Virtual Reality
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ORIGINAL ARTICLE

A haptic-feedback virtual reality system to improve the Box and Block Test (BBT) for upper extremity motor function assessment

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Abstract
The Box and Block Test (BBT) has been widely used to assess gross upper extremity (UE) motor function. We designed a haptic-feedback virtual reality (VR) system, named the VBBT, to improve the BBT for more specific assessments. The VBBT task required users to move virtual blocks from one compartment of a virtual box to the other within one minute. The focus of this pilot study was to examine the validity, reliability and motivation of the novel assessment. Totally, 113 healthy subjects and 16 post-stroke patients were recruited for a thorough evaluation. We found that scores of the BBT and VBBT were significantly correlated, both of which declined as participants' age. The normative ranges of kinematic metrics in different age groups were used to identify deficiencies in UE motor function involving smoothness, hand dexterity and motion efficiency. Also, a significant correlation between the VBBT and Action Research Arm Test (ARAT) ($|r| \geq 0.56$) indicated concurrent validity of the novel assessment. Test–retest results indicated that the VBBT assessment had high reliability (ICCs = 0.62–0.80). The Intrinsic Motivation Inventory results showed that the VBBT was given higher scores for the enjoyment ($p < 0.05$) and completion effort ($p < 0.05$) than that for the BBT, indicating patients have greater motivation in the VBBT assessment. In conclusion, the VBBT can provide validated, reliable and motivative assessment for UE motor function with kinematic metrics. It suggests that the haptic-feedback VR contributes to the BBT in specific assessments of UE motor function.

Keywords Virtual Box and Block Test · Haptic device · Stroke · Validity · Reliability · Motivation

1 Introduction

Stroke is one of the most threatening diseases to human health worldwide due to its extremely high mortality and disability (Ovbiagele et al. 2013). With the increasing and aging world's population, the number of stroke patients will inevitably continue to increase. It was reported that the lifetime risk of stroke among adults aged 25 years or older ranged from 22.8% in 1990 to 24.9% in 2016, showing a relative increase of 8.9% (Feigin et al. 2018). The number of stroke patients was estimated to be double the present level by 2050 (Collaborators 2019). Impairments in upper extremity (UE) function are a common consequence in post-stroke patients. Approximately 60–80% of patients remain deficient in UE motor function into the chronic phases (Broeks et al. 1999). Thus, the recovery of UE function requires long-term rehabilitative intervention. Most patients have to continue their self-rehabilitation at home or in the local community, since they cannot afford the high cost of rehabilitation training in special rehabilitation units (Volpe et al. 2009; Olesh et al. 2014).

At present, some intelligent rehabilitation devices have been developed to make home-based training possible for post-stroke patients (Lee et al. 2018; Wei et al. 2018; Escalona et al. 2020). After a period of device-assisted training at home, the recovery of UE function should be

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accurately evaluated for further effective intervention (Song et al. 2019; Escalona et al. 2020). Several assessments of UE function have been widely used in stroke rehabilitation, such as the Fugl-Meyer Assessment for Upper Extremity (FMA-UE) (Fugl-Meyer et al. 1975; van Wijck et al. 2001; Velstra et al. 2011), Action Research Arm Test (ARAT) (Velstra et al. 2011), Wolf Motor Function Test (WMFT) (Taub et al. 1993). However, these assessment scales seem to be unsuitable for home-based rehabilitation due to several limitations (Thompson-Butel et al. 2015; Santisteban et al. 2016). One limitation refers to the requirement of on-site supervision and subjective ratings by occupational therapists, making them impossible for self-use assessments at home. Additionally, most assessments are insensitive to fine motor skills (Krabben et al. 2011). These limitations of the assessment scales probably result in non-selective and targeted rehabilitative training (Cunningham et al. 2015; Walker et al. 2016). Therefore, an objective and sensitive assessment of UE motor function is necessary for rehabilitation at home. This would enable the transmission of quantitative data of a patient's UE motor function to a professional therapist for remote administration and guidance, speeding up the patient's recovery progress.

Recent advancements in virtual reality (VR) rehabilitation have allowed automated and remote assessments to be commercially available for post-stroke patients. VR rehabilitation assessments are characterized by various functional tasks (Saposnik et al. 2016; Bortone et al. 2018). The recovery of motor function can be evaluated based on the quality of task performance. Some quantitative kinematic and biomechanical metrics have been considered critical references for off-site assessment (Gervasi et al. 2010; Saposnik et al. 2016). In addition, VR environments with high immersion and interaction improve patient motivation to participate in unsupervised assessments. Recently, haptic devices have been incorporated into VR rehabilitation. As an interactive tool, the haptic device provides force feedback such as tactile or grasping sensations to patients during task performance that contributing to immersion and enjoyment within VR experiences (Al-Sada et al. 2020).

The Box and Block Test (BBT) has been widely used for UE motor function assessment (Santisteban et al. 2016) as well as prosthetic assessment (Young et al. 2019) due to its merits, such as simple operation, short time consumption and high validity (Mathiowetz et al. 1985). Several virtual BBT programs have been developed in some previous research (Alvarez-Rodríguez et al. 2020; Everard et al. 2022; Gieser et al. 2016; Oña et al. 2020), however, without haptic rendering, movements of grasping in virtual environments are significantly different from those of natural grasping in real physical environments (Furmanek et al. 2019).

In our current work, we designed a haptic-feedback virtual Box and Block Test (VBBT) system which facilitate a sense of the grasping force and the block's gravity during block-transfer task performance and examined the effectiveness of VBBT for UE motor function assessment (Dong et al. 2020). The overall work is organized as follows (Fig. 1). Firstly, we developed a VBBT system combined with a haptic device. The VBBT task required users to move virtual blocks as many as possible from one compartment of a virtual box to the other within one minute. During the task, a haptic device was used to collect data, including the trajectory, velocity and grasping force from both healthy subjects ($n = 113$) and stroke patients ($n = 16$) and then, calculated kinematic metrics (e.g., N_{ZC}-ACC, N_{ZC}-DRF, PLR, DDP), respectively. We determined a normative range for each metric by 95% confidence interval of healthy subjects' performance, which was used to quantitatively identify patients' specific deficiencies of the UE motor function. We performed a correlation analysis on patients' performance between the conventional assessments (e.g., ARAT, FMA-UE, BBT) and the kinematic metrics to examine the concurrent validity of the VBBT. We conducted a test–retest analysis on healthy subjects' performance within the interval of 4 weeks to examine the reliability of the VBBT. We finally performed an intrinsic motivation inventory (IMI) on patients to examine their motivation in the VBBT compared to that in the BBT.

