TITLE: Depth Sensor–Based Assessment of Reachable Work Space for Visualizing and Quantifying Paretic Upper Extremity Motor Function in People With Stroke

RUNNING HEAD: Reachable Work Space for People With Stroke

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**KEYWORDS:** Upper Extremity, Kinematic Outcomes, Hemiplegia, Psychometric Properties, Rehabilitation

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**Background.** Quantitative evaluation of upper extremity (UE) motor function is important in people with hemiparetic stroke. A depth sensor–based assessment of reachable work space (RWS) was applied to visualize and quantify paretic UE motor function.

**Objective.** The objectives of this study were to examine the characteristics of RWS and to assess its validity, reliability, measurement error, and responsiveness in people with hemiparetic stroke.

**Design.** This was a descriptive, repeated-measures, observational study.

**Methods.** Fifty-eight people with stroke participated. RWS was assessed on both paretic and nonparetic UEs, and the RWS ratio was determined by dividing the RWS of the paretic UE by that of the nonparetic UE. The concurrent validity of the RWS was determined by examining the relationship with the Fugl-Meyer Assessment UE motor score. Test-retest reproducibility was examined in 40 participants. Responsiveness was determined by examining the RWS results before and after 3 weeks of intensive training of the paretic UE in 32 participants.

**Results.** The lower area of RWS bordering shoulder was significantly larger than the upper area, and the medial-lower area of RWS bordering shoulder was significantly larger than the lateral-lower area. The RWS ratio was highly correlated with the Fugl-Meyer Assessment UE motor score ($r = 0.81 [P < .001]$). The RWS ratio showed good intrarater relative reliability (ICC = 0.94) and no fixed or proportional bias. The minimal detectable change of the RWS ratio was 16.6. The responsiveness of the RWS ratio was large (standardized response mean = 0.83).

**Limitations.** Interexaminer reliability was not assessed.

**Conclusions.** The RWS assessment showed sufficient validity, reliability, and responsiveness in people with hemiparetic stroke. A depth sensor–based RWS evaluation is useful for visualizing and quantifying paretic UE motor function in the clinical setting.
Upper extremity (UE) motor dysfunction is a common problem in people with stroke,¹ and its assessment is essential for clinical decision making and understanding the effectiveness of the rehabilitative approach. Many assessments have been developed to measure motor dysfunction in clinical practice; these include the Fugl-Meyer Assessment,² Motricity Index,³ Chedoke-McMaster Stroke Assessment,⁴ and Reaching Performance Scale.⁵ However, these assessments have several limitations. For instance, most of them are scored based on ordinal scales and observational rating scales. Thus, changes in movements of the paretic UE cannot be detected unless they meet the set criteria of the ordinal scale.⁶ In addition, it takes time to acquire skills and knowledge to accurately use these assessments, and differences in proficiency level may lead to examiner bias.⁷ Moreover, people who are not familiar with the assessments (eg, patients, family of patients) cannot understand patient function or degree of change in the scores. To address these problems, we adapted a depth sensor, the Microsoft Kinect sensor (Microsoft Corp, Redmond WA, USA), to assess UE motor function in people with hemiparetic stroke.

The Kinect sensor can obtain kinematics information by capturing color, depth, and infrared streams without any markers attached to the body. The device has several benefits for use at clinical sites such as low-cost, portability, and short preparation time for measurements. Because of these benefits, use of the Kinect-based evaluation has been increasing to measure variables such as UE movement, postural control, and gait.⁸ Kurillo et al proposed using Kinect-based reachable work space (RWS) assessments to visualize and quantify UE motor function.⁹ RWS assessments have also been used in patients with progressive neuromuscular disease.¹⁰-¹⁴ Unlike traditional range of motion (ROM) assessments using goniometry, which assess single-plane ROM of a single joint, the Kinect-based RWS assessment can assess multi-plane ROMs of the distal UE part (end effector). It is well known that the active ROM and paretic UE use are decreased in patients with stroke.¹⁵-¹⁷ Additionally, the required ROM
of the UE is currently defined based on healthy adults and is different for each activity of daily living. Therefore, RWS assessments, including information about the maximum and multi-plane ROMs of the end effector, are meaningful for determining the rehabilitation approach for specific tasks in daily life.

