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A Virtual Reality Dataset to Support Hand Action Observation in Rehabilitation and Motor Learning Studies

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The recovery of motor function is increasingly understood as a process influenced not only by physical training but also by perceptual and cognitive strategies. Action Observation Treatment (AOT), a neurorehabilitation approach in which patients observe goal-directed motor actions before executing them, has demonstrated clinical benefits; however, its wider implementation is hindered by a lack of standardized procedures. We present an open-access dataset of 33 upper limb gestures specifically developed to support the administration of Virtual Reality-based AOT (VR-AOT). The gestures were selected in collaboration with expert physiotherapists to ensure clinical relevance, and are provided as motion capture recordings along with Unity-based 3D animations embedded in configurable virtual scenes. The dataset is designed for flexibility, allowing users to modify parameters such as viewpoint, laterality, and repetition count. Technical validation confirms its usability and therapeutic applicability across multiple clinical and research contexts. This dataset offers a standardized yet customizable resource for developing and comparing VR-AOT protocols, with potential applications in neurorehabilitation and motor learning research.

Background & Summary

Over the past few decades, advances in cognitive neuroscience, neuroimaging, and neurophysiology have broadened the range of strategies available to guide, support, and enhance rehabilitation. These approaches now extend beyond traditional muscle- and joint-based interventions to include central strategies such as action observation[1,2], motor imagery[3,4], and non-invasive brain stimulation. Among them, Action Observation Treatment (AOT) has emerged as particularly promising. AOT leverages the human mirror mechanism, i.e., the neural principle whereby the observer's motor system is activated in a manner corresponding to the execution of the same action[5,6]. This motor resonance extends beyond cortical activation to modulate corticospinal excitability[7,8], reinforcing the functional link between observation and execution. These features make action observation an invaluable component in processes aimed at promoting motor learning or recovery, given its potential to pre-activate the motor system in an externally driven manner before actual execution. Building on this principle, AOT typically chains action observation with motor imagery[9] (see for a meta-analysis documenting the neural substrates of these processes, along with their overlap), before engaging the individual in physically performing the action.

This protocol has shown significant potential for enhancing motor learning in healthy individuals[10,11], limiting motor deterioration following limb immobilization[12], and supporting recovery in both adult and pediatric populations across various clinical conditions[2].

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Despite its robust neurophysiological foundation, AOT faces several challenges that hinder its broader implementation and optimal efficacy. One key limitation is the lack of standardized stimuli and procedures[2,13]. Existing AOT protocols vary widely in terms of action types and gesture complexity, with the stimuli selected, videotaped, and administered by the clinical personnel responsible for the patient's rehabilitation protocol. This results in substantial variability across studies, which limits replicability, reduces clinical scalability, and complicates comparisons. These issues highlight the need for open-access, standardized AOT stimulus repositories.

Beyond action type, recent research indicates that various stimulus features—such as viewpoint[14,15], number of repetitions, and the use of 3D visualization[16]—modulate neural responses to action observation and may influence the effectiveness of AOT. While traditional video-based stimuli offer limited flexibility, virtual reality (VR) provides a promising alternative. VR's immersive and interactive nature allows for the delivery of more naturalistic and controllable action stimuli, while enabling precise manipulation of parameters such as perspective, timing, and movement complexity. Preliminary findings suggest that VR-based AOT (VR-AOT) may enhance patient engagement and increase activation within the action observation network[12,17].

However, integrating VR into AOT remains logistically challenging. Developing VR-based stimuli typically requires multidisciplinary expertise, including software engineering, 3D animation, and programming, as well as access to specialized hardware such as head-mounted displays. These demands limit accessibility, particularly in clinical and resource-constrained environments, reinforcing the need for publicly available VR-AOT repositories to support broader adoption of this training approach. Currently, there is no comprehensive VR-based repository of AOT stimuli. Existing resources are scarce, often limiting to videotaped action observation[18]. While previous work from our group introduced a virtual-reality repository of occupational therapy exercises based on action observation[19], that resource primarily focused on occupational therapy gestures designed for specific functional contexts, without systematically targeting standardized upper-limb exercises typically employed in neurological rehabilitation pathways such as stroke or neurodegenerative conditions. These conditions often require structured upper-limb rehabilitation pathways based on standardized exercises that, while spanning proximal to fine motor control, are generally simpler and more modular than the complex occupational gestures represented in the previous repository.

The present dataset substantially extends the previous effort by (i) providing a repertoire of 33 graded upper-limb gestures typical of several neurorehabilitation protocols and (ii) embedding the stimuli within a fully configurable Unity project that allows systematic manipulation of viewpoint, laterality, repetition count, and stimulus sequencing. Such flexibility is particularly valuable in rehabilitation settings, where individual variability and contextual demands require tailored interventions. Moreover, in contrast to general motion-capture datasets that primarily provide kinematic recordings for biomechanical or computer vision purposes, the current repository has been explicitly designed for Action Observation Treatment. The gestures were selected based on clinical relevance, implemented within interactive virtual environments enabling realistic hand–object interactions, and distributed both as a Unity project and a ready-to-deploy Android application, thus improving accessibility for users with limited technical expertise. This dual format enhances usability while maintaining scientific rigor, supporting current efforts to translate neurotechnology innovations into real-world therapeutic applications[20,21]. Finally, we provide large-scale expert validation across 42 physiotherapists, documenting expert-rated suitability across diverse neurological and musculoskeletal contexts. This AOT-specific design, combined with structured clinical validation and flexible deployment options, addresses the current lack of standardized, reusable, and clinically grounded VR-AOT stimulus libraries.

By offering high-quality, standardized stimuli and a flexible VR platform, this resource aims to facilitate the development, testing, and personalization of AOT protocols in experimental and clinical settings, while promoting reproducibility and enabling robust cross-study comparisons.

Methods

Data collection and unity integration. Whole-body kinematic data were acquired from a 24-year-old, right-handed healthy volunteer[22], during the execution of 33 exercises commonly used in upper-limb motor rehabilitation. Procedures have been approved by the CNR Research Ethics and Integrity Committee (project QUASAR, date 22.09.2022) and signed informed consent was obtained by the volunteer. The exercise set was identified and selected in collaboration with expert physiotherapists from the Humanitas Clinical and Research Center (Milan, Italy), who also supervised the acquisition sessions to ensure clinical appropriateness and procedural accuracy.