2 Related work

In recent years, VR has emerged as an innovative approach for UE rehabilitation. Mounting evidences showed that VR technology provides therapeutic benefits in improving UE motor function. This section presents VR for the treatment and assessment of UE motor impairment and explains the rationality behind the virtual rehabilitation therapy.

2.1 VR for the treatment and assessment of upper extremity motor impairment

Motion-tracking devices and robotic devices are mainly used to treat and assess UE motor impairment in VR rehabilitation (Alarcón-Aldana 2020; Eric et al. 2015; Gutiérrez et al. 2021). Both of them help patients with UE motor impairment caused by various diseases to engage in therapeutic interactions in a user-friendly manner (Caserman et al. 2019; Colombo et al. 2019; Garcia-Hernandez et al. 2021).

Leap Motion Controller (LMC) and Kinect are two most popular motion-tracking devices commonly used for VR rehabilitation (Crocetta et al. 2018; Lupinetti et al. 2019). They are major tools for UE recovery treatment in the late rehabilitative period (Knippenberg et al. 2017). Focusing on capturing fine movements of hands and fingers, LMC was mentioned in a host of research on VR rehabilitation

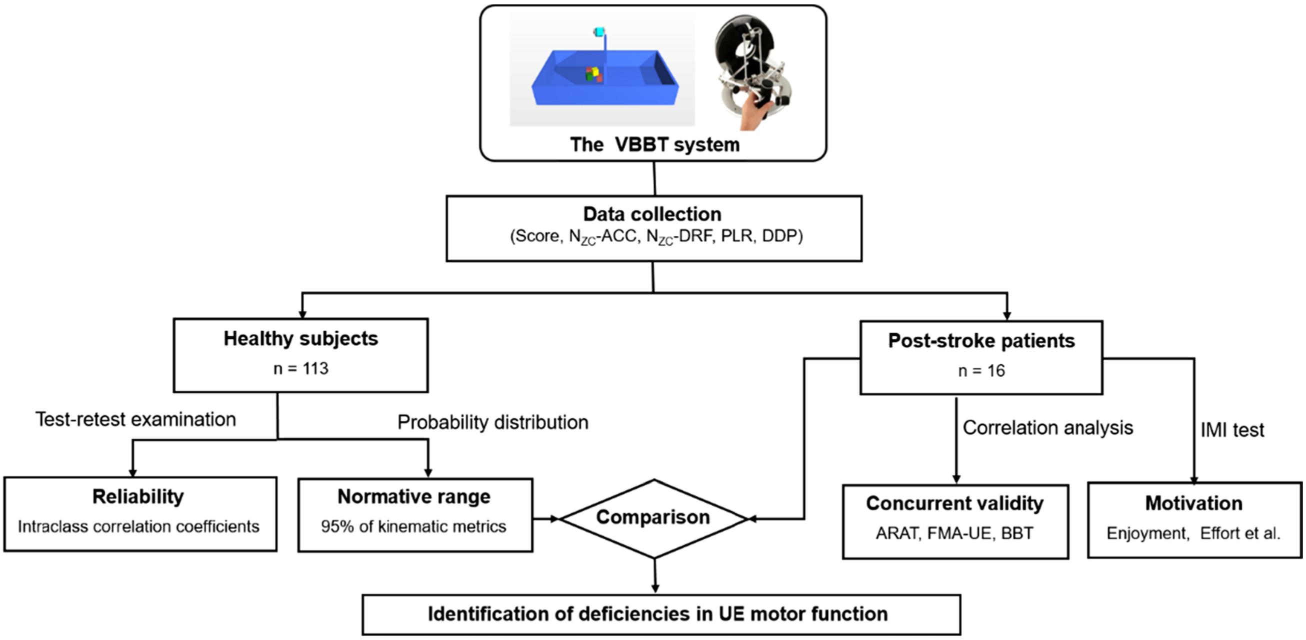


Fig. 1 The organization of VBBT development and its evaluation procedure

(Fernández-González et al. 2019; Heinrich et al. 2021; Vosinakis and Koutsabasis 2018). An earlier study reported that a task-specific VR program with LMC improved the UE motor function of patients after stroke with higher-and lower-functional levels (Fong et al. 2022). In another study, a series of virtual games aided by LMC were developed to treat patients with Parkinson's Disease (Fernández-González et al. 2019). Moreover, several VR systems with LMC were reported to be used to recover the UE motor function in cerebral palsy children (Yildirim et al. 2021), multiple sclerosis (Cuesta-Gómez et al. 2020) and burn patients (Wu et al. 2019). In addition, LMC has also been used as a tool to assess deficiencies in UE motor function caused by central nerve injuries, such as Parkinson's disease (Oktay and Kocer 2020), cerebral palsy (Li et al. 2020a, b; Tarakci et al. 2020), and stroke (Weiss Cohen and Regazzoni 2020). Kinect, another common motion-tracking device, is commonly used to recover gross movements of elbow and shoulder joints through digitally scaling a human model for simulation in virtual environment (Caserman et al. 2019; Garcia-Hernandez et al. 2021; Norouzi-Gheidari et al. 2020; Puthenveetil et al. 2015). Previous studies indicated that it could help patients with UE motor impairment to recover accurate and stable movements of their arms, elbows and shoulders (Garcia-Hernandez et al. 2021). Also, it could be used as an alternative for standard physiotherapy for patients with UE motor impairment in their early postoperative phase after breast cancer surgery (Feyzioğlu et al. 2020). Clinical evidence indicated that Kinect-aided VR training systems had a positive and significant effect on recovering the functional levels of UE motor ability in post-stroke rehabilitation (Adomavičienė et al. 2019; Valencia et al. 2017). Although the Kinect fails to track fine movements (Knippenberg et al. 2017), clinical reports suggested that Kinect-aided assessment could reflect the motor performance of patients with upper motor neuron lesions (Cho et al. 2015; Daoud et al. 2020; Francisco-Martínez et al. 2022; Ozturk et al. 2016; Pashley et al. 2021; Tran et al. 2013). Other motion-tracking devices, such as wearable inertial measurement units (Fei et al. 2021; Han et al. 2017; Lin et al. 2017) and hand controllers (Arlati et al. 2021; Everard et al. 2022), have been verified to be effectively used in VR rehabilitation for the treatment or/and assessment of UE motor impairment. However, most motion-tracking devices fail to provide force inputs that are able to support the weight of limbs or offer resistance/assistance for patients.