Several studies have used the Kinect sensor to assess UE motor function in patients with stroke. These studies showed differences between reaching movement patterns of the paretic UE and nonparetic UE and suggest that the Kinect sensor might be useful for automatic scoring of existing clinical assessments. In addition, the kinematic and temporal outcomes obtained via the Kinect sensor have good reliability. However, no study regarding the psychometric properties of quantitative kinematic outcomes assessed with or without the Kinect sensor have been published. We applied RWS assessments to people with hemiparetic stroke and examined the characteristics of the RWS. In addition, validity, reliability, measurement error, and responsiveness of the assessments were examined.

[H1] Methods

[H2] Participants

Participants were recruited from an outpatient rehabilitation clinic of a university hospital from March 2017 to March 2019. Fifty-eight people with stroke participated in this study. The inclusion criteria were an age of 20 to 80 years; no pain in either UE; and the ability to maintain a sitting position without any stress. Exclusion criteria were a history of orthopedic diseases in both UEs and an inability to understand instructions regarding motor tasks because of cognitive impairment. The purpose and procedures of the study were explained to all participants, and informed consent was obtained in accordance with the Declaration of Helsinki. This study was approved by the ethics committee of Keio University School of Medicine.
[H2] Clinical Assessments

Paretic UE motor function was assessed with the Fugl-Meyer Assessment UE motor score (FMA-UE), which consists of 4 categories with a maximum score of 66 (A = shoulder/elbow/forearm; B = wrist; C = hand; and D = coordination). The FMA-UE is commonly used as a stroke-specific UE outcome measure and has been shown to be reliable.\textsuperscript{6,28-32} FMA-UE measurements were performed by board-certified physiatrists with more than 5 years of experience.

[H2] RWS Assessment

RWS was measured using the Kinect for Windows V2 sensor (Microsoft, Redmond, WA, USA) and dedicated software (ICpro-K2; Hu-tech Co, Ltd, Tokyo, Japan). Participants performed 8 motor tasks twice for both UEs while sitting approximately 2.5 m away from the Kinect sensor, which was placed at a height of 0.9 m. The tasks were determined according to the methods reported by Kurillo et al.\textsuperscript{9} Tasks consisted of shoulder abduction; shoulder flexion with the shoulder horizontally adducted at 45, 90, and 135 degrees; shoulder horizontal abduction and adduction with the shoulder flexed at 30 and 90 degrees; shoulder flexion with horizontal adduction; and shoulder extension. Participants performed each task while keeping the elbow extended as much as possible. If excessive trunk movements, such as trunk flexion, extension, lateral bending, and axial rotation, were observed for compensation of UE movements, the task was performed and measured again. Measurements were performed on the nonparetic UE first to confirm that the participants understood the task.

[H2] RWS Analysis
Recorded data were analyzed following the methods described in a previous study.  

At first, interpolation of lost data points with spline interpolation and smoothing using a second-order Butterworth filter with a cutoff frequency of 5 Hz were conducted, and the analysis sections were extracted using dedicated software (Hu-tech Co, Ltd). After preprocessing, the RWS was determined by an in-house code in MATLAB (MathWorks, Natick, MA, USA). First, the work space boundaries of the captured wrist trajectory were determined by spherical fitting with least-squares methods. Second, the trajectory coordinates (3-dimensional Euclidean space) were transformed into the spherical coordinates with the angles corresponding to shoulder flexion/extension and abduction/adduction measurements on a spherical surface in order to apply the signal processing method used in image analysis. Then, the maximal boundaries were located by fitting a concave polygon to the data points using the alpha shape geometry with π/4 radius. Third, Catmul-Rom splines were applied with the control points sampled from the original boundary polygon to smooth the concave boundary. Because the task was performed in the anterior plane to the body, the area in the frontal plane was determined from the azimuth angle and evaluated as the effective area of the RWS on the spherical surface. Finally, the boundary area was mapped with back-projection, and we identified the RWS area in the 3-dimensional Euclidean space. The RWS area was divided into 4 quadrants (lateral-lower, medial-lower, lateral-upper, and medial-upper) based on the shoulder position. The total RWS area was calculated as the sum of the spherical surface effective area across the quadrants. The total RWS area of the paretic UE was divided by that of the nonparetic UE. This calculated value was defined as the RWS ratio. An RWS ratio of 100% means that the RWS of the paretic UE is equivalent to that of the nonparetic UE. In addition, the RWS ratio in each of the 4 quadrants was calculated to examine the characteristics of the RWS.
[H2] Procedure for Test-Retest Reproducibility and Responsiveness

To assess test-retest reproducibility, the RWS evaluation procedure was repeated by an independent examiner within 2 days in 40 participants.

