Upper limb kinematics in immersive virtual reality: comparison between healthy individuals and people with stroke using controllers and hand-tracking during a Box and Block Test

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Abstract

Background: Manual dexterity impairment affects about 80% of people with stroke (PWS), limiting daily activities. While the conventional Box and Block Test (BBT) reliably assesses gross manual dexterity, it provides limited information on movement quality. Immersive Virtual Reality (iVR) offers a cost-effective alternative to motion capture systems for kinematic analysis, allowing interaction via controllers or infrared-based hand tracking.

Aim: The primary aim was to examine the feasibility of iVR-based kinematic assessment, and the secondary aim was to compare upper limb kinematics between PWS and healthy individuals (HI).

Design: Cross-sectional study.

Setting: Cliniques universitaires Saint-Luc (Brussels, Belgium) and the Belgian population.

Population: Forty-two participants (21 PWS, 21 HI), matched for age.

Methods: Participants performed two validated iVR-based BBT versions in randomized order: controller-based (BBT-VR-C) and hand-tracking (BBT-VR-HT). Kinematic outcomes included wrist movement smoothness (SPARC) for both interaction modalities, and the intervals between movement onset and maximal hand opening (opening), and between maximal opening and object contact (closing) for the BBT-VR-HT.

Results: In BBT-VR-HT, the opening interval was higher in PWS (0.7[0.45–1.39]s vs 0.2[0.13–0.41]s, p = 0.005), whereas the closing interval did not differ between groups (0.3[0.13–1.62]s vs 0.3[0.20–0.48]s, p=0.507). Compared with HI, PWS exhibited lower SPARC values (BBT-VR-C: -2.3[-3.02–-2.02] vs -2.0[-2.34–-1.94], p=0.05; BBT-VR-HT: -3.5[-5.34–-3.04] vs -2.9[-3.26–−2.37], p=0.005), indicating reduced movement smoothness.

Conclusions: This study confirms the feasibility of iVR BBT versions for post-stroke movement quality assessment.

Clinical rehabilitation impact: iVR BBT versions enable assessment of movement quality after stroke, providing kinematic information not captured by the traditional test.

Key terms: Stroke; Kinematics; Virtual reality; Upper Extremity; Functional Assessment

INTRODUCTION

The estimated prevalence of manual dexterity difficulties after a stroke is 80%.[1] Many people with stroke (PWS) experience impairments in movements such as difficulties in hand opening, thumb opposition, or finger flexion, which limit their ability to perform daily life activities.[2] Given the impact of these deficits, frequent assessment of upper limb motor function is strongly recommended in neurorehabilitation.[3] Several standardized tests exist to evaluate motor performance, with the Box and Block Test (BBT) being one of the recommended tests to assess manual dexterity.[4,5] The BBT measures gross manual dexterity by counting the number of blocks a participant can successfully transfer with their hand from one side of a box to another within 60 seconds.

While the conventional BBT is commonly used in clinical settings and primarily provides a quantitative assessment of manual dexterity, it is unable to offer insights into movement quality.[6] To address this limitation, kinematic analysis has been increasingly encouraged by experts' consensus to assess movement quality in post-stroke rehabilitation, providing a more detailed understanding of motor deficits and recovery.[6,7] Although growing interest has been shown in assessing kinematics of the lower limbs, arms, trunk, and fingers kinematics remains relatively underexplored. Baak et al. showed slower and poorly synchronized grasping movements in PWS, with deficits mainly affecting the finger opening phase.[8] Complementing these findings, Lang et al. demonstrated that grasping is more impaired and recovers less effectively than reaching in PWS, with persistent deficits in grasp speed, accuracy and efficiency.[9,10]

To objectively quantify these features, upper limb kinematic measures obtained through passive optoelectronic motion capture systems have demonstrated good reliability[11], highlighting their value for monitoring motor recovery during rehabilitation.[12] While such setups remain a benchmark in movement analysis, they are costly, time-consuming, and often limited to specialized laboratory settings. Recent studies using portable technologies such as inertial measurement units have highlighted the relevance of kinematic assessment during BBT-like tasks in neurological populations. For instance, Cocco et al. reported altered upper limb kinematics in PWS using an IMU-based BBT paradigm.[13] Similarly, Thouant et al. showed that kinematic analyses can reveal compensatory movement strategies in PWS.[14] However, they did not assess finger kinematics or fine motor mechanics during grasping.

In recent years, immersive Virtual Reality (iVR) has emerged as a promising tool in neurorehabilitation, offering new opportunities for interactive training and precise movement tracking.[15] Two primary input modalities exist, allowing users to interact with the virtual setting: controllers and hand-tracking.[16] Controllers offer tracking of the device and provide haptic feedback, whereas hand-tracking relies on infrared sensors to reconstruct the hands in three dimensions, allowing natural hand movements but without haptic feedback. In this context, kinematic analyses conducted within iVR could represent a more accessible and cost-effective alternative to traditional motion capture systems. Most studies using iVR kinematic measures have employed haptic devices or controllers to track wrist motion,[17,18] revealing moderate to strong correlations between kinematics and clinical scores.[17] A recent validation study on healthy individuals (HI) demonstrated that Oculus Quest 2 hand-tracking can provide reliable hand-position measurements comparable to a commercial marker-based motion-capture system.[19] However, despite these advances, iVR hand-tracking remains rarely used to assess grasping kinematics during standardized in iVR.[20] Furthermore, iVR adaptations of the BBT have demonstrated validity in clinical-like settings,[17,18] including comparisons across controller-based VR, hand-tracking, and mixed reality approaches. However, it remains unclear how stroke-related motor impairments are reflected in kinematic parameters derived from iVR, and whether these parameters are influenced by the interaction modality used (controller vs hand-tracking).[6]

To address these gaps, the primary endpoint of this study was to test whether assessing upper limb kinematics of HI and PWS is feasible during the BBT using iVR. As secondary objectives, we aimed to examine differences between controller-based (BBT-VR-C) and hand-tracking (BBT-VR-HT) interaction modalities, to compare PWS and HI, and to explore the relationships between these kinematic parameters and functional outcomes in PWS. We hypothesized that iVR-based assessment of upper limb kinematics during the BBT would be feasible in both groups, and that exploratory analyses would reveal differences in reach-to-grasp kinematics between PWS and HI.