Kinematic data were recorded using a dual-system setup. The primary motion capture system was the Xsens Biomech Awinda (Xsens Technologies, Netherlands), which features 17 miniature inertial measurement units (IMUs) that integrate 3D accelerometers, gyroscopes, and magnetometers. These sensors were placed on the participant's body using manufacturer-specified straps, enabling the tracking of 23 body joints and segments, including:

- Head and neck
- Eighth and tenth thoracic vertebrae
- Third and fifth lumbar vertebrae
- Right and left shoulder, arm, forearm, and hand
- Pelvis
- Right and left thigh, shank, foot, and forefoot

To obtain a clearer picture of hand and finger kinematics, Manus Prime II Xsens gloves (Manus, Netherlands) were used in conjunction with the Awinda system. Each glove features industrial-grade flex sensors and integrated inertial measurement units (IMUs), enabling precise tracking of three joints per finger.

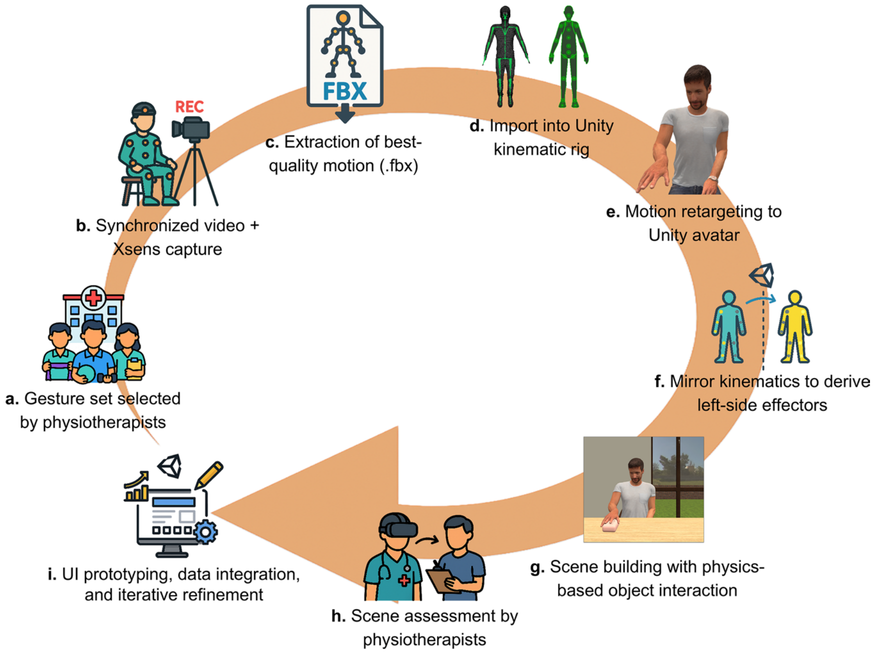

Fig. 1 Workflow for generation and validation of upper-limb VR-AOT stimuli. (**a**) Selection of a core set of upper-limb gestures by physiotherapists based on clinical frequency and relevance; (**b**) Synchronous recording of each gesture using RGB video and the Xsens MVN Awinda inertial system (17 wireless IMUs, 60 Hz); (**c**) Export of the highest-quality recordings in.*fbx* format for compatibility with the Unity animation pipeline; (**d**) Import and mapping of.fbx files to Unity's native kinematic rig; (**e**) Retargeting of motion data to a standard Unity humanoid avatar using the built-in rigging system; (**f**) Kinematic mirroring of right-arm stimuli to generate corresponding left-arm ones; (**g**) Assembly of a virtual environment with physics colliders, inverse kinematics, and custom assets to enable realistic hand-object interaction; (**h**) Evaluation of all scenes by 42 expert physiotherapists (see *Technical Validation section*); (**i**) Integration of results into the Unity project to refine the user interface, codebase, and final dataset.

Before recording, anthropometric measurements of the subject were obtained to allow scaling of the biomechanical model. Then both static and dynamic calibration was performed to allow alignment of the reference systems of the inertial sensors with those of the body segments.

Data integration in unity. The 33 gestures performed by the actor (see next paragraph) have been transformed into 33 VR-based animations, in line with a previous study from our group on the rehabilitation of occupational gestures[19].

Kinematic data were processed using Xsens MVN Analyze software to compute the orientation and position for each body segment and each finger. The resulting skeleton-based animation data were exported in FBX format, compatible with Unity 3D for real-time animation.

The FBX files containing the motion capture data were imported into the Unity 3D game engine software (version 6000.0.24f1) to animate a rig humanoid avatar (available at https://renderpeople.com/free-3d-people). For each exercise, colliders were placed on the avatar's hand and the objects that had to be manipulated. This ensured the realistic rendering of hand-object interactions. When a collision occurred between the hand and an object, the object's position was dynamically aligned with the finger kinematics until it was released. The object release was implemented through delegated animation events, by marking the exact frames in the animation where hand-object contact was lost. Finally, each animation was reviewed for consistency checks and, if necessary, edited using the Unity animation tool to adjust body segment postures or movements. Finally, given that the original recordings were performed using the right arm, the animations were mirrored within Unity to produce equivalent left-arm gestures (see Fig. 1).

Scene description. Table 1 provides a comprehensive list of the 33 upper-limb exercises, designed for unimanual performance in a seated position. The task complexity ranges from basic proximal joint movements (e.g., shoulder flexion) to advanced fine motor activities (e.g., finger flexion). This progression enables therapists to tailor exercises to various stages of recovery. For example, the early rehabilitation phase may emphasize gross motor tasks that target the shoulder and elbow, while more advanced stages can incorporate precision tasks involving the wrist and fingers, according to the patient's progression. This modular design supports the creation of personalized, adaptive rehabilitation plans tailored to patients' abilities and clinical goals. To visualize how the graded tasks are instantiated in the virtual environment, Fig. 2 displays representative frames captured from two exercises, each rendered in both allocentric and egocentric perspective.