To assess responsiveness, we measured the RWS of 32 inpatients before and after intensive training of the paretic UE. During training periods, participants used electromyogram-controlled neuromuscular electrical stimulation (MURO Solutions; Pacific Supply Co, Osaka, Japan) combined with a wrist-hand splint for 8 hours each day over 3 weeks. Details of the methods and effects of the intervention on UE motor function are described elsewhere. In addition, conventional occupational therapy was administered for 1 hour on weekdays. Therapy included gentle stretching exercises, active muscle reeducation exercises, repetitive task-oriented training, and instructions on using the paretic UE in daily life. The FMA-UE was also measured before and after intensive training to assess the relationship between RWS changes and FMA-UE changes.

[H2] Data Analyses

Data were analyzed using SPSS software (SPSS version 24.0 for Windows; IBM Corp, Armonk, NY, USA) for statistical analyses and MATLAB for calculation of the value obtained from the numeric operation. A \( P \) value of <.05 was considered significant.

[H2] Characteristics of RWS in People With Stroke

One-way repeated-measures analysis of variance was used to test the effect of area (lateral-lower, medial-lower, lateral-upper, medial-upper) on the RWS ratio. Post hoc analysis was performed with Bonferroni corrections.

[H2] Concurrent Validity
Concurrent validity was assessed by determining the Spearman rank correlation coefficient for the relationship between UE motor function (FMA-UE total score, proximal score [categories A and D, maximum score of 42], and distal score [categories B and C, maximum score of 24]) and RWS ratio. The following classification was used: 0.20 to 0.40 = low correlation; 0.40 to 0.70 = moderate correlation; 0.70 to 0.90 = high correlation; and 0.90 to 1.00 = very high correlation.37

[H2] Relative Reliability

Intrarater relative reliability was assessed by calculating model 1.1 ICs and 95% confidence intervals (CIs). The following classification was used: >0.90 = excellent reliability; 0.75 to 0.9 = good reliability; 0.50 to 0.75 = moderate reliability; and <0.5 = poor reliability.38

[H2] Absolute Reliability

Absolute reliability was assessed using Bland-Altman analysis.39,40 It can be assessed as the presence or absence of systematic bias (ie, fixed bias and proportional bias). The 95% CIs of the differences were calculated to assess the presence or absence of fixed bias. No fixed bias was present if the 95% CIs included zero. The 95% CIs were derived as follows:

$$\bar{d} \pm t \times S_{diff}/\sqrt{n},$$

where $\bar{d}$ is the mean difference, $t$ is the value of the Student $t$ statistic corresponding to 2-sided $P = .05$ at $n - 1$ degrees of freedom, $S_{diff}$ is the SD of the difference, and $n$ is the sample size.
Linear regression was used to assess the presence or absence of proportional bias. No proportional bias was present if the coefficient was equal to zero (ie, the $P$ value was $>.05$).

The limits of agreement were derived by a formula that was suitable for our sample size:

$$d \pm t \times S_{diff} \times \sqrt{1 + 1/n}.$$  

Measurement error was assessed with the standard error of measurement (SEM), which was derived as follows:

$$SEM = S_x \times \sqrt{(1 - Rx)},$$

where $S_x$ is the SD of all observations from the test and retest and $Rx$ is the ICC.

The minimal detectable change (MDC), which indicates the magnitude of change necessary to exceed the measurement error, was derived as follows:

$$MDC = SEM \times 1.96 \times \sqrt{2},$$

where 1.96 is the 2-sided $z$ value for the 95% CIs and $\sqrt{2}$ is used to account for the variance of repeated measurements.

