demonstrated a broad range of deficits on the robotic assessment. The number of deficits detected in each individual did not always match well with traditional measures of severity (ie, GCS, PTA, LOC). This is not surprising, given the considerable variability in the time since injury and the heterogeneous nature of TBI. To truly understand the relationship between the more traditional measures of TBI severity and the current robotic assessment tools, a larger study will be necessary. Despite this, the current study raises some interesting issues.

There was considerable mismatch between the findings from FMA[23] and visually guided reaching. Many of the subjects with TBI scored a maximal (or near maximal) score on the FMA, yet numerous deficits were identified with the robotic reaching task. This is not surprising, given the known problems with ceiling effects on the FMA.[31] Another assessment of manual dexterity, the PPB, seemed to better match the robotic reaching results. The clinical test, however, gives little insight into the underlying reason an individual performs poorly. Did they have a problem with coordination, slowed movements, and/or proprioception? Robotic assessment can help answer these questions.

Many subjects with TBI in this study exhibited deficits on the robotic position-matching task. Our clinical experience has been that position sense deficits can go unrecognized with current clinical assessment tools. Other authors have commented that the standard clinical assessments of position sense are insensitive and unreliable.[32] In stroke, we have shown that approximately 50% of inpatients have position sense difficulties[30] and that these correlate with poor performance on the Functional Independence Measure.[33] The assessment of proprioception represents a potential area where the robotic assessment tools may be able to provide clinicians with more information than a traditional clinical examination.

Cognitive issues represent a potential challenge for attempting to measure sensorimotor deficits in TBI. We screened cognition in this study with the MoCA. Previous studies have proposed a cutoff score of 26 for mild cognitive impairment.[26] However, individuals with scores less than 26 can still be capable of basic sensorimotor skills and motor learning. We routinely see patients with MoCA scores in the mid-teens who actively participate and improve in daily rehabilitation. A somewhat extreme example in this study is subject 7, who had a MoCA score of 8 and performance that was nearly within the normative range on sensory and motor testing. Potentially, the reason that subjects with low MoCA scores could perform well on the robotic testing is that the tasks used in this study were relatively simple and that the staff operating the robot took the time to ensure the subjects could understand the task instructions. It is likely that if we had examined elements of higher cognitive function such as divided attention or visuospatial memory, the influence of this subject's cognitive deficits would have been more obvious on the robotic testing. Much like neuropsychometric testing, robotic measures can be designed to probe different areas of cognition. This is a potential area for future research.

After TBI, many individuals have bilateral deficits. This presents challenges in determining loss of position sense by using the arm position-matching task in individuals with severe motor deficits in both arms, as was the case with subject 12. However, she was able to reach all targets and hold at the end position with her left hand (data not shown), and thus her position-matching deficits likely represent a true proprioceptive problem. This issue, however, does serve to highlight a limitation of the arm position-matching task for individuals with severe bilateral deficits. Other variants of the arm position-matching task will need to be designed to overcome this limitation.

Another potential limitation in this study is that the KINARM robot (BKIN Technologies Ltd., Kingston, ON, Canada) allows movement only in the horizontal plane. Because real-world movements are multiplanar, practicing movements that are restricted to the horizontal plane may have limited generalizability to performance functional activities. However, some authors have recommended this position[34] because it provides support for individuals with weakness and allows testing in a "gravity-eliminated" environment. This may be an important consideration when studying motor function in individuals with disabilities. With regard to the position-matching task, essentially the same muscles crossing the shoulder or elbow would undergo stretch for vertically oriented movements. As position sense is derived predominantly from muscle spindles,[35-38] theoretically, similar results should be obtained whether working in two or three dimensions.

In this study, we chose not to include a standardized clinical measure for proprioception, which could be viewed as a limitation. We have used the clinical thumb localizer task in previous studies in stroke.[30,33] Unfortunately, this test and a simpler test in which an examiner moves the distal segment at a joint and asks the subject which direction it was moved in have both been shown to be unreliable.[32] Most researchers who attempt to quantify position sense with any sort of accuracy have used some form of mechanized approach.[39-42] Limitations in the sample size preclude us from making meaningful conclusions about the relationship between failure in the position sense task by subjects with TBI and performance of activities of daily living. In stroke patients, however, we have shown that the robotic measure of position sense is correlated with performance of activities of daily living as measured by the Functional Independence Measure, independent of the subjects' performance on the reaching task.[33]

Another important aspect of using robotic assessment tools for measuring sensorimotor function lies in the definition of "normal." Using normative reference data to identify abnormalities is standard practice in many areas of medicine (eg, blood tests such as hemoglobin, glucose, or electrolyte levels in laboratory medicine). This methodology is extremely useful in evaluating the severity of deficits and can also be used to determine when performance returns to normal. Many current clinical assessments used in rehabilitation simply assume that the top (or bottom) end of their observer-based ordinal scale represents normal functioning. Inherently, this can lead to floor or ceiling effects (eg, the FMA). The method of using "normal" reference ranges, however, does have some challenges. In this study, each task had a number of different parameters. However, a question arises about how a clinician interprets the results when a single parameter is abnormal, as was the case TBI subject 1, depicted in Figure 4. In other fields of clinical testing (eg, a multiparameter blood screening panel collected to work up a differential diagnosis), a single abnormal measurement is not uncommon. One must interpret the results of any single parameter or test within a context that considers the whole patient. Furthermore, the magnitude by which a single parameter deviates from normative values is also an important factor to consider. In this case, subject 1 is well outside the normal range and had continued to have clinical complaints that may have been related to impaired sensory function. In the present study we operationally defined failure at a task based on a set number of parameters for which a subject with TBI fell outside the normative range. We fully acknowledge the need to develop methodology that also accounts for very poor performance on a single parameter, and this represents an area for future study.

## CONCLUSIONS

This study was our first attempt to use robotics to measure deficits in individuals with TBI. The study focused on using robotic tasks that had been previously validated in individuals with stroke.[28,30,33] On the basis of the outcomes of the present study, a more thorough "tool kit" including automated assessments of different aspects of cognition (eg, visual spatial abilities, sustained and divided attention, memory) is under development. Ultimately, the use of robotic monitoring of neurologic function may represent a significant advancement for monitoring and predicting recovery following TBI, but more research is clearly necessary.[14]

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