MATERIAL AND METHODS

Study Design

This complementary analysis focuses on two previously validated iVR-based versions of the BBT, one using BBT-VR-C and the other using BBT-VR-HT, for which usability, test-retest reliability, and concurrent validity have been demonstrated in PWS and HI.[17,18] Data from PWS were obtained from previously published studies,[17] whereas a subset of the HI data was newly collected in the present study using the same protocol. The prospective cross-sectional observational study was conducted at the Cliniques universitaires Saint-Luc, Brussels and within the Belgian population between October 2022 and January 2025. This study is registered on clinicaltrials.gov (NCT04694833), approved by the Saint-Luc-UCLouvain Hospital-Faculty Ethics Committee (reference 2015/10FEV/053), and adheres to the STROBE guidelines.

Participants

A total of 42 participants were included in the study, comprising 21 PWS and 21 HI matched for age (±2 years). The sample size was determined from a power calculation conducted for the initial validation study of the BBT-VR.[17] PWS were recruited through hospital records and rehabilitation unit referrals, and HI were recruited via word-of-mouth and social networks in the Belgian population. All participants provided written informed consent prior to testing.

The inclusion criteria for PWS were a diagnosis of a first-ever cortical or subcortical stroke with identifiable cerebral lesions according to World Health Organization criteria,[21] the ability to understand basic instructions, and the capability to move at least one cube using the affected hand in the traditional BBT. The exclusion criteria included the presence of any other neurological or orthopedic disorder affecting upper limb function, or severe visual impairment preventing accurate interpretation of iVR instructions. For HI participants, the inclusion criteria required no history of neurological or orthopedic impairments affecting manual dexterity.

Materials

Data collection was conducted using two previously validated iVR versions of the BBT (BBT-VR-C and BBT-VR-HT).[17,18] The BBT-VR-C was developed using Unity (version 2021.3.22f1, C#) and ran on the standalone Meta Quest 2® headset. Participants manipulated virtual cubes using button-based grips on the controllers. The BBT-VR-HT, in contrast, utilized the built-in hand-tracking system of the Meta Quest 2®. An overview of the two setups is presented in Figure 1. Participants grasped virtual cubes using natural hand and finger movements, detected by the headset's infrared cameras. To ensure consistency with the traditional BBT, both BBT-VR versions replicated the standard setup, including a 53.7 cm × 24.4 cm × 8.5 cm box with a central divider and 2.5 cm cubes, ensuring full comparability between conditions.[22] For both tests, participants were instructed to move as many cubes as possible from one box compartment to the other within 60 seconds, ensuring that the hand moving the cube did not cross the partition, as required in the traditional test. Each participant completed both iVR tests in a randomized order to mitigate learning effects.

To facilitate the delivery of instructions and view the participant's setup, we used the MetaHorizon® and SideQuest® applications. These applications allowed real-time viewing of the virtual environment experienced by the participant by mirroring the headset's display onto a smartphone or computer screen.

Experimental procedure

Before the BBT-VR, participants were provided with a 30-second familiarization period for each test to adapt to the environment and controls. During the experiment, three trials were conducted for each test, using the dominant hand for HI participants and the paretic hand for PWS. A 30-second rest period was given between each trial to minimize fatigue. For data analysis, only the score and kinematics from the final trial of each test were retained, ensuring that potential learning effects were minimized. In addition to the BBT-VR, PWS participants also underwent the classical BBT as well as clinical assessments (emNSA), including the computerized adaptation of the Fugl-Meyer Assessment (CAT-FM), the National Institutes of Health Stroke Scale (NIHSS), and the Montreal Cognitive Assessment (MoCA).[17,18] The entire experiment lasted approximately 90 minutes per participant.

Kinematic analysis

The raw data were exported as CSV files from the Meta Quest's embedded logging system, whose internal data processing remains undisclosed. All data processing and visualization were conducted using Python in the Visual Studio Code® environment and MATLAB R2019b (MathWorks®).

3D hand movement trajectories were processed through a series of preprocessing steps. These included spectral analysis to separate movement signals from noise and Butterworth lowpass filtering (4th order, cutoff frequency = 10 Hz, sampling frequency = 72 Hz) to smooth the signals. To improve signal quality, spatial outliers caused by headset noise were removed using a non-parametric, histogram-informed distance thresholding method.[23] Specifically, 3D Euclidean distances between each point and a predefined spherical reference center were computed and modeled using a univariate histogram. Upper and lower thresholds were derived by detecting continuous sequences of low-density bins above and below the mean distance.