Robotic devices are characterized by mechanical structures that assist or resist patients in moving their hands in a predetermined pathway (Eric et al. 2015; Okamoto et al. 2012; Yoo, Cha et al. 2013). The range of robot-guided movements, from passive to active-assisted and active-resisted, is determined by how much the patients contributed to their movements under the robotic involvement (Eric et al. 2015; Hesse et al. 2003; Oña et al. 2019). Steinisch et al. presented a feasibility study in which a passive robotic device was combined with virtual tasks to activate relative areas of the motor cortex, demonstrating the potential of the VR system to monitor UE motor recovery (Steinisch et al. 2012). Active-assisted movements motivated by robotic-VR training were proven to have more beneficial effects on cortical reorganization and treatment outcomes than passive movements did (Masiero et al. 2011). Particularly, active-resisted movements are effective for patients with motor dysfunctions of UE to recover from mild functional impairment (Morita et al. 2006). A positive correlation was also observed between the disease recovering and resistance training (Brown et al. 2015). As described in previous studies, robotic devices combined with VR can be used to assess the UE motor impairment caused by various neurological diseases (Hawe et al. 2020; Semrau et al. 2013; Zariffa et al. 2011).

Haptic devices, a type of interactive devices, are able to provide tactile and force sensations (refer to cutaneous and kinesthetic feedback, respectively) while users manipulate objects in virtual environments (Lederman and Klatzky 2009). The synchronous multi-sensory (e.g., visual, auditory, tactile) input stimulations are beneficial for neural plasticity and reorganization in the brain, so as to speed up the recovery of motor function (Choukou et al. 2021; Law et al. 2018). In previous studies, VR systems aided by haptic devices were gradually applied to treat patients with motor neuron lesions, showing their potential to offer better rehabilitation of neuromuscular impairments than conventional therapy can do (Baur et al. 2018; Bortone et al. 2020; Broeren et al. 2004; Chiang et al. 2017). It was reported that patients with cervical spinal cord injuries performed better in the virtual tasks with haptic feedback than in those without haptic feedback (Gutiérrez et al. 2021). The most likely explanation may be related to the deficiencies of sensation and motor function in UE. Haptic-feedback VR systems enriched therapeutic methods for UE motor impairment in patients with neurological diseases. They provided sensory information about the size and texture of a virtual object as well as simulating the feeling of grasping it. This is crucial for patients to recover their motor function after suffering neurological diseases. In the last decade, haptic-feedback technology has also been used to assess UE motor function. Gerber et al. (2014) combined haptic devices with a 3D virtual environment to design functional tasks, such as tool use, object moving and spelling in activities of daily life (ADL), to assess the cognitive and fine motor function of chronic traumatic brain injury (TBI) patients. Fluet et al. (2011) developed the haptic Virtual Peg Insertion Test (VPIT) to quantitatively measure performance while placing nine pegs into holes. The VPIT test–retest study concluded that some kinematic metrics acquired by the haptic device remained consistent and reliable when performed by stroke patients (Tobler-Ammann et al. 2016). In our previous study, we designed several virtual guiding tasks combined with haptic feedback to evaluate wrist motor function in patients with upper motor neuron lesions (Liu et al. 2019). Deficiencies in wrist motor function were identified when patient performance was outside normative ranges. Relevant study has indicated that rehabilitative assessments by VR with haptic feedback not only provide a more immersive and interactive environment but also offer reliable quantitative measurements of patients' performances (Hussain et al. 2019; Furmanek et al. 2019; Levin et al. 2015).

2.2 The rationality for the effectiveness of VR rehabilitation

It is shown that VR is effective in both treating and assessing motor impairment for its significant advantages of ensuring safety, boosting motivation, enhancing body consciousness and increasing ecological validity.

Firstly, VR creates safe environments for patients to practice motor movements or perform assessments. Stimulating interactive settings offer chances for patients that can be trained systematically and safely in the tasks requiring attention, motor function and judgment, so as to alleviate their impairment (Gutiérrez et al. 2021; Wann et al. 1997). For example, the most concern to patients and their family members is whether they are able to adapt to daily and social activities again, such as cooking in the kitchen and driving on the road. As an effective tool, VR can provide simulated driving or cooking training for individuals with cognitive or physical dysfunctions (e.g., autism spectrum disorder, stroke, Parkinson's disease) to regain their capabilities of such activities (Huang et al. 2018; Strickland 1997; Zahabi and Abdul Razak 2020). In a word, virtual scenarios enable patients to perform specific tasks for rehabilitation free of danger.

Motivations of patients for rehabilitation training can be enhanced by VR, thereby facilitating recovery. VR training programs are more of entertaining games than treatment/assessment approaches to patients (Høeg et al. 2021). Higher motivation and more fun are useful to kill the boredom and tiredness of time-consuming and repetitive tasks in rehabilitation therapy. It is indicated in a study that a VR system was good for patients to improve their rehabilitation motivations and adherence when it was interesting enough to attract their attention and prevent mental exhaustion (Winter et al. 2021). Studies on cerebral palsy children showed that game-based training programs improved participants' motivations and promoted their engagement of exercises in rehabilitation treatment (Caserman et al. 2019). A positive correlation between therapeutic enjoyment and motor function improvement in stroke patients indicated the importance of enthusiasm for training in improving therapeutic outcomes (Putrino et al. 2017).

Enhanced body consciousness is a key element for effective VR intervention (Augenstein et al. 2022). Immersive VR is able to provide more realistic exercise experiences with egocentric present in simulated virtual scenarios compared to other mediums (Choi et al. 2020). Patients observe their interactions with virtual scenarios, which augments their experiences of exercise for neural plasticity (Matamala-Gomez et al. 2020). Body consciousness is generated by the integration of visual and proprioceptive information created in neural plasticity. The visual-proprioceptive integration could be promoted by haptic-added VR treatment through empowering patients' experience with a sense of controlling over the virtual objects (Ishikawa et al. 2021). Therefore, haptic-feedback VR systems play an important role in functional recovery for patients with upper motor neuron lesions.