	Scene Name	Movement Description
E1	Hit Ball - Dorsal	Hit a ball on a table using the back of the hand, keeping the elbow extended.
E2	Hit Ball - Palmar	Hit a ball on a table using the palm of the hand, keeping the elbow extended.
E3	Hit Ball - Flex	Hit a ball on a table by flexing the elbow.
E4	Hit Ball - Ext	Hit a ball on a table by extending the elbow.
E5	Drag Soap	Drag a soap on a table using the back of the hand with the elbow extended.
E6	Drag Ball	Drag a ball on a table using the back of the hand with the elbow extended.
E7	Drag Cloth - Flex	Move a cloth on a table using an elbow flexion-extension motion, with the forearm resting on the table.
E8	Reaching Knee-Table	Reach a target placed on a table, starting with the hands on the knees.
E9	Reaching High Target	Reach a target positioned above table level, starting with hands on the knees.
E10	Reaching Lateral	Starting with the arm along the body, move and place the hand on the lateral surface of the contralateral thigh.
E11	Drag Bottle	Move a bottle on the table to the point of maximum elbow extension.
E12	Move Can	Reach for, grasp, and place a can on a surface 10 cm high.
E13	Bring Soap	Reach for, grasp a bar of soap, and lift it using elbow flexion.
E14	Open Box	Reach, grasp the top of a box and open it using elbow flexion/extension and forearm rotation (prono-supination).
E15	Drag Box	Move a box on a table first to the right and then to the left.
E16	Drag Journal	Move a journal on the table until full elbow extension is reached.
E17	Pour Bottle	Reach, grasp a bottle, and pour water using elbow flexion/extension.
E18	Clean Table	Clean a table using circular shoulder movements with a cloth.
E19	Rolling Pin	Roll a rolling pin on a table using the palm of the hand.
E20	Flip Glass	Grasp and flip over a glass.
E21	Press Phone-Key	Press keys on a telephone keypad using the index finger.
E22	Play Piano	Play piano keys using all five fingers, with the elbow resting on the table.
E23	Hammer	Use a hammer to strike a nail on a table with elbow flexion-extension.
E24	Round Spoon	Hold a teaspoon and rotate it in a cup using wrist movement.
E25	Plug-Unplug	Insert and remove a plug from a socket using elbow flexion-extension.
E26	Grasp Cubes	Grasp small cubes with the first three fingers and place them in a container.
E27	Open Jar	Screw and unscrew the lid of a jar.
E28	Handle	Rotate a tabletop handle.
E29	Writing	Draw a circle on paper with a pen.
E30	Sprayer	Pull the trigger of a spray bottle.
E31	Throw Ball - L	Throw a tennis ball upward and forward, starting with the arm at the side.
E32	Throw Ball - H	Throw a tennis ball downward and forward, starting with the arm at the side.
E33	Tooth Brush	Simulate brushing teeth with a toothbrush.

Table 1. Upper-Limb Rehabilitation Exercises: Scene Names, Movement Descriptions, and Involved Joints. The table outlines 33 goal-oriented exercises (E1–E33), each implemented as an independent Unity scene. The *Scene Name* column corresponds to the identifier used within the application; *Movement Description* provides a brief summary of the requested motor task.

Data Records

The complete dataset is available through Zenodo[23] and comprises five primary components:

1. **UpperLimbAOT-VR_UnityProject/** — a fully self-contained Unity 6000.0.24f1 project directory.
2. **UpperLimbAOT-VR.apk** — a pre-compiled Android application package for immediate deployment on Meta Quest-series head-mounted displays.
3. **QuickStart_Guide.pdf** — a step-by-step installation and usage manual detailing project setup on both Unity Editor and Meta Quest devices.
4. **README.md** — a brief project overview and fundamental usage notes.
5. **Videos/** — a supplementary folder containing video demonstrations of the actions. This folder is divided into **AllocentricView/** and **EgocentricView/**, each of which includes **Left/** and **Right/** subfolders with.mp4 files showing the recorded actions from both perspectives.

Project root and directory convention. All domain-specific materials are nested beneath "Assets/UpperLimbAOT-VR/" introducing an intermediate namespace (*UpperLimbAOT-VR*) that segregates experimental assets from Unity-generated infrastructure (e.g., Assets/Editor/ and Packages/) and thereby streamlines version control.

Scene inventory. All scenes are located within **Assets/UpperLimbAOT-VR/Scenes/**.

Fig. 2 Temporal and perspective-based visualization of two representative VR-AOT actions. Representative frames from two actions shown across three temporal phases: rest (left), interaction onset (center), and completion/execution (right). The top two rows (blue background) depict a simple gesture (i.e., striking a ball with the back of the hand) from allocentric (**a**) and egocentric (**b**) perspectives. The bottom two rows (light green background) show a complex, goal-directed action (i.e., grasping a bottle and pouring water into a glass) in allocentric (**c**) and egocentric (**d**) views.

- **ControlScene/Control.unity** — the principal interface responsible for initial configuration and for orchestrating stimulus presentation (ordering, difficulty, viewpoint, repetition).
- **Allocentric perspective** – AllocentricView/Right/ — 33 third-person (allocentric) scenes depicting right-arm movements. – AllocentricView/Left/ — 33 third-person scenes depicting left-arm movements.

- **Egocentric perspective** – EgocentricView/Right/ — 33 first-person (egocentric) scenes depicting right-arm movements. – EgocentricView/Left/ — 33 first-person scenes depicting left-arm movements.

Lighting prefabs are co-located with each scene to ensure photometric consistency across perspectives.

Supporting assets. All supporting assets listed below are located within Assets/UpperLimbAOT-VR/.

- **3DModels/** — static meshes and rigged avatars, including the humanoid skeleton and environmental props utilised across the scenes.
- **GraphicAssets/** — raster textures, user-interface sprites (.png,.tga), URP Asset renderer settings, skybox configurations, and post-processing data utilised within the project's rendering pipeline and user interface components.
- **Kinematics/** — authorial motion data: the animator state machine in Controller/, together with limb-specific animation clips within Left/ and Right/.
- **Materials/** — includes physically-based shader materials utilised within Unity's Vulkan rendering pipeline, as well as material assets associated with specific 3D models (e.g., cups, boxes, nails) employed in the experimental scenes.
- **Prefabs/** — reusable GameObject assemblies comprising selected scene objects and various interaction widgets utilised throughout the project.
- **Scripts/** — bespoke C# scripts encompassing the scene-loading routine, randomisation controller, and data-logging subsystem.
- **StreamingAssets/** — high-definition instructional videos (.mp4, 1920 × 1080 @ 30 fps, H.264) streamed during runtime by the control scene. **Note:** for correct loading in Unity, this folder must reside directly at Assets/StreamingAssets, *not* inside Assets/UpperLimbAOT-VR/.