As the BBT involves repetitive movement sequences, segmentation was carried out to distinguish between the multiple reaching and transport phases. The segmentation boundaries were determined from the timestamps of the cube grasp and release events recorded by the headset. The reaching phase started when the wrist advanced past the central divider and ended when the cube was grasped. In the BBT-VR-C condition, the wrist point corresponded to the controller position, whereas in the BBT-VR-HT condition, it was estimated by the Meta Quest hand-tracking system using computer vision and machine learning to reconstruct joint positions from camera data.[19] For both conditions, the transport phase started when the cube was grasped and ended upon its release in the appropriate area. Graphical representations, including histograms, trajectory plots (see Figure 2), and velocity profiles, were generated to ensure accurate data segmentation. After segmentation, sub-trajectories corresponding to reaching or transport phases were discarded when their overall movement direction was inconsistent with the expected task pattern, based on visual inspection. Exclusion relied on a single objective binary criterion, namely whether the movement trajectory was directed toward the target or moved and released in the opposite direction. This step was applied uniformly across all participants by a single investigator (TN). The processed kinematic data was exported to an Excel file and subsequently analyzed to assess movement quality through various kinematic indices. Following segmentation, the continuous trajectories were divided into successive reach and transport phases corresponding to individual block transfers, reflecting the cyclic nature of the BBT task. Kinematic metrics were then computed separately for the reach and transport phases. The full list of extracted metrics, along with their abbreviations and definitions, is provided in Table 1.[9,10,24] All metrics were calculated for each segmented movement and subsequently averaged per participant and condition for statistical analysis. All kinematic metrics were computed for both interaction modalities (BBT-VR-C and BBT-VR-HT), except for hand aperture-related parameters, which were calculated exclusively in the BBT-VR-HT condition, as only hand-tracking enables direct measurement of finger movements. For each phase (reach and transport), outcomes were categorized as main or exploratory after examination of the data (see Table 1).

Statistical Analysis

All statistical analyses were conducted using SPSS version 29.0.1.0 (IBM®) and Sigma Plot version 13.0 (Systat Software Inc.®).

Feasibility was evaluated descriptively by computing the percentage of incorrect kinematic data points and segments. To assess protocol feasibility, we defined that at least 95% of participants completing the iVR intervention and 95% of participants being able to displace at least one virtual cube in both BBT-VR-C and BBT-VR-HT would indicate acceptable feasibility. In addition, in line with common practice in movement analysis, we considered that a proportion of excluded trials below 5% would reflect acceptable data quality.[25]

Statistical analyses were performed to assess differences in demographic characteristics and kinematic indices between PWS and HI under both BBT-VR-C and BBT-VR-HT conditions. Normality of continuous variables was tested using the Shapiro–Wilk test. Baseline demographic and clinical characteristics were compared between groups to verify equivalence. Independent samples t-tests or Mann–Whitney U tests were used depending on the distribution of the data, while Z-tests for proportions were applied for categorical variables.

The kinematics was compared between groups under both conditions using independent samples t-tests or Mann-Whitney U tests. Continuous variables are reported as mean and standard deviation or as median with interquartile range. Effect sizes using absolute Cohen's d and 95% confidence intervals were computed to quantify the magnitude of between-group differences. For kinematic variables showing high inter-individual variability among PWS, we performed Pearson's or Spearman's correlation tests, depending on data distribution, with the classical BBT score assessing the relationship between kinematic metrics and traditional dexterity performance. The proportion of variance explained by the traditional BBT score was also quantified using the coefficient of determination (R^2). Categorical variables are summarized using frequencies and percentages. Statistical significance was $p < 0.05$ for all tests. A False Discovery Rate (FDR) correction (Benjamini-Hochberg procedure) was applied to analyses involving exploratory kinematic outcomes to account for multiple comparisons, while main kinematic outcomes were analyzed without correction. To address the delay since stroke variability, a sensitivity analysis restricting kinematic comparisons to the acute/subacute cohort (n = 15) was performed.

RESULTS

Detailed demographic data are presented in Table 2. There were no significant differences between the groups for the main demographic indicators. All participants completed the sessions. On average, HI displaced 52 ± 17.9 blocks in the BBT-VR-C and 56 ± 19.6 blocks in the BBT-VR-HT, whereas PWS displaced 22 ± 11.2 and 26 ± 16.2 blocks, respectively. Each evaluation lasted one minute, and no serious or non-serious adverse events were reported.

One PWS displaced only a single cube in the BBT-VR-HT and was therefore excluded from the kinematic analysis for this test. In the BBT-VR-C, one PWS failed to displace any virtual cubes, and for another, the export file containing hand and finger positions was corrupted. These issues led to their exclusion from the kinematic analysis for this condition. Consequently, kinematic analyses were performed on 40 participants (20 HI and 20 PWS) for the BBT-VR-HT and on 38 participants (19 HI and 19 PWS) for the BBT-VR-C condition, while cross-modality comparisons were conducted on 40 participants (21 HI and 19 PWS).

Following data cleaning and segmentation, approximately 0.35% of kinematic data points were removed across 9 participants (5 HI, 4 PWS). Inconsistent movement direction was identified in 14 participants (7 HI, 7 PWS), representing 1.8% of all movements and occurring exclusively in the BBT-VR-HT condition (see Supplementary Material B).

All predefined feasibility criteria were met, including full session completion, a task success rate of 97.6% exceeding the predefined 95% threshold, and a low proportion of excluded data and incorrect movements below the predefined 5% threshold, supporting acceptable data quality.[25]

Reach and transport time

As presented in Table 3 and Figure 2, during the BBT-VR-HT, PWS took 1.8 times longer than HI both to reach the block (0.9 [0.69-2.90] s vs 0.5 [0.41-0.70] s) and to transport the cube (0.9 [0.69-2.90] s vs 0.5 [0.40-0.68] s). In the BBT-VR-C condition, reaching time in PWS was 2.3 times longer than in HI (0.79 [0.55-1.41] s vs 0.34 [0.26-0.48] s), while transport time was 2.0 times longer (1.0 [0.71-1.82] s vs 0.5 [0.37-0.68] s) (see Table 3).