An ecologically valid environment is offered to patients by VR (Arlati et al. 2021). It refers to the similarity between the tasks of the test and that imposed in the realistic environment. Ecological elements are fundamental for rehabilitation therapy to facilitate the adaptation of patients to the real world with the capabilities acquired during training (Levin et al. 2015). A virtual ecological environment involving realistic elements from the real world can elicit more natural behavioral responses of the participants (Arlati et al. 2021). Evidence shows that VR enhanced the ecological value since the collected data were close to that in the real life (Furmanek et al. 2019). Better prognostic indices of motor function were obtained in a controlled VR situation (Pieri et al. 2022). However, in the rehabilitation therapy of UE motor function, lacking haptic feedback may be responsible for the failure to meet the rehabilitation expectations for it may significantly affect the sensations and the ecological validity of the experience in VR (Villa et al. 2018).

3 Patients and clinical assessments

3.1 Ethical approvals

All subjects were given written and verbal information on the current study. Written informed consent was obtained for each participant prior to study involvement in accordance with the Declaration of Helsinki, and ethical approval was approved by the Biological and Medical Ethics Committee of Beihang University (Number: BM20180017). This study was registered on Chinese Clinical Trials Registry (ChiCTR2100042355 at http://www.chictr.org.cn/).

3.2 Patients

Post-stroke patients were recruited from a rehabilitation unit in Beijing, China. The patient inclusion criteria were as follows: (1) received a stroke diagnosis at least three months earlier confirmed by brain CT or MRI findings, (2) was aged older than 18 years, (3) was right-handed with an affected right hand, (4) could sit steadily on a chair without armrest support, (5) was able to move 3 blocks in the BBT within one minute, and (6) understood the whole experimental procedure. The exclusion criteria were as follows: (1) unstable fracture of the UE on the hemiplegic side; (2) spatial or visual disorders; (3) epilepsy caused by visual stimuli (lights, television, etc.) in the previous six months; and (4) dizziness in the VR environment. Finally, a total of 16 post-stroke patients were included in this study.

3.3 Clinical assessments

All patients were required to perform a series of standard clinical assessments to examine their cognitive function as well as UE motor function. The assessments included Mini-Mental State Examination (MMSE), Brunnstrom Stage, FMA-UE, ARAT and BBT in sequence, which are elaborated as follows.

3.3.1 MMSE

The MMSE was used to evaluate cognitive function of patients. The MMSE consists of different kinds of questions with a maximum score of 30 points. The questions are divided into seven categories, including orientation to time, orientation to place, registration of three words, attention and calculation, recall of three words, language and visual construction (Folstein et al. 1975).

3.3.2 Brunnstrom stage

Brunnstrom stage is an easy-used assessment method to classify post-stroke motor recovery into six stages (Akay and Marsh 2001). Stage I is the flaccid stage, stage II is the synergic stage, and stage III is the spastic stage. Further into stage IV, there is a decreased spasticity and the patient is able to perform gross movement with reduced synergy. In stage V, spasticity is significantly decreased and the patient can perform more complex movement. In stage VI, spasticity disappears, with single joint movement becoming possible and coordination approaching normal.

3.3.3 FMA-UE

The FMA-UE, the most frequently used outcome scale for UE motor assessment, was used to evaluate deficiencies of patients in our study. The FMA instrument includes a few small objects and several different tools (e.g., scrap of paper, ball, cotton ball, pencil, reflex hammer, cylinder, goniometer, stopwatch) for the assessment of sensation, reflexes, and range of motion (Fugl-Meyer et al. 1975). The FMA-UE assessment consists of

33 items involving movement, coordination, and reflex action of the shoulder, elbow, forearm, wrist, hand.

A zero score is given for the item if a subject cannot complete the task totally. A score of 1 is given when the task is performed partially, and a score of 2 is given when the task is performed fully. The maximum total score that can be obtained in Fugl Meyer assessment is 66.

3.3.4 ARAT

The ARAT was used to examine UE function using observational methods with 19 items organized in 4 sections: grasp (6 items), grip (4 items), pinch (6 items), and gross movement (3 items). The ARAT instrument includes materials such as wooden blocks of various sizes, cricket ball, sharpening stone, alloy tubes, washer and bolt, and marbles. Scores for each ordinally scaled item range from 0 to 3 (0 = unable to complete any part of the task, 1 = the task is only partially completed, 2 = the task is completed but with great difficulty and/or in an abnormally long time, and 3 = the movement is performed normally), and scores for the whole test range from 0 to 57 (Yozbatiran et al. 2008).

3.3.5 BBT

The VBBT system was developed to improve BBT for assessments of UE motor function. Therefore, BBT score, the number of moved blocks in one minute, was the most important outcome for a comparison with VBBT. The BBT instrument consists of 150 wooden cube blocks (2.5 cm in size) in a wooden box that is divided into two equal-sized squared compartments (25.4 cm × 25.4 cm) by a central partition (15.2 cm in height). The subject was instructed to grasp one block at a time, transport it over the partition, and released it in the other compartment. The number of successfully transferred blocks over the partition in one minute was the outcome for the tested hand. Two blocks at the same time counts as one point. Blocks drops or bounces out of the second compartment onto the floor are still rewarded (Mathiowetz et al. 1985).

4 VBBT system

4.1 Devices and scenario

A haptic-feedback device (Omega.7, Force Dimension Inc., Switzerland, Fig. 2a) was used to provide interactive forces, including grasping force and block activity. The haptic device allowed a translating force of 12.0 N and grasping force of 8.0 N, as well as an operating space of Φ160mm × 110 mm for translation and 240° × 140° × 180° for rotation. A VR headset (Oculus Rift, Facebook Inc., US) was used to provide a 3D virtual environment that allowed spatial visualization and operation. An open source software library Chai3D combined with the OpenGL library was used to render visualization and haptic interaction in the VBBT program. All signals are sampled at a rate of 100 Hz and are stored on a laptop (IntelCore 7, 3.2 GHz, Windows 10).