This arrangement affords researchers, clinicians, and software developers a clear, modular structure that facilitates rapid replication, adaptation, and extension of the experimental stimuli.

Technical Validation

To evaluate the clinical relevance and perceptual validity of the VR-stimuli, a structured assessment was conducted with 42 expert physiotherapists. Procedures have been approved by the Research Ethics Board (REB) of the University of Parma (project 23-2024-N, date 28.02.2024) and signed informed consent was obtained by each volunteer. Each participant reviewed the full set of 33 stimuli and completed a questionnaire (available in the data repository), which was designed to evaluate multiple dimensions of the stimuli.

Participants rated each stimulus on a 5-point Likert scale (1 = strongly disagree; 5 = strongly agree) across the following criteria:

1. *Comprehensibility:* Clarity of the gesture and ease of understanding the task;
2. *Realism*: Perceived accuracy and fidelity of the movements;
3. *Immersivity*: Degree of experiential engagement and immersion;
4. *Egocentric Embodiment*: Sense of ownership when observing from a first-person viewpoint;
5. *Allocentric Embodiment:* Sense of ownership when observing from a third-person perspective.

In addition to perceptual ratings, participants assessed the clinical applicability of each gesture for:

- The six stages of stroke recovery as defined by the Brunnström[24] (stages I–VI).
- Central neurological disorders (e.g., Stroke, Multiple Sclerosis, Parkinson's Disease, Pediatric Cerebral Palsy, and Traumatic Brain Injury);
- Peripheral conditions (e.g., Peripheral Nervous System pathologies, orthopedic trauma, and prosthetic rehabilitation).

At the conclusion of the evaluation, participants completed a debriefing questionnaire that captured qualitative feedback on the perceived advantages, limitations, and feasibility of adopting VR-AOT in their clinical practice.

Participants. The sample consisted of 42 physiotherapists (28 females, 14 males), with a mean age of 40.6 years (SD = 10.4; median = 36.5) and 12.3 years of clinical experience (SD = 6.8, median = 10). Regarding prior knowledge, 71% of participants were familiar with AOT ($\chi^2 = 7.71$, $p < 0.05$), and 40% had previously administered AOT in clinical practice ($\chi^2 = 1.52$, $p = 0.217$). In contrast, the majority had limited exposure to VR technologies: 79% reported no prior VR experience ($\chi^2 = 13.71$, $p < 0.001$), and 95% had never used VR in combination with AOT ($\chi^2 = 34.38$, $p < 0.001$).

Statistical analysis. All stimuli were rated on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree), with a score of 3 representing the neutral threshold that separates negative scores (<3) from positive ones (>3). Before proceeding with the statistical analyses, a Shapiro-Wilk test was applied to each distribution to verify the assumption of sphericity. Given that most of these tests failed, we adopted non-parametric approaches for the subsequent analyses. Wilcoxon signed-rank tests were performed to assess whether ratings for Comprehensibility, Realism, and Immersivity significantly exceeded the threshold of 3, while differences between Egocentric and

	Scene Name	Comprehensibility	Realism	Immersivity	Egocentric	Allocentric
E1	Hit Ball - dorsal	4,6*	3,7*	4,3*	3,4	3
E2	Hit Ball - palmar	4,7*	4*	4,4*	4*	3,4
E3	Hit Ball - Flex	4,8*	4,1*	4,6*	4,2*	3,5
E4	HitBall - Ext	4,4*	3,8*	4,6*	4,1*	3,5
E5	Drag soap	4,6*	4,3*	4,6*	4,2*	3,5
E6	Drag ball	4,5*	4*	4,5*	4,1*	3,5
E7	Drag cloth - flex	4,8*	4,4*	4,7*	4,2*	3,5
E8	Reaching knee-table	4,7*	4,4*	4,6*	4,5*	3,7
E9	Reaching high target	4,6*	4,1*	4,5*	4,2*	3,5
E10	Reaching lateral	3,6*	3,5	4,4*	3,6*	3,2
E11	Drag bottle	4,8*	4,4*	4,6*	4,3*	3,6
E12	Move can	4,6*	3,9*	4,6*	4,1*	3,5
E13	Bring soap	4,4*	3,7*	4,4*	3,9*	3,1
E14	Open box	4,6*	4,1*	4,6*	4,1*	3,3
E15	Drag box	4,5*	4*	4,5*	4*	3,4
E16	Drag journal	4,3*	3,5	4,4*	3,7*	3,1
E17	Pour bottle	4,8*	4,4*	4,6*	4,3*	3,6
E18	Clean table	4,8*	4,4*	4,6*	4,3*	3,5
E19	Rolling pin	4,2*	3,2	4,4*	3,6*	3,2
E20	Flip glass	4,1*	3,4*	4,4*	3,7*	3,2
E21	Press phone-key	4,5*	4*	4,5*	4*	3,3
E22	Play piano	4,6*	4,2*	4,4*	4,1*	3,5
E23	Hammer	4,7*	3,7*	4,5*	3,9*	3,3
E24	Round spoon	4,7*	4*	4,5*	4*	3,3
E25	Plug-unplug	4,2*	3,6*	4,4*	3,7*	3,3
E26	Grasp cubes	4,7*	4,2*	4,5*	4,1*	3,4
E27	Open jar	4,1*	2,7	4,3*	3,1	2,8
E28	Handle	4,2*	3,3	4,3*	3,6*	3,2
E29	Writing	4,1*	3,2	4,4*	3,5	3,1
E30	Sprayer	4,8*	4,3*	4,5*	4,2*	3,5
E31	Throw ball - L	4*	3,3	3,5	NA	2,8
E32	Throw ball - H	4,1*	3,4	3,5	NA	2,7
E33	Toothbrush	4,1*	2,9	3,6	NA	2,9

Table 2. Perceptual ratings of the VR-AOT stimuli across five dimensions. Mean ratings of Comprehensibility, Realism, Immersivity are presented for each of the 33 VR-based exercises, along with the perceived ownership reported from Egocentric and Allocentric perspectives. Each row corresponds to a different gesture, and each column presents the mean value above across participants. Asterisks indicate a significant p-value at the one-sample t-test against 3 ($p < 0.05$, Bonferroni corrected). NA indicates non-applicable scores for 3 exercises that cannot be presented from egocentric perspectives because their execution develops so close to the agent's body to impede a proper first-person action observation.