Reach phase in BBT-VR-HT

As presented in Table 3, a significant difference was found for the opening interval, which was approximately 3.5 times longer in PWS compared to HI (0.7 [0.45-1.39] s vs 0.2 [0.13-0.41] s, $p = 0.005$). In contrast, no significant group differences were observed for mean hand aperture, peak aperture rate, hand aperture at touch, or the closing interval.

Transport phase

Smoothness, calculated with SPARC, was significantly lower for PWS than HI during the BBT-VR-HT condition (-3.5 [-5.34–-3.04] vs -2.9 [-3.26–-2.37], $p = 0.005$) and marginally lower in the BBT-VR-C condition (-2.3 [-3.02–-2.02] vs -2.0 [-2.34–-1.94], $p = 0.05$). In addition, in both BBT-VR-HT and BBT-VR-C, PWS showed significantly lower mean and peak transport velocities than HI ($p < 0.001$). CVspeed was approximately 1.5 to 2 times greater in PWS compared to HI in both conditions (BBT-VR-HT: $p = 0.004$; BBT-VR-C: $p = 0.002$). SAT was approximately 1.8 times lower in PWS than HI for both BBT-VR-HT (1.6 (0.91) vs 2.9 (1.08), $p < 0.001$) and nearly 2 times lower in BBT-VR-C (2.4 [1.32–3.29] vs 4.6 [3.86–6.82], $p < 0.001$) conditions.

Relationship between kinematic metrics and traditional manual dexterity score

As there was high between-individuals variability for SPARC in PWS, we examined whether this variability reflected differences in clinical status by correlating SPARC with the traditional BBT score and the CAT-FM (see Figure 4). We found a significant and strong correlation between the traditional BBT score and both SPARC ($r = 0.73$; $p < 0.001$) and the

CAT-FM score ($r = 0.73$; $p < 0.001$), with 53% of the variance explained in both cases (R^2= 0.530).

Influence of the delay since stroke

Our sensitivity analysis showed that kinematic metrics for the acute/subacute cohort (n = 15) remained highly consistent with the full cohort (see Supplementary Table D1).

BBT-VR-C vs BBT-VR-HT

Like HI, PWS exhibited significantly lower SPARC with hand-tracking ($p < 0.001$). For PWS, transport time, mean and peak velocity were comparable between BBT-VR-C and BBT-VR-HT conditions (non-significant, $p > 0.05$). However, PWS showed a higher CVspeed ($p < 0.001$) in the BBT-VR-HT condition compared to the BBT-VR-C condition, while no significant difference was observed for SAT.

For HI, SPARC was 1.4 times lower in the hand-tracking condition (-2.8 [-3.3 to -2.4]) compared to the controller condition (-2.0 [-2.32 to -1.94], $p < 0.001$). However, no significant differences were found between BBT-VR-C and BBT-VR-HT conditions for transport time, mean or peak velocity ($p > 0.05$). Additionally, the SAT was significantly lower ($p < 0.001$) and the CVspeed significantly higher ($p < 0.001$) when using hand-tracking versus controllers.

DISCUSSION

To the best of our knowledge, this study is the first to show the feasibility of using iVR to assess hand and finger kinematics in PWS during a manual dexterity task. Our primary aim was to assess the feasibility of the measurement approach and the comparison between HI and PWS during an iVR adaptation of the BBT, using controllers and hand-tracking interaction modalities. The present study extends previous works[17,18] by providing a more detailed and structured analysis of reach-to-grasp kinematics, with a specific focus on movement quality and phase-specific motor control. The hand-tracking modality specifically enabled detailed analysis of the reach phase, providing insights into hand aperture dynamics. In this phase, while most outcomes were comparable between groups, PWS demonstrated a significantly prolonged reach phase, marked by a delayed initiation of hand opening, as indicated by a longer opening interval. In the transport phase, which could be assessed in both hand-tracking and controller conditions, PWS consistently displayed longer transport times, reduced mean and peak velocities, poorer speed-accuracy trade-offs, and greater speed variability relative to HI. These differences reflect the ability of the method to capture variations in movement profiles.

When comparing interaction modalities, both groups exhibited less smooth and less controlled movements when using hand-tracking compared to controllers, as reflected by lower movement smoothness, reduced speed-accuracy trade-offs, and increased speed variability. Contrastingly, transport time and mean and peak velocity remained comparable between modalities in both groups.