A virtual test box with a barrier partition in the middle was created in the VR environment (Fig. 2b). The block was created one by one in the compartment of the box on the side of the tested hand. In the case of the VBBT, when a subject had completed one trial in which a block was moved from one compartment to the other, another block was then automatically created (Online Resource 1). This was designed to provide movement consistency and avoid obstructions to the target block by other blocks during grasping. Each block was attributed physical properties, including tactile contact and gravity (8.82×10^{-2} Newtons). In the VBBT, a virtual grasping tool was attached to the handle of a haptic device. As a subject moved the handle in the real environment, the virtual tool synchronously performed the same motion in the virtual environment. The contact force between the virtual tool and an object (e.g., a block or the barrier partition) is computed by means of the force render algorithms defined in the Chai3D framework. In the virtual environment, the tool point presents two positions: the current position (CP) and the target position (TP). If there is no object on the path between CP and TP, the tool will be moved directly by the subjects. On the contrary, direct motion will be changed. In this case, the tool still close to the target by moving along to the constraint surface of the object. The motion which locally minimize the distance to the target will be chosen. When the tool cannot be closed to the target any more, it stops at a position where minimizes the distance between the tool and the target. Forces are generated by a virtual spring which exists between the subject and the tool. The stiffness of the spring is modulated by the object properties. Once all contact forces have been computed at each haptic point of the tool, the resulting forces are combined together and converted into a force sent to the haptic device, providing a sense of haptic interaction for the subjects. The force threshold to grasp and release a blocks was set to 0.2 N. The block would fall if the grasping force was not maintained above 0.2 Newtons (Fig. 2c), this force threshold was lower than that in some previous works with neurological patients (Gagnon et al. 2014; Tobler-Ammann et al. 2016).

4.2 Data collection

In the VBBT, originally, the haptic device collected kinematic data, including position and velocity of virtual objects, as well

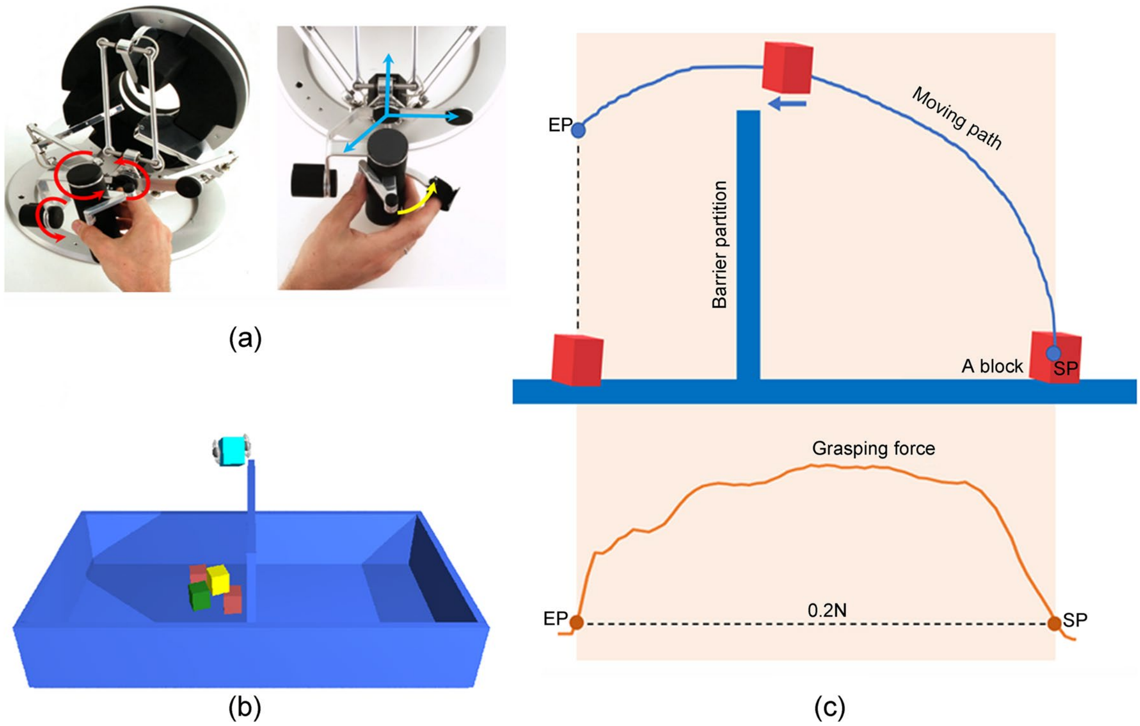


Fig. 2 The VBBT system. **a** The haptic device. **b** The VBBT scenario. **c** A schematic diagram of one VBBT trial

as the grasping force of the virtual tool. Considering previously validated metrics for UE assessment in the literature (Bardorfer et al. 2001; Rohrer et al. 2002; Furmanek et al. 2019), we determined that the kinematic metrics used in the VBBT would be defined as follows:

(1) N_{ZC}-ACC: The number of zero-crossings of the moving acceleration in a block transfer, which was used to assess the smoothness of UE movement.
(2) N_{ZC}-DRF: The number of zero-crossings of the derivative of the releasing force, which was used to assess the stability of fingers during grasp-to-release movement.
(3) PLR: The ratio of the path length and linear length in a block transfer trial, which was used to assess the efficiency of UE movement.
(4) DDP: The distance between the barrier partition and the drop position of a block, which was used to present the efficiency of UE movement.

5 Procedure

5.1 Procedure for healthy subjects

For healthy subjects, they were asked to perform the BBT and VBBT, respectively. Both BBT and VBBT are time-based assessments. The BBT was performed according to previously published instructions (Mathiowetz et al. 1985). In the VBBT, the subjects were seated on a standard height chair with their left hand pronated and rested on a table in their left side, with the right elbow flexed about 90 degrees and the shoulder abducted about 30 degrees, facing the haptic device that was placed on the table in the front of them. We first introduced the operation of the haptic device to the subjects. In the familiarization session, the subjects, wearing the VR headset, were instructed to perform the VBBT until they fully familiarized with the whole performance, and then, they were given one minute to move as many blocks as possible until the program automatically stopped. Four weeks after the first experimental session, healthy subjects were asked to perform the BBT and VBBT again as a retest.