The SEM and MDC was also expressed as a percentage ($SEM\%, MDC\%$) to compare the amount of error between measurements. The $SEM\%$ and $MDC\%$, which are independent of the units of measurement, were derived as follows:

$$SEM\% = \left(\frac{SEM}{\text{mean}}\right) \times 100$$

and

$$MDC\% = \left(\frac{MDC}{\text{mean}}\right) \times 100.$$  

[H2] Responsiveness
Responsiveness was calculated on the basis of improvements in paretic UE motor function after intensive training. The paired t test and the Wilcoxon signed rank test were used to confirm the statistical significance of the change in the RWS ratio and the FMA-UE total score, respectively. The number of participants with an increased RWS ratio after training (ie, a value obtained by subtracting the RWS ratio before training from that after training that exceeded zero) was counted. The number of participants who showed an increase in the RWS ratio more than the MDC was also counted, because responsiveness should not be evaluated separately from reliability.  The standardized response mean (SRM) of the RWS ratio and the FMA-UE total score were calculated by dividing the mean change score by the SD of the change score in the same participants. The following classification according to Cohen was used: 0.20 to 0.50 = small; 0.50 to 0.80 = moderate; and >0.80 = large.  The Spearman rank correlation test was used to assess the relationship between the change in the RWS ratio and the FMA-UE total score.

[H2] Role of the Funding Source
This research was partially supported by a Japan Agency for Medical Research and Development (AMED) grant and JSPS KAKENHI. The funder played no role in the design, conduct, or reporting of this study.

[H1] Results
A total of 58 people with stroke participated in this study, and the results for the RWS and the FMA-UE total score were used to examine the characteristics of the RWS and the concurrent validity. RWS assessments were conducted twice with 40 of the 58 participants to examine reliability. RWS assessments were conducted with 32 of the 58 participants before
and after intensive training to examine responsiveness. Table 1 shows the participant characteristics for each examination.

[H2] Characteristics of RWS in People With Stroke

The RWS ratio of each area was largest in the medial-lower area (mean = 68.3% [SD = 24.8%]) followed by the lateral-lower (mean = 59.8% [SD = 27.4%]), medial-upper (mean = 32.8% [SD = 31.2%]), and lateral-upper areas (mean = 27.3% [SD = 27.5%]). The main factor of area was significant between the 4 areas ($F_{3,57} = 104.88$ [$P < .001$]). Post hoc analysis revealed that the RWS ratio of the medial-lower area was significantly larger than the lateral-lower ($P = .03$), lateral-upper ($P < .001$), and medial-upper ($P < .001$) areas, and the RWS ratio of the lateral-lower area was significantly larger than the lateral-upper ($P < .001$) and medial-upper ($P < .001$) areas.

[H2] Concurrent Validity

Figure 1 shows correlations between the RWS ratio (mean = 45.0% [SD = 24.1%; range = 8.1%–96.5%]) and the FMA-UE total score (total: mean = 33.1 [SD = 13.1; range = 12–63]; proximal: mean = 23.5 [SD = 7.8; range = 9–39]; distal: mean = 9.6 [SD = 6.4; range = 1–24]). The RWS ratio was highly correlated with the FMA-UE total score and the proximal score (total: $r = 0.81$ [$P < .001$]; proximal: $r = 0.89$ [$P < .001$]). In addition, the RWS ratio was moderately correlated with the FMA-UE distal score ($r = 0.59$ [$P < .001$]). Figure 2 shows graphic illustrations of the RWS in representative people with stroke.

[H2] Reliability
The RWS ratio showed good to excellent intrarater relative reliability (ICC = 0.94 [range = 0.89–0.97]). Figure 3 shows the Bland-Altman plot. Table 2 shows the results of Bland-Altman analysis, SEM, and MDC. No fixed bias or proportional bias was present.

[H2] Responsiveness

The paired t test showed a significant increase in the RWS ratio (before: mean = 43.7% [SD = 21.3%]; after: mean = 50.5% [SD = 23.2%]) (P < .001), and the Wilcoxon signed rank test showed a significant increase in the FMA-UE total score (before: mean = 31.5 [SD = 11.2]; after: mean = 37.0 [SD = 11.7]) (P < .001) after training. Figure 4 shows graphic illustrations of RWS in representative participants before and after training. The number of participants with an increased RWS ratio after training was 28 (87.5%); in 5 of them, the amount of increase was more than the MDC. The SRM of the RWS ratio was 0.83. The SRMs of the FMA-UE total score, proximal score, and distal score were 2.02, 1.57, and 1.44, respectively. There was no significant correlation between the change in the RWS ratio and the FMA-UE total score (r = −0.08 [P = .67]).