Delayed reaching phase in PWS

The increased reaching time observed in PWS during the iVR task is likely attributable to sensorimotor impairments affecting the affected arm, which limit the ability to rapidly and efficiently reach toward a target.[9] This finding is consistent with previous studies conducted in physical environments, where PWS similarly demonstrated prolonged reaching times and reduced peak velocities during reaching, reach-to-grasp, and pointing tasks when compared to HI.[8–10,26]

Specifically, our findings highlighted that during the reaching phase, the significant difference between HI and PWS emerged primarily in the initial part of the movement (opening interval) rather than in the latter part of the reach (closing interval). This pattern aligns with a previous study[8] assessing reach-to-grasp movements of a cylindrical lever using a pinch grip, which similarly reported that delays in the reaching phase in PWS were most evident early in the movement. Comparable patterns have also been reported in virtual settings. For example, in a non-VR study, comparing HI and people with Parkinson's disease during a finger-tapping task, the authors found that finger-tapping speed was significantly greater in HI than in people with Parkinson's disease.[27] These results suggest that hand opening may execute more rapidly and efficiently in HI than in neurologically impaired populations, reinforcing the notion that conditions affecting the central nervous system compromise hand motor control. We could also hypothesize that the initial phase of reaching, particularly the timing of hand aperture onset and early aperture scaling, is highly dependent on anticipatory motor planning and feedforward control mechanisms.[28] These processes are frequently disrupted following stroke and other neurological pathologies, possibly leading to delayed initiation of hand opening and reduced ability to appropriately scale aperture size early in the movement. Another hypothesis worth considering relates to the distal sensorimotor impairments commonly observed in PWS, including finger flexor spasticity, dystonia, or reduced selective motor control of the fingers and thumb. These deficits could prolong the time required to initiate and execute hand opening, leading to a disproportionately slower onset-aperture interval compared to the rest of the reaching movement.

In our study, HI, on average, had their peak aperture at 20% of total movement time, whereas PWS had their peak aperture at around 37% of total movement time. However, these findings do not show the same tendency as other non-VR studies in HI, which typically report that peak hand aperture occurs at around 42% of movement time[9] or even later, between 55% and 75% depending on task constraints and object characteristics.[28–31] This discrepancy is likely due to differences in task design and in how the percentage of movement time was calculated. In PWS, peak aperture has been reported to occur even earlier in the literature, at around 30% of movement time.[9] Besides methodological differences, this could also be explained by the fact that PWS included in our study may have presented milder distal sensorimotor impairments and retained greater manual dexterity than those in previous investigations. This might have enabled them to execute a more gradual and larger hand opening, thereby extending the time needed to reach peak aperture. Notably, in one previous study[9], six of the PWS exhibited a peak hand aperture at 0% of movement time, as their largest aperture occurred passively in the starting position. Second, task constraints and interaction modalities in our iVR setup differ substantially from those in conventional physical tasks. In particular, the absence of haptic feedback when using hand-tracking technology removes important tactile cues that, with repetition, can guide aperture timing and scaling early in the movement.[32] This could have potentially led PWS to open their hand more cautiously and over a longer time period.

Transport phase

The increased transport time, reduced mean and peak velocities, and poorer speed-accuracy indicate slower, less smooth, and less efficient movements in PWS.[9] These results align well with prior research conducted in both physical and virtual environments, consistently reporting transport-related deficits in PWS.[8,9] Baak et al. observed longer transport times and lower peak velocities in PWS compared to HI during physical reach-to-grasp tasks, highlighting reduced movement speed in this population.[8] Similarly, Lang et al. reported prolonged grasp times and diminished peak transport velocities in PWS, reinforcing the notion of slowed upper limb movements following stroke.[9]

Significantly lower SAT observed in PWS across both interaction modalities further reinforces the presence of inefficient and less controlled transport strategies following stroke. SAT reflects a fundamental aspect of motor control, capturing the ability to balance movement speed and precision during goal-directed actions. In neurological populations, this balance is often disrupted, with individuals either slowing down excessively to maintain accuracy or producing faster but less accurate movements. As such, SAT provides insight into motor strategy and the efficiency of sensorimotor control. Previous work in stroke rehabilitation has shown that this trade-off can be modified with training. For instance, speed-focused interventions have been associated with faster, smoother, and more symmetrical movements, along with short-term improvements in the speed-accuracy relationship, suggesting a shift toward more efficient feedforward control.[33] In addition, other studies have demonstrated that improvements in movement accuracy can emerge from reduced trial-to-trial variability rather than changes in systematic error, highlighting that motor learning may primarily reflect enhanced control within an existing movement repertoire.[34] No minimal clinically important difference has been formally established for SAT.[35,36] Therefore, its interpretation relies primarily on relative changes over time or comparisons with baseline or reference performance. Improvements in SAT should be understood in the context of a more favorable speed-accuracy balance, reflecting enhanced motor control rather than isolated changes in speed or accuracy alone.

Despite maintaining comparable task success, PWS relied on slower and more corrective movements, reflecting reduced efficiency in regulating movement execution. These findings support the interpretation that transport deficits in PWS go beyond reduced speed and involve limitations in movement control. These findings are consistent with recent studies using inertial sensors during BBT-like tasks, which also reported altered kinematics and reduced movement efficiency in PWS.[13] These alterations include decreased movement smoothness and increased reliance on compensatory strategies.[13] Given these deficits, it is also important to consider how different interaction modalities may influence movement quality, particularly regarding smoothness and variability.

Hand-tracking vs controllers' modalities

While transport time, mean velocity, and peak velocity did not differ significantly between the controller and hand-tracking modalities in either group, our results revealed that movement smoothness (SPARC), efficiency (SAT), and speed variability (CVspeed) were consistently poorer when using hand-tracking. The distinct interaction characteristics of each modality may have influenced participants' movement strategies and, consequently, the observed kinematic outcomes. One plausible explanation for this finding is the absence of haptic feedback in the hand-tracking modality.–Without the tactile cues provided by the controller, participants likely relied more heavily on visual feedback and proprioception, which may have led to an increase in corrective submovements and micro-adjustments during transport, ultimately degrading movement smoothness and increasing variability. This hypothesis aligns with prior research highlighting that the lack of physical interaction or resistive feedback in VR environments tends to result in less fluid and more segmented motor trajectories.[31,32,37,38] Comparable effects have been reported outside of VR, where digital anesthesia of the thumb and fingers has been shown to disrupt grip-load coordination and increase corrective submovements, thereby degrading movement smoothness.[39,40] Similarly, it is possible that participants adopted subtly different movement strategies across modalities. The physical presence of the controller may have constrained the hand's degrees of freedom and stabilized wrist and finger movements, inadvertently promoting smoother, more controlled trajectories. In contrast, the increased freedom in the hand-tracking condition, while more naturalistic, might have encouraged broader variability in joint coordination and movement execution, further contributing to the observed differences in smoothness and variability metrics. This is in line with previous work showing that PWS rely on compensatory movement strategies to adapt to motor impairments.[14]