Allocentric Embodiment ratings were analyzed using paired-sample t-tests. Given that the same test was applied to 33 exercises, the significance threshold was adjusted using the Bonferroni correction. In addition, the interdependence between Comprehensibility, Realism, and Immersivity scores was tested with a non-parametric Spearman correlation.

Since one of the major applications of AOT concerns the upper limb rehabilitation of stroke patients, additional analyses assessed the utility of gestures across the six Brunnström stages. Wilcoxon signed-rank tests against a three-mean distribution ($p < 0.05$, Bonferroni-corrected) were conducted for each stage. Additionally, Spearman's rank correlation was tested between the perceived difficulty and clinical utility of each gesture across the recovery stages.

A similar approach was applied to assess the perceived utility of the stimuli for other clinical conditions.

Results

The large majority of the exercises were rated positively (scores significantly greater than 3) on Comprehensibility (average 4.5), Realism (average 3.8), and Immersivity (average 4.4) (Table 2), confirming that the stimuli were interpretable and biomechanically plausible. The highest comprehensibility scores were recorded for six exercises *(Hit Ball- Flex, Drag Cloth – Flex, Drag Bottle, Pour Bottle, Clean Table, Sprayer*, means = 4.8), accompanied by equally positive and significant immersivity ratings. While most gestures received strong realism ratings, a small subset (e.g., *Open Jar*, *Throw Ball – H*, and *ToothBrush*) yielded intermediate scores (Realism ≤ 3.5), indicating some critical aspect in the rendering of the gestures.

The comparatively lower realism ratings observed for a limited subset of gestures likely reflect technical and perceptual factors inherent to their motor characteristics. For example, actions such as *Open Jar* involve complex bimanual-like rotational dynamics and fine finger coordination, which may be more sensitive to subtle discrepancies in hand-object interaction rendering. Similarly, *Toothbrush* entails movements performed close to the face, where viewpoint constraints and partial occlusion in virtual environments may affect perceptual fidelity. High-velocity ballistic actions such as *Throw Ball – H* may also amplify minor temporal or kinematic deviations in avatar animation. Notably, despite these comparatively lower realism scores, these gestures were generally rated positively on comprehensibility and immersivity, suggesting that their functional interpretability was preserved. These findings primarily highlight potential targets for future refinement of animation fidelity rather than limitations in dataset usability.

The three scores resulted positively and significantly correlated with each other (Realism vs Comprehensibility: Rho = 0.84; Realism vs Immersivity: Rho = 0.82; Comprehensibility vs Immersivity: Rho = 0.68; all p-values < 0.001).

Despite both egocentric (average 4.0 ± 0.3) and allocentric (average 3.3 ± 0.3) perspectives being rated positively in terms of ownership, a significant difference was found between them (Wilcoxon signed-rank test, $W = 465$, $p < 0.001$), suggesting that each perspective triggers the embodiment process differentially during action observation.

Overall, the results validate that the stimuli reported in the dataset preserved satisfactory perceptual quality throughout the kinematics-to-avatar rendering process, as evidenced by the ceiling scores for Comprehensibility and Realism of the movement. Combined with the immersive nature of the dataset and the enhanced embodiment elicited by the egocentric perspective, these VR-AOT stimuli show strong potential for use in VR-based motor rehabilitation protocols.

The Brunnström approach to stroke motor recovery outlines six stages, describing the progression of movement and coordination after a stroke. These stages are: flaccidity, spasticity appears, increased spasticity, decreased spasticity, complex movement combinations, and spasticity disappears. Considering this variety, it is highly unlikely that any exercise will be suitable for all of them. This assumption reflects pretty well in the stage-dependent course of the suitability scores for each exercise (see Fig. 3, Panel a). Overall, most of the developed stimuli (with the exception of Reaching Lateral, Handle, and the two Throw Ball exercises) received ratings significantly above the neutral threshold in at least one Brunnström stage, indicating perceived suitability within the stroke rehabilitation framework. A general increase in mean utility ratings was observed across later stages (IV–VI), suggesting that more complex gestures were considered more appropriate as recovery progresses. However, substantial variability was present across exercises, with several gestures receiving positive ratings already at Stage IV and others primarily at Stages V–VI. These patterns reflect the graded structure of the gesture set and the range of perceived difficulty embedded within the dataset.

This variance reflects that, even if our exercises align with the mid-to-late phase of motor recovery from stroke, their difficulty range makes them suitable for use at various stages of recovery. This assumption was further supported by correlation analyses examining the relationship between perceived utility for each Brunnström stage and task difficulty (Fig. 3 Panel b). In the early stages (I–III), correlations between perceived utility and difficulty were weakly negative or close to the significance threshold threshold (Stage I: $\rho = -0.38$, $p = 0.027$; Stage II: $\rho = -0.29$, $p = 0.097$; Stage III: $\rho = -0.29$, $p = 0.105$), indicating that simpler gestures were generally rated as more suitable. In later stages (particularly Stage VI - $\rho = 0.54$, $p < 0.001$), a positive association emerged between perceived utility and task difficulty. This shift reflects how experts differentially rated gesture suitability depending on recovery stage, consistent with the graded motor demands represented within the dataset.

Indeed, in the early phases of recovery (Stages I–III), correlations were weakly negative and close to the significance, suggesting that simpler tasks were viewed as more useful and reflecting a prioritization of feasibility over challenge.

In contrast, the later stages (IV–VI) showed a shift toward positive associations between utility and difficulty. While the correlation in Stage IV is negligible ($\rho = 0.09$, $p = 0.60$), a moderate trend emerged at Stage V ($\rho = 0.21$, $p = 0.249$), culminating in a significant and substantially positive correlation at Stage VI. This pattern suggests that as functional recovery progresses, more complex tasks are perceived as increasingly valuable, aligning with the principles of progressive motor rehabilitation. Overall, these results highlight the adaptability of our VR-AOT dataset to various stages of motor recovery, underscoring its potential application in personalized rehabilitation pathways.