5.2 Procedure for patients

For post-stroke patients, they were also asked to perform several widely used assessment scales of UE motor function and cognitive function, including MMSE, Brunnstrom Stage, FMA-UE, ARAT and BBT. All assessments were performed according to the standard instructions reported in previous studies (Folstein et al. 1975; Müller 1970; Fugl-Meyer et al. 1975; Yozbatiran et al. 2008; Mathiowetz et al. 1985). Then, the patients were asked to perform the VBBT with the same procedures as healthy subjects. Adequate rest was provided for the patients when they felt tired during the performance. Specially, the test was immediately stopped once the patients felt uncomfortable. When the patients finished the VBBT, they were given a simplified IMI to assess their motivation for the BBT and VBBT, and an informal interview was conducted regarding their motivation. There were 7 questions corresponding to 7 items in the IMI, including difference, understandability, enjoyment, attraction, relaxation, effort and tiredness. The patients gave scores (from 1 to 7) to show how true each question was for both the BBT and VBBT, in which 1 indicated "not at all true" and 7 indicated "very true." The questions in the questionnaire were as follows:

Q1: I don't think there is a significant difference between the BBT and VBBT. (Difference)
Q2: I think the BBT/VBBT is quite easy to understand. (Understandability)
Q3: I enjoy to perform BBT/VBBT very much. (Enjoyment)
Q4: I think the BBT/VBBT can hold my attention very well. (Attraction)
Q5: I feel very relaxed in performing the BBT/VBBT. (Relaxation)
Q6: I put a lot of effort into the BBT/VBBT. (Effort)
Q7: I feel very tired after the BBT/VBBT. (Tiredness)

6 Statistical analysis

A demographic analysis was performed with both healthy subjects and post-stroke patients. We divided the subjects into three groups according to their ages: the young group, 18–44 years; the middle-aged group, 45–59 years; and the senior group, 60 years or older. In all healthy subjects, correlation between BBT scores and VBBT scores was performed using Spearman correlation coefficient. A regression analysis was performed between the age and the quantitative performances in BBT scores and VBBT scores. Normalities of all the metrics were assessed with the Kolmogorov–Smirnov test in each age group of healthy subjects, and the level of statistical significance was set to $p < 0.05$ (Vaisrub 2009). For metrics with non-normal distributions were then transformed to normal using Box-Cox equations (Box and Cox 1982). All the metrics compared among different age groups using one-way analysis of variance (ANOVA). Post hoc tests of differences between age groups were performed using least significant difference analyses. We determined a normative range by 95% confidence interval (CI) for two-sided measurements (2.5–97.5%) of healthy-subject performances for each metric. Specific deficiencies in a patient's motor function were identified when his/her metrics fell outside of the normative ranges. This allowed us to detect impairments on an individual level rather than relying on group differences. Spearman's rank correlation coefficients were calculated between the metrics collected in the BBT as well as the VBBT and the clinical scales, including FMA-UE and ARAT for concurrent validity. The strength of the correlation was classified according to Parish and Guilford (1957): 0.20 or below indicated little if any; 0.20–0.40 indicated weak; 0.40–0.70 indicated moderate; and 0.70–1.0 indicated strong. A two-way mixed single measure intra-class correlations (ICC) were calculated and used to examine the test–retest reliability of the BBT and VBBT (Weir 2005; Koo and Li 2016): 0.5 or below, poor reliability; 0.50–0.75, moderate reliability; 0.75–0.9, good reliability; and 0.9–1.0, excellent reliability; the Standard Error of Measurement (SEM) indicates the absolute reliability of the assessments was calculated according to the literature (Weir 2005; Vet et al. 2006). Data from the IMI evaluating the subjects' motivation were considered ordinal variables, and the analysis of the scores for the BBT and VBBT was performed using nonparametric tests (Vet et al. 2006). SPSS version 22.0 was used to analyze all the data.

7 Results

7.1 Demographics and clinical characteristics

A total of 113 healthy subjects and 16 post-stroke patients were included in the current study. As a pilot study, the sample size of post-stroke patients ($n = 16$) in our research is comparable with the previous studies (Rojo et al. 2022 (n = 13); Gagnon et al. 2014 ($n = 9$); Colombo et al. 2018 ($n = 10$); Knobel et al. 2020 ($n = 15$); Gerber et al. 2014 ($n = 19$)). It is appropriate to examine the validity of the VBBT, as a non-commercial system. For the healthy subjects, 19 males and 26 females aged 28.9 ± 7.2 years were in the young group; 12 males and 19 females, aged 51.4 ± 4.0 years were in the middle-aged group; 12 males and 25 females aged 70.8 ± 9.2 years were in the senior group. For the patients, none was in the young group; three males and one female aged 52.3 ± 4.4 years were in the middle-aged group; 8 males and 4 females aged 73.1 ± 6.0 years were in the senior group. The patients experienced stroke

Table 1 Demographic and clinical characteristics of patients

Demographic and clinical parameters	$n=16$
Gender (M/F)	(11/5)
Age (mean ± SD)	67.88 ± 10.93
Stroke cause (Ischemia/Haemorrhage)	(14/2)
Stroke duration (mean ± SD)	8.06 ± 8.27
MMSE (mean ± SD)	26.2 ± 4.7
ARAT (mean ± SD)	45.31 ± 11.54
FMA-UE (mean ± SD)	53.68 ± 10.57
BBT (mean ± SD)	33.13 ± 11.92
BS-Arm (mean ± SD)	5.38 ± 0.81
BS-Hand (mean ± SD)	5.88 ± 0.34

SD Standard Deviation, *M* Male, *F* Female, *MMSE* Mini Mental Status Examination, *ARAT* Action Research Arm Test, *FMA-UE* Fugl-Meyer Assessment for Upper Extremity, *BBT* Box and Block Test, *BS* Brunnstrom stage on the hemiplegic side

between 3 and 36 months prior to the research. All the demographic and clinical characteristics are listed in Table 1.

7.2 Block moved performances in BBT and VBBT

Spearman Correlation Coefficient was performed in scores (the number blocks transferred in one minute) between BBT and VBBT, indicating that there was a medium correlation between the two assessments ($r=0.42$, $p<0.001$; Fig. 3a). In addition, we performed regression analysis on the quantitative performances in BBT and VBBT score, aiming to determine the extent to which the age can affect task performance of successfully transferring blocks. The results showed that the goodness-of-fit measure, *R*-squared in VBBT ($R^2=0.57$, $p<0.001$; Fig. 3b) is significantly higher than that in BBT ($R^2=0.16$, $p<0.001$; Fig. 3c), indicating that the number of transferred blocks completed by the subjects significantly decreased as the age increased. It suggests that age differences should be taken into consideration for the VBBT performance. Therefore, we divided the subjects into three groups (young, middle-aged and senior) to characterize the subjects' performances. Also, to examine the validity of the normative performances, we made a comparison between the BBT scores from the recruited subjects and that from the existing literature (Li et al. 2020a, b), indicating that there was no discrepancy between them ($p=0.876$).