A second hypothesis relates to the technical limitations inherent in current markerless hand-tracking systems, particularly those based on Meta Quest 2 technology. A recent validation study indicated that although positional data from hand-tracking is generally reliable, the accuracy and reliability of derived kinematic measures involving acceleration and deceleration can be reduced compared to other metrics like position or orientation.[19] However, this same study has shown that reliability improves substantially when the head remains relatively still and when the interactive environment is positioned close to the participant, as was the case in our experimental setup. In our study, both SPARC and CVspeed were highly sensitive to fluctuations in acceleration and deceleration, since they reflect variability in instantaneous velocity throughout the movement. Interestingly, while SPARC values show high inter-individual variability for the BBT-VR-HT in PWS, they still strongly correlated with classical BBT performance, supporting their potential clinical relevance.

Interpretation of movement smoothness using SPARC

The present results highlight the potential of iVR to capture detailed kinematic markers of motor performance, including movement smoothness assessed with SPARC. Such measures may help characterize subtle alterations in sensorimotor control that are not fully reflected by conventional clinical or temporal outcomes. Movement smoothness, quantified using the SPARC metric, provides complementary insight into motor control by reflecting the continuity and coordination of movement. In line with previous work, smoothness can be interpreted as a proxy of movement quality, where less smooth trajectories reflect more corrective submovements, and impaired sensorimotor control.[41] Importantly, SPARC is considered as the most robust smoothness metric, as it is less influenced by movement duration and is less sensitive to signal noise, making it particularly suitable for complex or unconstrained tasks.[41] Longitudinal evidence supports the clinical relevance of SPARC, as improvements in smoothness have been shown to parallel recovery of motor impairment.[35,36] For instance, Saes et al. demonstrated a significant longitudinal association between SPARC and upper limb motor recovery (e.g., FMA-UE), suggesting that changes in smoothness reflect underlying neurological recovery processes.[36] Similarly, improvements in SPARC have been shown to be associated with changes in clinical measures such as UE-FMA and ARAT, supporting its predictive validity as a kinematic biomarker.[35] However, up till now, no minimal clinically important difference has been formally established for SPARC.

Clinical implications

This study highlights the feasibility and added value of assessing hand and finger kinematics in iVR environments for PWS. These results align with current international recommendations emphasizing the importance of quantifying task outcomes but also characterizing movement quality during functional, multisensory, and ecologically valid tasks.[5] Importantly, iVR platforms offer a cost-effective and portable alternative to conventional motion capture systems, making it possible to assess movement quality more frequently, in clinical settings, and potentially at home during rehabilitation programs. Although these advantages are shared by other portable and user-friendly technologies, such as inertial sensors, which have been used to assess upper limb kinematics and compensatory strategies in stroke populations,[13,14] the present iVR-based approach extends this line of work by enabling the assessment of finger kinematics during grasping tasks.

While both controller-based and hand-tracking interaction modalities are clinically usable, our findings indicate that hand-tracking can provide additional clinically relevant information regarding the quality of hand and finger movement. Controller-based assessments may provide consistent wrist measures for acceleration-dependent metrics due to stable inertial sensing. However, hand-tracking enables richer, unconstrained tracking of hand and finger movements, capturing hand aperture dynamics and movement strategies that controllers cannot. Despite some limitations in acceleration-derived metrics, especially during fast movements or complex trajectories, recent validation studies[18,19] and our results show that, with appropriate task design and stable head positioning, hand-tracking has the potential to deliver more clinically meaningful insights into movement quality in PWS.

Recommendations for future research

Future research should aim to directly compare kinematics obtained in iVR environments with those collected in physical conditions, using identical task protocols, to assess the validity of virtual metrics. Moreover, longitudinal studies are needed to investigate how movement quality metrics captured in iVR evolve over the course of rehabilitation and how they relate to functional recovery. Tracking hand and finger kinematics during ecologically relevant, multisensory tasks in iVR over time could help determine the specific impact of virtual interventions on manual dexterity, movement efficiency, and compensatory strategies. Additionally, future work should explore the reliability and validity of various kinematic parameters across different hardware configurations and interaction modalities and assess their responsiveness to rehabilitation-induced changes in motor behavior.