Finally, the stimuli were evaluated for their clinical utility for seven additional diagnostic domains drawing onto motor rehabilitation in their clinical course, namely Parkinson's Disease (PD), Multiple Sclerosis (MS), Pediatric Cerebral Palsy (CP), Traumatic Brain Injury (TBI), Peripheral Nervous System pathologies (PNS), orthopedic trauma (OT), and prosthetic rehabilitation (PROSTH) (Table 3). Across conditions, the majority of exercises received mean ratings above the neutral threshold, indicating broad perceived applicability of the dataset in diverse rehabilitation contexts (Table 3). While the magnitude of ratings varied across exercises and conditions, this variability reflects differences in task characteristics and perceived feasibility rather than evidence of differential clinical efficacy. Overall, the results support the general usability of the VR-AOT stimuli across a wide range of neurological and musculoskeletal rehabilitation settings.

Kinematic smoothness analysis. Upper-limb kinematics recorded within each VR scene were sampled at 60 Hz using the Unity engine (version 6000.0.24f1), yielding the trajectories of the hand (defined as the wrist joint position within the animation rig). Such an indicator was used to quantify movement smoothness via the SPectral ARC length (SPARC)[25], an adimensional measure computed from the arc length of the normalized power a

Degree of appropriateness of excercises across stroke stages of recovery

	Exercise	Brunnstrom stage I	II	III	IV	V	VI
1	Hit Ball - Dorsal	2,6	3,2	2,6	3,5	3,9	3,9
2	Hit Ball - Palmar	2,8	3,1	2,6	3,6	3,9	4,0
3	Hit Ball - Flex	3,0	2,8	2,3	3,3	3,7	3,6
4	Hit Ball - Ext	3,2	3,5	3,1	3,7	4,0	3,8
5	Drag Soap	3,1	3,3	3,0	3,6	3,9	3,9
6	Drag Ball	3,0	3,3	3,0	3,7	4,0	3,8
7	Drag Cloth - Flex	3,7	3,7	3,3	4,1	4,2	4,1
8	Reaching Knee-Table	3,0	3,5	2,9	3,8	4,1	4,1
9	Reaching High Target	2,9	3,1	2,7	3,8	4,1	4,0
10	Reaching Lateral	2,5	2,6	2,5	3,1	3,5	3,3
11	Drag Bottle	3,1	3,4	3,1	3,9	4,3	4,2
12	Move Can	3,0	3,1	2,8	3,9	4,2	4,2
13	Bring Soap	2,5	2,8	2,4	3,3	3,7	3,7
14	Open Box	2,8	3,0	2,7	3,7	4,2	4,2
15	Drag Box	2,9	3,0	2,8	3,6	4,0	4,0
16	Drag Journal	2,9	3,0	2,7	3,4	3,7	3,7
17	Pour Bottle	2,8	3,1	2,8	3,7	4,3	4,4
18	Clean Table	3,4	3,5	3,2	3,9	4,2	4,0
19	Rolling Pin	2,9	3,1	2,8	3,4	3,8	3,7
20	Flip Glass	2,3	2,6	2,3	3,3	3,7	3,9
21	Press Phone-Key	2,6	2,9	2,5	3,6	4,1	4,3
22	Play Piano	2,7	2,9	2,5	3,4	4,2	4,4
23	Hammer	2,3	2,6	2,2	3,2	3,8	3,9
24	Round Spoon	2,6	2,8	2,5	3,3	4,0	4,2
25	Plug-Unplug	2,4	2,6	2,4	3,3	3,8	4,1
26	Grasp Cubes	2,8	3,1	2,8	3,7	4,1	4,1
27	Open Jar	2,2	2,6	2,2	3,2	3,7	3,8
28	Handle	2,2	2,4	2,2	2,9	3,3	3,3
29	Writing	2,3	2,7	2,4	3,2	3,8	4,0
30	Sprayer	2,5	2,7	2,2	3,5	3,9	4,1
31	Throw Ball - L	2,5	2,6	2,3	3,0	3,5	3,6
32	Throw Ball - H	2,1	2,3	2,0	2,9	3,3	3,7
33	Tooth Brush	2,3	2,6	2,3	3,1	3,7	3,9

b

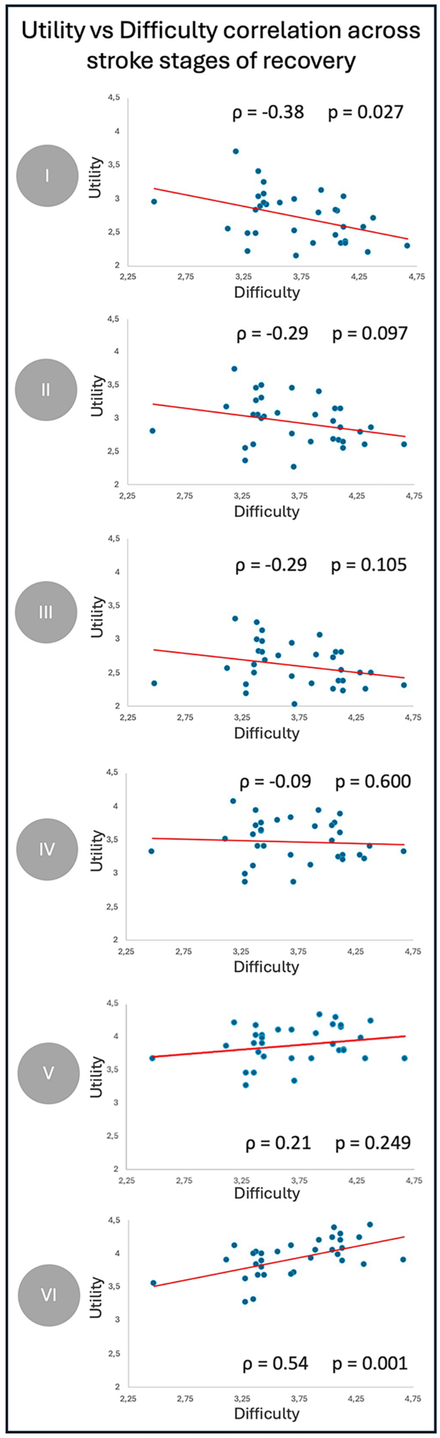

Fig. 3 Clinical utility and its relationship with task difficulty across the Brunnström stroke recovery stages. Panel a: Mean utility ratings for each of the 33 VR gestures across the six Brunnström stages of stroke recovery (I–VI). Each cell color reflects the extent of the utility score, while red contours indicate scores significantly above the threshold of 3 (Wilcoxon signed-rank test, $p < 0.05$, Bonferroni-corrected), demonstrating the widespread perceived suitability of the gestures across all recovery stages. Panel b: Scatter plots display the relationship between the mean ratings of utility and difficulty, along the Brunnström stages of stroke recovery (I-VI). Each panel also displays a linear regression line (red), and the Spearman's correlation coefficient (ρ), along with its p-value.

spectrum of the movement velocity profile, providing a robust estimate of smoothness that is less sensitive to noise and movement duration than traditional jerk-based metrics. By convention, SPARC values are negative, with values closer to zero indicating smoother movements and more negative values indicating reduced smoothness.