[H1] Discussion

In the present study, we applied RWS assessments to participants with hemiparetic stroke and assessed the psychometric properties. Results showed concurrent validity of the RWS ratio with the FMA-UE total score, good to excellent intrarater relative reliability, absence of systematic bias, and large responsiveness. To our knowledge, this is the first study to assess comprehensive psychometric properties regarding kinematic outcomes in people with stroke. Overall, our findings suggest that Kinect-based RWS assessments are acceptable for visualizing and quantifying UE motor function in a clinical setting.
[H2] Characteristics of RWS in People With Stroke

In terms of characteristics of RWS in people with stroke, the RWS ratio of the lower area was larger than that of the upper area. This is a natural consequence because diminished muscle activation and weakness are common after stroke.\textsuperscript{45,46} Thus, reaching the upper area is difficult for people with stroke because the required force is gradually increased by gravity load. In addition, the RWS ratio of the medial-lower area was larger than the lateral-lower area. These results can be explained by the abnormal coupling of UE muscles. Dewald et al\textsuperscript{47} reported coactivational relationships between shoulder abductors and elbow flexors as well as shoulder adductors and elbow extensors. These abnormal couplings could lead to the differences between the RWS of the medial-lower and lateral-lower areas. Previous studies have examined the change in RWS by loading to assess characteristics other than active ROM such as muscle strength and endurance.\textsuperscript{11,12,48,49} Further studies of the loading effects on RWS in people with stroke are needed to link the results of RWS to paretic UE use in actual daily life.

[H2] Concurrent Validity

The RWS ratio was highly correlated to the FMA-UE total score and proximal score, but the correlation between the RWS ratio and distal score was moderate. These results are reasonable because the RWS assessments consisted of proximal UE motor tasks. The reason for the moderate correlation between the RWS ratio and FMA-UE distal score was thought to occur because the severity of UE paralysis was a confounding factor. The difference in the correlation strength between the proximal and distal scores demonstrates that the RWS provides specialized assessments of proximal UE motor function. Ellis et al reported that horizontal work space assessed by an arm-mounted robotic system in the laboratory setting was correlated with clinical assessments including the FMA-UE total score and proximal
score.\textsuperscript{49} In the present study, RWS assessments could quantify multi-plane ROMs using low-cost devices without attaching a device or marker to the body, and results were consistent with a previous study.\textsuperscript{49} The population in this study did not include people with severe paralysis who could hardly move the paretic UE, and the inclusion of people with mild paralysis was not sufficient to show the floor effect. Therefore, the floor and ceiling effects of RWS assessments remain unclear.

Differences in RWS assessments based on the severity of paresis can be understood from Figure 2. Nonexperts such as patients and their family can understand UE motor function by seeing this graphic representation of RWS. This will be useful for sharing concerns and setting goals for patients.

[H2] Reliability

Results from the test-retest assessments indicated that RWS assessments showed good to excellent intrarater relative reliability. These results are comparable or superior to previous reports of clinical UE assessments and kinematic outcomes.\textsuperscript{27,50-52}

We did not see any fixed or proportional bias from results of the Bland-Altman analysis. In terms of the MDC, previous studies set the acceptable or satisfactory value as 10\% of the possible highest score.\textsuperscript{30,53} The meaningful highest score of the RWS ratio in this study was 100, which indicates that the RWS of the paretic UE and the nonparetic UE was equivalent. The MDC of the RWS ratio was slightly larger than the above criteria. We consider that one of the reasons related to this error is the accuracy of the Kinect motion capture. Several studies reported that Kinect-based UE motor assessments had high accuracy evaluated by simultaneous measurements with marker-based 3-dimensional motion capture systems, along with good to high repeatability.\textsuperscript{9,27,54} However, other studies reported that markerless tracking is unstable compared with marker-based tracking, and joint-tracking
errors involving the orientation of body segments have been shown to occur. Additionally, fluctuations of participant performance might reflect this error. Amano et al reported that the MDC of the FMA-UE score calculated from the test-retest method was larger than that seen from the simultaneous method in which 2 examiners score the same performance. The difference in the MDC between the methods might reflect fluctuations in performance.