Limits

Several limitations should be acknowledged in this study. First, the newly added subset (10/21) of HI did not perform the BBT limiting the possible learning effect between conditions. However, as the task order was randomized, only a subset of participants could have benefited from prior exposure, thereby limiting any systematic bias. Second, the PWS group was heterogeneous in terms of clinical status, including individuals from early subacute to chronic stages post-stroke. This variability may have influenced the observed kinematic profiles and reduced the ability to detect stage-specific motor control characteristics. However, a sensitivity analysis restricted to acute/subacute participants (n = 15) yielded kinematic estimates highly consistent with the full cohort. Third, participants' general affinity for iVR or digital technologies, as well as prior occupational or leisure expertise in manual dexterity, were not formally assessed, and these factors may have affected motor performance and iVR interaction strategies. Fourth, the study did not include a direct comparison between hand and finger kinematics obtained in the iVR task and those measured in a real-world, physical version of the BBT. Such comparisons would be valuable to confirm the validity of kinematic outcomes in iVR and better interpret deviations in motor behavior between modalities. Additionally, although the immersive task was designed to replicate the functional demands of the physical BBT, the absence of haptic feedback and differences in interaction modalities may have affected motor strategies, particularly during grasp and release phases. Nonetheless, these interaction modes reflect current technology available in clinical VR systems and provide important insights into how sensory constraints shape motor behavior in digital rehabilitation environments. Finally, although our sample size appears sufficient to provide adequate statistical power for the present analyses, the relatively small cohort may limit the generalizability of the findings. Future studies with larger and more diverse samples would be valuable to determine the extent to which our findings generalize to broader populations.

CONCLUSIONS

This study supports the feasibility of iVR-based kinematic assessments in clinical settings. The iVR adaptations of the BBT identified impaired movement quality in PWS, particularly in speed, variability, and efficiency during reaching and transport. These findings highlight the potential added value of iVR for post-stroke motor assessment, providing detailed kinematic insights beyond traditional scores. Among modalities, hand-tracking enabled a more detailed assessment of natural hand and finger movements and showed potential for capturing clinically meaningful features of movement quality.

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Statement and declarations

Ethical considerations: This study is approved by the Saint-Luc-UCLouvain Hospital-Faculty Ethics Committee (reference 2015/10FEV/053).

Consent to participate: All participants provided written informed consent before starting the study.

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Author contributions:

Therese Ntabuhashe: Conceptualization, Methodology, Investigation, Formal Analysis, Software, Visualization, Writing- Original draft preparation.

Thierry Lejeune: Conceptualization, Methodology, Investigation, Visualization, Writing- Reviewing and Editing, Supervision.

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Elric De Pluymer: Investigation, Visualization, Writing- Reviewing and Editing.

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Titles of figures:

Figure 1. Illustration of the Box and Block test in the two experimental conditions: (A) Controller condition (BBT-VR-C); (B) Hand-tracking condition (BBT-VR-HT).

Figure 2. Typical trace of the wrist trajectory after processing, during the two analyzed phases of the movement (approach and transport). The blue line represents healthy individuals, and the red line represents people with stroke. The orange structure corresponds to the box, and the black arrows indicate the movement direction.

Figure 3. Group comparisons of transport time, temporal intervals (opening and closing intervals), smoothness (SPARC), and speed–accuracy trade-off (SAT) between the two iVR conditions (BBT-VR-C and BBT-VR-HT). Bars represent mean ± SD, with individual participant data shown as dots. Asterisks indicate significant differences between conditions ($p < 0.05$).

Figure 4. Relation between Box and Block Test (BBT) score and CAT-FM with the smoothness metric (SPARC), assessed using Pearson's correlation. Each blue dot represents one participant. The red line indicates the linear regression fit with its 95% confidence interval (shaded area).

Tables:

Table 1. Overview of kinematic metrics

	Metric	Abbreviation	Definition
Reach phase			
Main outcomes	**Opening interval**	**/**	Time from movement onset to the maximum distance between the tip of the thumb and the tip of the index finger.
	Closing interval	**/**	Time from the maximum distance between the tip of the thumb and the tip of the index finger to block contact.
Exploratory outcome	**Peak aperture rate**	**/**	Maximum rate of increase of the distance between the tip of the thumb and the tip of the index finger.
	Hand aperture at touch	**/**	Distance between the tip of the thumb and the tip of the index finger at block contact.
	Maximum hand opening velocity	**Vel-max**	Maximum velocity of increase of the distance between the tip of the thumb and the tip of the index finger.
Transport phase			
Main outcome	**Spectral Arc Length**	**SPARC**	Smoothness metric derived from the frequency spectrum of the velocity profile, invariant to movement duration and amplitude (see Supplementary Material A). Higher SPARC values reflect smoother movements.
Exploratory outcome	**Transport time**	**/**	Time interval from block contact to block release.
	Mean velocity	**Vmean**	Mean transport velocity of the wrist during block displacement.
	Peak velocity	**Vpeak**	Peak transport velocity of the wrist during block displacement.
	Speed-Accuracy Trade-Off	**SAT**	Quantifies the balance between movement speed and precision; $SAT = 10 \times (TSD/Lpath) \times Vmean$ where Vmean represents the mean wrist velocity (m/s), Lpath is the actual wrist path length (m), and TSD is the theoretical shortest distance between movement onset and target (m). Higher SAT values indicate more efficient motor control.
	Coefficient of Variation of Speed	**CVspeed**	Ratio of the standard deviation to the mean of the velocity Lower values indicate more stable and consistent speed control.
Reach and Transport phase			
Exploratory outcome	**Mean hand aperture**	**Mean hand ap.**	Average distance between the tip of the thumb and the tip of the index finger during the reaching phase.