	Scene Name	OT	PNS	PD	MS	TBI	CP	PROSTH
E1	Hit Ball - dorsal	3,6*	3,7*	3,3	3,5	3,5	3,6*	4,1*
E2	Hit Ball - palmar	3,6*	3,6*	3,2	3,4	3,4	3,5	4*
E3	Hit Ball - Flex	3,3	3,6*	3,1	3,2	3,4	3,4	3,9*
E4	HitBall - Ext	3,6*	3,8*	3,4	3,5	3,6*	3,6*	4*
E5	Drag soap	3,7*	3,9*	3,3	3,3	3,4	3,4	4*
E6	Drag ball	3,6*	3,8*	3,4	3,5*	3,5	3,5	4*
E7	Drag cloth - flex	3,8*	3,8*	3,4	3,6*	3,8*	3,7*	4,1*
E8	Reaching knee-table	3,7*	3,8*	3,6*	3,7*	3,8*	3,8*	3,9*
E9	Reaching high target	3,6*	3,8*	3,5	3,6*	3,7*	3,7*	4*
E10	Reaching lateral	3,2	3,1	2,8	2,9	2,9	3	3,4
E11	Drag bottle	4*	4*	3,8*	3,9*	3,9*	4*	4,2*
E12	Move can	3,8*	3,8*	3,7*	3,8*	3,9*	3,8*	4*
E13	Bring soap	3,5	3,5	3,2	3,3	3,3	3,2	3,6*
E14	Open box	3,6*	4*	3,7*	3,8*	3,8*	3,8*	4*
E15	Drag box	3,3	3,6*	3,3	3,4	3,6*	3,5	3,6*
E16	Drag journal	3,4	3,5	3,1	3,2	3,3	3,2	3,6
E17	Pour bottle	4,1*	4,1*	4,1*	4,1*	3,9*	4*	4,2*
E18	Clean table	3,9*	3,9*	3,9*	3,9*	4*	3,7*	4,1*
E19	Rolling pin	3,5	3,6	3,4	3,5	3,4	3,6	3,7*
E20	Flip glass	3,7*	3,6*	3,4	3,4	3,3	3,4	3,7
E21	Press phone-key	3,5	3,7*	3,7	3,8*	3,8*	3,8*	3,4
E22	Play piano	3,8*	4*	3,8*	3,9*	3,7*	3,9*	3,6
E23	Hammer	3,6*	3,5	3,6*	3,5	3,5*	3,5	3,7*
E24	Round spoon	3,6*	3,7*	3,9*	3,7*	3,7*	3,7*	3,7*
E25	Plug-unplug	3,5	3,6*	3,7*	3,6	3,5	3,6*	3,4
E26	Grasp cubes	3,8*	3,8*	3,9*	3,8*	3,7*	3,9*	3,8*
E27	Open jar	3,4	3,5	3,3	3,3	3,3	3,4	3,2
E28	Handle	3,1	3,1	2,9	3,1	3	3	3,1
E29	Writing	3,5	3,6*	3,7*	3,7*	3,6	3,6*	3,5
E30	Sprayer	3,7*	3,7*	3,6	3,6*	3,6*	3,5	3,7
E31	Throw ball - L	3,6	3,4	3,5	3,3	3,3	3,4	3,5
E32	Throw ball - H	3,8*	3,6	3,4	3,2	3,2	3,4	3,6
E33	Toothbrush	3,6	3,6	3,6	3,6	3,5	3,6	3,7

Table 3. Suitability of VR-AOT exercises across neurological and musculoskeletal conditions. For each of 33 exercises, the degree of utility across different pathological conditions is reported. Asterisks indicate a significant p-value at the Wilcoxon signed-rank test against 3 ($p < 0.05$, Bonferroni corrected). OT: Orthopaedic conditions; PNS: Peripheral Nervous System diseases; PD: Parkinson's disease; MS: Multiple Sclerosis; TBI: Traumatic Brain Injury; CP: Cerebral Palsy; PROSTH: Prosthetic rehabilitation.

It has been widely used in the quantitative assessment of motor control in both healthy subjects and neurological patients due to its robustness and reliability in capturing movement intermittency and irregularity. In healthy individuals performing point-to-point reaching movements, SPARC values typically range between approximately −1.5 and −2[26], whereas more negative values are commonly observed in populations with motor impairments[27].

Because SPARC was originally developed and validated for discrete, point-to-point movements characterized by a single dominant velocity peak[26,28], we first applied established kinematic segmentation procedures based on local minima surrounding the primary velocity peak[29–31] to segment the 33 gestures into movement phases including reaching, object transport (when present), and return to the initial position. Grasping and manipulation phases were excluded because they involve sustained contact dynamics and fine finger movements that do not conform to the assumptions underlying this smoothness metric. For gestures such as Press Phone-Key (E21) and Sprayer (E30), large portions of the animation correspond to static positioning or finger-dominated interactions with the object. In these cases, segments characterized by minimal hand displacement were excluded from the smoothness computation, leading to the removal of approximately 60% of the total movement duration for Press Phone-Key (E21) and 64% for Sprayer (E30)[32].