Both BBT and VBBT scores in three age groups were initially normally distributed. More blocks were moved in the BBT (95% range = 53–89, median = 77 in the young group; 95% range = 61–91, median = 74 in the middle-aged group; 95% range = 48–87, median = 68 in the senior group; Fig. 4a) than the VBBT (95% range = 28–45, median = 37 in the young group; 95% range = 20–45, median = 28 in the middle-aged group; 95% range = 11–37, median = 24 in the senior group; Fig. 4b). An analysis of one-way ANOVA

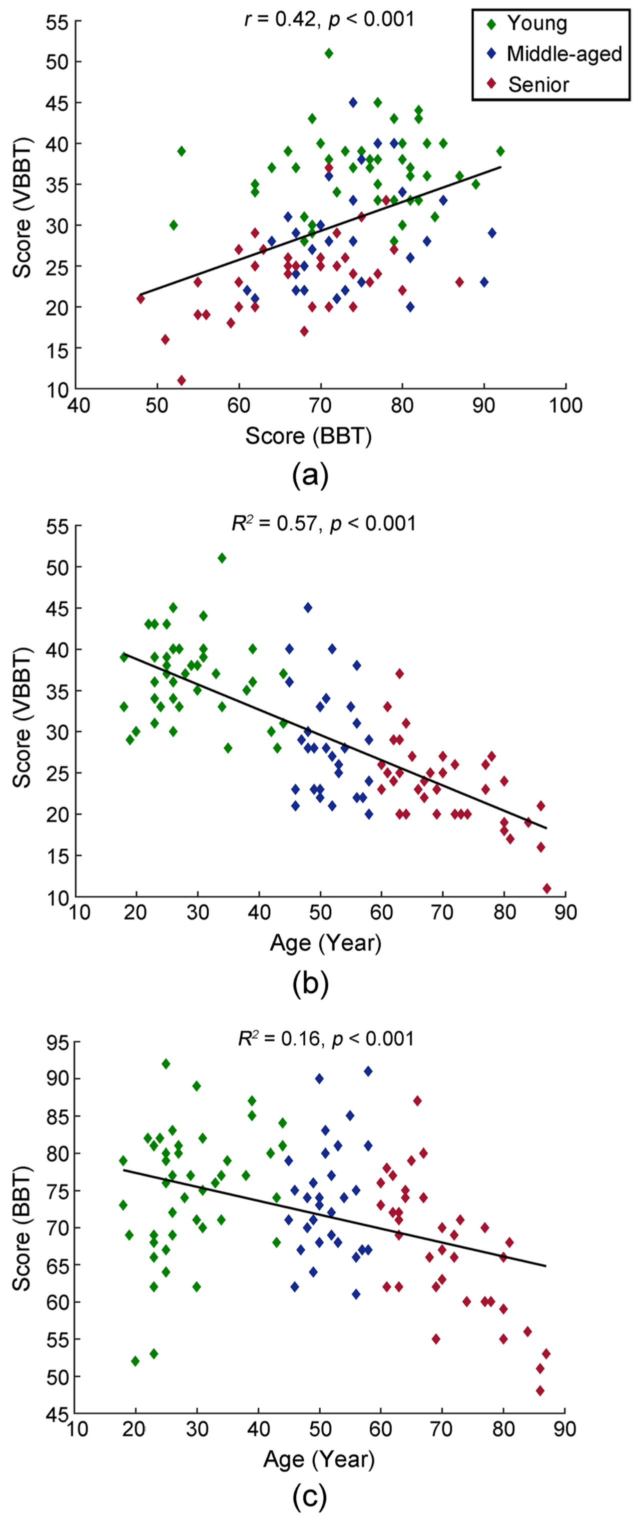


Fig. 3 BBT and VBBT scores performed by the healthy subjects with the age distribution. **a** A Spearman Correlation Coefficient on BBT and VBBT scores. **b** A linear regression between VBBT scores and ages. **c** A linear regression between BBT scores and ages

procedure on BBT scores found a significant main effect among age groups ($F_{2,110} = 10.42$, $p < 0.001$, $\eta^2 = 0.159$, power = 0.986). A subsequent post hoc analysis showed that no significant difference was found between young group and middle-aged group ($p = 0.490$), while significant differences exist when compare young group with senior group ($p < 0.001$) as well as middle-aged group with senior group ($p = 0.0012$). For the VBBT, the result was found for VBBT scores across the three groups showed that significant differences were found between different age groups ($F_{2,110} = 60.11$, $p < 0.001$, $\eta^2 = 0.522$, power = 1.000), where young group was significantly different from middle-aged group ($p < 0.001$) and senior group ($p < 0.001$), middle-aged group was significantly different from senior group ($p < 0.001$).

BBT and VBBT scores are the main outcomes to evaluate gross manual dexterity for UE motor function. None of the middle-aged patients could move more blocks than 2.5% of the middle-aged healthy subjects (lower limit of the normative range) in either the BBT or the VBBT. In senior group, only one patient moved more VBBT blocks than the lowest 2.5% of the senior healthy subjects; this individual also moved more BBT blocks than the lower limit of the normative range in the BBT.

7.3 Kinematic metrics

Four kinematic metrics, including N_{ZC}-ACC, N_{ZC}-DRF, PLR and DDP, were used to reflect motion smoothness, hand dexterity and motion efficiency during task performance. For the healthy subjects, three metrics (N_{ZC}-ACC, N_{ZC}-DRF and PLR) of different age groups with non-normal distributions were converted to normal distributions based on Box-Cox transforms, while one metric (DDP) was initially normally distributed. One-way ANOVA results confirmed that all the kinematic measurements were significantly affected by age groups.