Table 2. Participants demographics

	Healthy individuals (n=21)	People with stroke (n=21)	p-value
Age (#years)	65.5 (7.40)	65.7 (7.24)	0.917
Sex (F/M)	7/14	6/15	0.980
Height (cm)	173.0 (7.71)	171.3 (7.18)	0.460
Weight (kg)	81.0 (13.20)	77.4 (20.14)	0.491
Time since stroke onset (months)	/	3.2 [0.58–5.72]	/
CAT-FM (%)	/	87.68 (15.37)	/
NIHSS (/42)	/	8 [6 – 11]	/
MoCA (/30)	/	23.5 [23 – 26]	/
BBT-VR-C (#blocks)	52 (17.9)	22 (11.2)	<0.001
BBT-VR-HT (#blocks)	56 (19.6)	26 (16.2)	<0.001
BBT (#blocks)	/	33 (16.2)	/

BBT-VR-C: Box and Block in immersive virtual reality using controllers; BBT-VR-HT: Box and Block Test in immersive virtual reality using hand-tracking technology; CAT-FM: computerized adaptation of the Fugl-Meyer Assessment; F: female; L: left; M: male; NIHSS: National Institutes of Health Stroke Scale; R: right. For the 19-subject analysis (after removal of 3 participants), no significant differences remained. Data are expressed as median [interquartile range] for non-normally distributed variables and as mean (standard deviation) for normally distributed variables.

Table 3. Comparison of hand and finger kinematics between healthy individuals and people with stroke under controller and hand-tracking conditions.

	BBT-VR-HT				**BBT-VR-C**				**BBT-VR-C vs BBT-VR-HT**	
	HI	**PWS**	**p[1]**	**Cohen's d[1]**	**HI**	**PWS**	**p[2]**	**Cohen's d[2]**	**p[3] (HI)**	**p[4] (PWS)**
	(n=20)	**(n=20)**			**(n=19)**	**(n=19)**			**(n=21)**	**(n=19)**
Reach phase										
Main outcomes										
Opening interval (s)	0.2 [0.13–0.41]	0.7 [0.45–1.39]	0.005	−0.87	/	/	/	/	/	/
	44 (17) %	57 (28) %	0.088							
Closing interval (s)	0.3 [0.20–0.48]	0.3 [0.13–1.62]	0.507	−0.62	/	/	/	/	/	/
	56 (17) %	43 (28) %	0.088	-0.56						
Exploratory outcomes										
Reach time (s)	0.5 [0.41–0.70]	0.9 [0.69–2.90]	0.016	−0.74	0.34 [0.26–0.48]	0.79 [0.55–1.41]	<0.001	−0.79	0.021	0.277
Mean hand aperture (cm)	5.9 [4.93–7.17]	6.1 [4.94–6.69]	0.818	0.25	/	/	/	/	/	/
Peak aperture rate (m/s)	0.9 (0.41)	0.7 (0.25)	0.18	0.54	/	/	/	/	/	/
Hand aperture at touch (cm)	2.0 [2.00–2.06]	2.0 [1.99–2.05]	0.95	0.25	/	/	/	/	/	/
Transport Phase										
Main outcomes										
SPARC	-2.9 [-3.26–-2.37]	-3.5 [-5.34–-3.04]	0.005	0.83	-2.0 [-2.34–-1.94]	-2.3 [-3.02–-2.02]	0.050	0.61	<0.001	<0.001
Exploratory outcomes										
Transport time (s)	0.5 [0.40–0.68]	0.9 [0.68–2.90]	0.005	−0.75	0.5 [0.37–0.68]	1 [0.71–1.82]	<0.001	−0.79	0.580	0.775
Mean hand aperture (cm)	2.7 [2.20–3.30]	2.7 [2.31–3.10]	0.989	0.25	/	/	/	/	/	/
Vmean (m/s)	0.6 (0.22)	0.3 (0.15)	<0.001	1.78	0.6 [0.54–0.98]	0.3 [0.21–0.42]	<0.001	1.54	0.219	0.775

Vpeak (m/s)	1 [0.66–1.10]	0.4 [0.29–0.61]	<0.001	1.70	0.9 [0.72–1.34]	0.4 [0.28–0.56]	<0.001	1.61	0.424	0.848
SAT	2.9 (1.08)	1.6 (0.91)	<0.001	1.26	4.6 [3.86–6.82]	2.4 [1.32–3.29]	<0.001	1.54	<0.001	0.075
CVspeed	0.6 (0.09)	0.7 (0.16)	0.004	−1.04	0.3 [0.24–0.44]	0.4 [0.38–0.65]	0.002	−1.05	<0.001	<0.001

P-values were obtained using t-tests or Mann–Whitney tests depending on data normality, and paired t-tests or Wilcoxon signed-rank tests where appropriate. Effect sizes were computed using Cohen’s d and are reported together with their 95% confidence intervals (95% CI). Positive values of Cohen’s d indicate higher values in healthy individuals (HI) compared with people with stroke (PWS), whereas negative values indicate lower values in HI compared with PWS. BBT-VR-HT (HT) and BBT-VR-C (C) refer to the Box and Block Test performed in immersive virtual reality using hand tracking and controllers, respectively. Abbreviations: HI = healthy individuals, PWS = people with stroke, Vmean = mean velocity, Vpeak = peak velocity, SPARC = spectral arc length, SAT = speed–accuracy trade-off, CVspeed = coefficient of variation of instantaneous velocity. Statistical comparisons are labeled as follows: p^1 compares healthy and people with stroke under HT; p^2, under C; p^3 compares HT and C within the HI; and p^4, within the PWS. Data are expressed as median [interquartile range] for non-normally distributed variables and as mean (standard deviation) for normally distributed variables. P-values for exploratory outcomes were adjusted using the Benjamini–Hochberg false discovery rate (FDR) procedure, while main outcomes are reported without correction.

Supplementary materials:

A- Sparc metric

B- Artifact removal

C- Characteristics of people with stroke

D- Influence of clinical people with stroke heterogeneity on kinematic outcomes