With regard to the SEM% and MDC%, these values are independent of the units of measurement and useful for comparing the amount of error between measurements. The SEM% and MDC% have been shown to be relatively good as kinematic outcomes recorded from UE movements of people with stroke. From these results, the Kinect-based RWS assessments had good reliability as quantitative kinematic outcomes.

[H2] Responsiveness

Responsiveness was investigated by the RWS ratio before and after intensive training of the paretic UE. After intensive training, the RWS ratio and the FMA-UE total score were significantly increased compared to baseline, which indicated an improvement in UE motor function. The change in the RWS can be understood from Figure 4, especially the increase in the upper area.

The SRM of the RWS ratio was large, and it was not inferior to a previous report on kinematic outcomes. On the other hand, the SRM of the FMA-UE score was larger than the RWS ratio. The reason that the responsiveness of the RWS was inferior to the FMA-UE is related to the reliability of the RWS because responsiveness and reliability are inseparable. The MDC of the FMA-UE score was 5.2 to 7.4 points in a previous study. The percentage of the MDC with the highest possible score was smaller for the FMA-UE total score than for the RWS ratio. In addition, the FMA-UE assesses composite motor performance, whereas the RWS ratio is focused on quantification of the maximum ROM of
the UE end effector. Therefore, the FMA-UE was superior to the RWS in detecting the effect of the intensive training on the proximal and distal UE in terms of using the paretic UE in daily life. Interestingly, there was no correlation between the gain in the RWS ratio and the gain in the FMA-UE total score. A previous study showed that gains in these 2 variables do not always correlate, even if the scores of these variables are correlated at the same timepoint. This finding demonstrates that the RWS and the FMA-UE evaluate partially different constructs. In this study, RWS responsiveness was verified in people with moderate hemiparesis. See et al demonstrated that the responsiveness of the FMA-UE varied from baseline. Future studies of responsiveness should consider differences due to severity, the phase of recovery, and the type of intervention, even in quantitative kinematic outcomes. According to these results, the Kinect-based RWS assessments have large responsiveness for quantitative kinematic outcomes.

[H2] Limitations
We did not assess interexaminer reliability. However, in RWS assessments, examiners do not score movements but only instruct participants regarding movements. Thus, intraexaminer reliability is expected to be high.

The RWS assessments were quantitated from the maximum ROM of the UE end effector on the basis of calculation of the surface area of a fitted sphere. Therefore, it is uncertain whether participants can reach the internal space of the sphere. Further research regarding movement tasks is needed to resolve this problem.

In this study, the psychometric properties of the RWS assessment were assessed comprehensively. However, information regarding implementing this process into an actual clinical setting is still lacking. We consider that the introduction cost of the Kinect-based RWS assessments and the total time required for the assessments were acceptable. Further
studies for feasibility and usability are needed to recommend the standard use of quantitative kinematic assessments in the clinical setting.

**[H1] Conclusion**

The RWS assessment can be used to visualize and quantify paretic UE motor function, and results can be visualized by people unfamiliar with the assessment. The RWS assessment showed sufficient validity, reliability, and responsiveness in participants with hemiparetic stroke. We consider that results of the Kinect-based RWS assessment, which has a low introduction cost, can be meaningful in considering the rehabilitation approach of the paretic UE in the clinical setting.
Author Contributions and Acknowledgments

Concept/idea/research design: K. Okuyama, M. Kawakami, S. Tsuchimoto, M. Ogura, K. Okada, J. Ushiba
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Data collection: K. Okuyama, M. Kawakami, M. Ogura, K. Okada
Data analysis: K. Okuyama, M. Kawakami, S. Tsuchimoto
Project management: K. Okuyama, M. Kawakami
Fund procurement: J. Ushiba, M. Liu
Providing facilities/equipment: K. Mizuno, J. Ushiba
Consultation (including review of manuscript before submitting): S. Tsuchimoto, M. Ogura, K. Okada, K. Mizuno, M. Liu

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Ethics Approval

This study was approved by the ethics committee of Keio University School of Medicine. The purpose and procedures of the study were explained to all participants, and informed consent was obtained in accordance with the Declaration of Helsinki.