Across the gesture set, SPARC values generally ranged between −1.50 and −2.10 (Table 4), consistent with values previously reported for natural upper-limb reaching movements in healthy individuals[26,33]. A small number of gestures showed more negative values, including *Reaching Lateral* (E10) and *Handle* (E28), which involve extended lateral trajectories or rotational wrist dynamics, producing more complex velocity profiles. Similarly, actions characterized by rhythmic or repetitive movement patterns, such as *Round Spoon* (E24) and *Tooth Brush* (E33), yielded lower smoothness values due to multiple velocity peaks within the movement sequence[27]. The gesture *Play Piano* (E22) produced a markedly lower SPARC value (−6.79). In this animation, the hand remains

	Scene name	SPARC
1	Hit Ball - Dorsal	−1.77
2	Hit Ball - Palmar	−1.72
3	Hit Ball - Flex	−1.54
4	Hit Ball - Ext	−1.50
5	Drag Soap	−1.53
6	Drag Ball	−1.62
7	Drag Cloth - Flex	−1.81
8	Reaching Knee-Table	−1.58
9	Reaching High Target	−1.65
10	Reaching Lateral	−2.49
11	Drag Bottle	−1.57
12	Move Can	−1.76
13	Bring Soap	−1.76
14	Open Box	−1.94
15	Drag Box	−1.86
16	Drag Journal	−1.80
17	Pour Bottle	−2.04
18	Clean Table	−1.90
19	Rolling Pin	−1.74
20	Flip Glass	−1.68
21	Press Phone-Key	−1.58
22	Play Piano	−6.79
23	Hammer	−1.58
24	Round Spoon	−2.54
25	Plug-Unplug	−2.08
26	Grasp Cubes	−1.59
27	Open Jar	−1.67
28	Handle	−2.46
29	Writing	−1.90
30	Sprayer	−1.96
31	Throw Ball - L	−1.45
32	Throw Ball - H	−1.50
33	Tooth Brush	−3.08

Table 4. SPARC values for the 33 upper-limb gestures, computed either as the average across segmented phases (reaching, transport, and return) or over the entire movement epoch for gestures dominated by non-transport actions.

largely stationary while individual fingers sequentially interact with the keys, resulting in minimal hand displacement and a velocity profile dominated by small fluctuations rather than a discrete transport phase. Thus, the resulting SPARC value reflects the limited suitability of hand-based smoothness metrics for finger-dominated actions and should not be interpreted as indicative of poor kinematic quality in the underlying animation.

Overall, the kinematic profiles embedded in the VR animations yielded smoothness values comparable to those reported for natural upper-limb movements in all instances where such computations can be reliably performed, indicating that our VR dataset preserves plausible movement dynamics.

Usage Notes

Editor compatibility. It is crucial to open the project specifically with Unity version 6000.0.24f1 to ensure the compatibility and integrity of all scripts, prefabs, and associated assets. Using any other version, especially earlier releases, may lead to the regeneration of asset identifiers, invalidation of prefab references, and potential incompatibilities that could affect reproducibility and stability.

Scene-level testing and export. Each individual scene can be run and, if desired, exported as a standalone Unity package. Within the Unity Editor you may enter Play Mode for a single gesture scene, adjust the desiredLoopCount parameter - found in the SceneDataManager component of the SceneManager GameObject present in every scene - to control how many repetitions the avatar performs, and interact with the game window via mouse. When Meta Quest Link is active, the Game view is streamed directly to the headset, allowing real-time inspection in virtual reality.

Custom playback. The project includes a dedicated scene, CustomScene, containing a GameObject named CustomManager. At runtime you may supply an arbitrary, comma-separated list of scene IDs as a text string: the manager loads and plays them in the specified sequence, allowing repetitions of the same stimulus if required. An additional slider lets you specify the inter-scene delay; during this interval a black screen with a central fixation cross is presented. The feature is intended for fully customised stimulus delivery—e.g., experimental paradigms, demonstrations, or therapy sessions—and is available when running the project in the Unity Editor via **Meta Quest Link**.

APK deployment. The UpperLimbAOT-VR.apk targets minSdkVersion 31 and the arm64-v8a ABI. Installation via the Meta Quest Developer Hub (drag-and-drop) is recommended. Ensure that ControlScene is designated as the launch scene.

These recommendations aim to streamline user experience and facilitate efficient integration of the dataset into diverse research workflows. Although Action Observation Treatment primarily requires clear and goal-directed actions rather than extremely fine-grained kinematic precision, the motion-capture workflow adopted here was designed to ensure internal consistency, reproducibility, and parameter flexibility within a VR-native framework. Full-body inertial tracking combined with finger-level capture enables reliable retargeting to a humanoid avatar, accurate left–right mirroring, and stable hand–object interactions within Unity. This architecture supports systematic manipulation of experimental parameters (e.g., viewpoint, repetition, sequencing) and facilitates the platform's future extensibility.

The dataset is currently based on kinematic recordings from a single healthy adult performer. While this choice ensures biomechanical consistency and uniform animation quality across the gesture set, one could argue that it may limit the generalizability of the kinematic profiles, and that adopting normative kinematics[34] would have mitigated this issue. However, normative curves lose realism due to intra-population averaging, and reference datasets for upper-limb gestures, particularly those involving object interaction[35], are fewer than gait-related ones and suffer from much larger interindividual variabilities. For these reasons, the current implementation is sufficient for several AOT applications, as action clarity and recognizability are the primary determinants of motor resonance.

Future expansions may incorporate additional performers to introduce demographic variability (e.g., age, sex, anthropometry) or functional variability in motor patterns. In particular, recording individuals with age-related or mild motor characteristics could enable investigations into model–observer similarity effects or patient-specific stimulus adaptation. These possibilities should be considered optional extensions aimed at enhancing experimental flexibility rather than addressing a limitation of the current implementation.

Finally, the repository currently focuses on unimanual gestures performed in a seated position, reflecting typical early-to-mid-stage rehabilitation contexts. Future releases are planned to include bimanual and standing exercises, thereby broadening the range of potential clinical and experimental applications.

Data availability

The complete dataset is available through Zenodo at https://doi.org/10.5281/zenodo.15879945.23.

Code availability

Custom scripts were developed within the Unity engine (version 6000.0.24f1) to support both the Editor Mode and the Build Mode functionalities of the application. These scripts were specifically tailored to handle stimulus presentation, user interaction, data handling, and integration of motion capture animations. All scripts are fully documented and embedded within the Unity project that hosts the complete dataset.

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Competing interests

The authors declare no competing interests.

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