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Disclosures and Presentations
The authors completed the ICMJE Form for Disclosure of Potential Conflicts of Interest and reported no conflicts of interest. M. Kawakami, J. Ushiba, and M. Liu are founding scientists of the startup company Connect Inc for the social implementation of university research results. K. Okuyama and M. Ogura are employed by the company.

A portion of this study was presented at the following conferences:


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Table 1.
Participant Characteristics for Each Examination

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>RWS&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Concurrent Validity</th>
<th>Reliability</th>
<th>Responsiveness</th>
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<td>3.2 (2.4)</td>
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<td>FMA-UE total score&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>32.8 (13.2)</td>
<td>31.5 (11.2)&lt;sup&gt;d&lt;/sup&gt;</td>
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<td>9.6 (6.4)</td>
<td>9.5 (6.4)</td>
<td>8.4 (5.5)&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>CH = cerebral hemorrhage; CI = cerebral infarction; FMA-UE = Fugl-Meyer Assessment upper extremity motor score; RWS = reachable work space.

<sup>b</sup>Values are reported as numbers of participants unless otherwise indicated.

<sup>c</sup>Reported as mean (SD).

<sup>d</sup>Baseline scores are described.
Table 2.

Absolute Reliability in Reachable Work Space

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bland-Altman analysis</td>
<td></td>
</tr>
<tr>
<td>95% CIs of the difference</td>
<td>−1.29 to 0.60</td>
</tr>
<tr>
<td>Linear regression</td>
<td></td>
</tr>
<tr>
<td>( \beta )</td>
<td>0.03</td>
</tr>
<tr>
<td>( t ) value</td>
<td>0.23</td>
</tr>
<tr>
<td>( P )</td>
<td>.82</td>
</tr>
<tr>
<td>Limits of agreement</td>
<td></td>
</tr>
<tr>
<td>Upper</td>
<td>16.8</td>
</tr>
<tr>
<td>Lower</td>
<td>17.5</td>
</tr>
<tr>
<td>SEM(^b)</td>
<td>6.0 (4.4–8.1)</td>
</tr>
<tr>
<td>SEM(^b) %</td>
<td>13.6 (10.0–18.5)</td>
</tr>
<tr>
<td>MDC(^b)</td>
<td>16.6 (12.1–22.5)</td>
</tr>
<tr>
<td>MDC(^b) %</td>
<td>37.8 (27.6–51.3)</td>
</tr>
</tbody>
</table>

\(^a\)SEM = standard error of measurement; SEM% = percentage of SEM; MDC = minimal detectable change; MDC% = percentage of MDC.

\(^b\)Range are reported as 95% confidence intervals.
Figure 1.

Relationship between the reachable work space (RWS) ratio and the Fugl-Meyer Assessment upper extremity motor score (FMA-UE) total score (a), proximal score (b), and distal score (c). Spearman rank correlation coefficients, rho, and P values are presented.
Figure 2.

Graphical illustrations of the reachable work space (RWS) in representative participants with hemiparetic stroke. The area with 4 colors represents the RWS. The blue line represents the stick picture of the trunk and the upper extremity of the test side. The upper row shows the RWS of the paretic side, and the lower row shows the RWS of the nonparetic side. The size of the RWS is involved with upper extremity motor function. FMA-UE = Fugl-Meyer Assessment upper extremity motor score.

<table>
<thead>
<tr>
<th>Patient 1: Severe</th>
<th>Patient 2: Moderate</th>
<th>Patient 3: Mild</th>
</tr>
</thead>
<tbody>
<tr>
<td>FMA-UE score: 14</td>
<td>FMA-UE score: 28</td>
<td>FMA-UE score: 62</td>
</tr>
<tr>
<td>RWS ratio: 12.3%</td>
<td>RWS ratio: 59.5%</td>
<td>RWS ratio: 96.5%</td>
</tr>
</tbody>
</table>

Figure 3.

Bland-Altman plot of reachable work space (RWS). The solid line represents the mean difference in the RWS ratio. The dashed line represents the limits of agreements of the difference in the RWS ratio.
Figure 4.

Graphical illustrations of the reachable work space (RWS) in 2 representative participants with hemiparetic stroke before and after training. The RWS after training is increased compared with the RWS before training. FMA-UE = Fugl-Meyer Assessment upper extremity motor score.