Regarding the measurement of UE movement smoothness while transferring a block, N_{ZC}-ACC showed statistical differences across age groups ($F_{2,110} = 40.36$, $p < 0.001$, $\eta^2 = 0.423$, power = 1.000). As shown in Fig. 5a, young group was significantly different from middle-aged group ($p < 0.001$) and senior group ($p < 0.001$), middle-aged group was significantly different from senior group ($p < 0.001$). Regarding the measurement of the stability during grasping and releasing a block, N_{ZC}-DRF showed statistical differences across age groups ($F_{2,110} = 39.19$, $p < 0.001$, $\eta^2 = 0.416$, power = 1.000). As shown in Fig. 5b, young group was significantly different from middle-aged group ($p < 0.001$) and senior group ($p < 0.001$), middle-aged group was significantly different from senior group ($p < 0.001$). Regarding the measurement of efficiency for transferring blocks PLR showed statistical differences across age groups ($F_{2,110} = 17.77$, $p < 0.001$, $\eta^2 = 0.244$, power = 0.9998). As shown in Fig. 5c, young group was significantly different from middle-aged group ($p = 0.002$) and senior group ($p < 0.001$), middle-aged group was significantly different from senior group ($p = 0.020$). Regarding the measurement of efficiency for transferring blocks through different distances, DDP showed statistical differences across age groups ($F_{2,110} = 3.17$, $p = 0.046$, $\eta^2 = 0.054$, power = 0.597). As shown in Fig. 5d, young group was significantly different from middle-aged group ($p = 0.031$) and senior group ($p = 0.041$), while no significant difference was found between middle-aged group and senior group ($p = 0.995$).

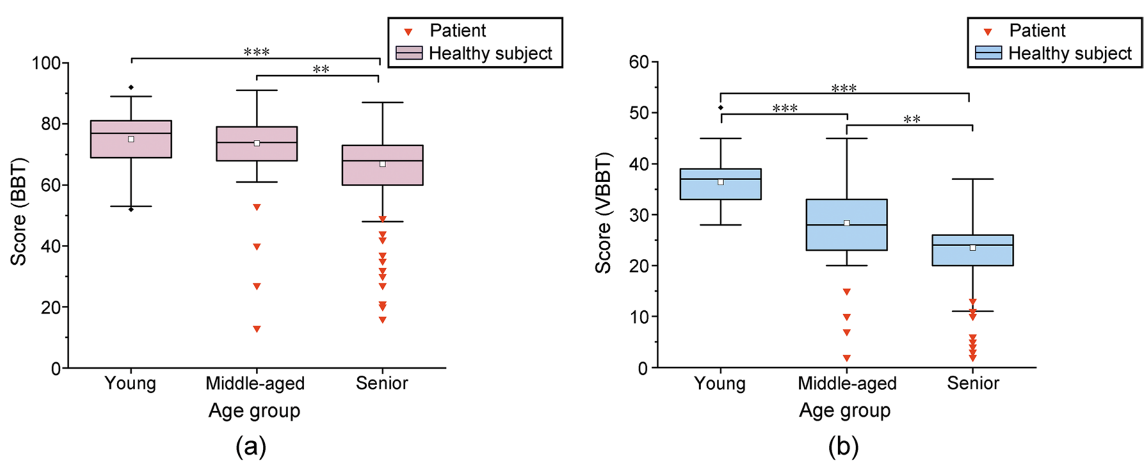


Fig. 4 The performances between BBT and VBBT. **a** BBT scores from heathy subjects and post-stroke patients with different age groups. **b** VBBT scores from heathy subjects and post-stroke patients with different age groups. $^{**}p < 0.01$, $^{***}p < 0.001$

7.4 Identification of specific deficiencies in UE motor function

We determined a normative range for each metric by 95% confidence interval of healthy subjects' performance to quantitatively identify patients' specific deficiencies of the UE motor function. The normative ranges of the metrics in the VBBT were determined by the measurements of healthy subjects ($n = 113$; 95% CI for 2-sided metrics, Fig. 5). Impairment of UE motor function in a patient's could be identified when his/her measurements fell outside of the normative ranges. For N_{ZC}-ACC, all the middle-aged patients fell outside of the normative range (1.2–4.2), and 9 out of 12 senior patients fell outside of the normative range (1.3–7.3). Figure 5a' showed two typical ACC curves correspond to one trail in the same age group during normalized time, completed by a healthy subject and a post-stroke patient, respectively. Increased N_{ZC}-ACC indicated that the smoothness of UE movement was affected by stroke disease. For N_{ZC}-DRF, all the middle-aged patients fell outside of the normative range (3.2–7.7), and 9 out of 12 senior patients fell outside of the normative range (4.3–12.3). Figure 5b' showed two typical DRF curves correspond to one trail in the same age group during normalized time, completed by a healthy subject and a post-stroke patient, respectively. Increased N_{ZC}-DRF suggested that the stability of fingers was destroyed. For PLR, only one middle-aged patients fell outside of the normative range (1.1–1.8), and 2 out of 12 senior patients fell outside of the normative range (1.1–1.7). Figure 5c' showed two typical path curves correspond to the VBBT performance of a healthy subject and a patient in the same age group. Raised PLR demonstrated that lower efficiency was produced by the patient to complete the task. For DDP, only one middle-aged patients fell outside of the normative range (10.0–91.2), and 5 out of 12 senior patients fell outside of the normative range (19.7–76.8). Figure 5d' showed two typical scatter plots of the drop position correspond to the VBBT performance of a healthy subject and a patient in the same age group. Enlarged DDP meant that the stroke patient made more efforts in transferring blocks.

According to the kinematic measurements of the patients (See Online Resource 2), the therapists could individually design rehabilitative training strategies for them. For example, patients P2-P5, P8 and P11 with N_{ZC}-ACC and N_{ZC}-DRF measures falling outside of the normative ranges, but DDP in the normative ranges could be suggested to focus their treatment on enhancing their UE movement smoothness. For patients P1 and P13, all their measurements fell outside of the normative ranges, and the therapists could decide to improve both the smoothness and efficiency of their UE function.

7.5 Concurrent validity

Concurrent validity was assessed by using of Spearman's rank correlation coefficient (r) for the relationship between the VBBT/BBT metrics and the ARAT and the FMA-UE, as well as the relationship between the VBBT metrics and the BBT scores. The results on concurrent validity for the patients are presented in Table 2. A strong correlation was found between the BBT scores and the ARAT ($|r| = 0.83$, $p < 0.001$), while a moderate correlation was found between BBT scores and the FMA-UE ($|r| = 0.66$, $p = 0.003$). A strong correlation was found between VBBT scores and the ARAT ($|r| = 0.84$, $p < 0.001$), while a moderate correlation was found between VBBT scores and the FMA-UE ($|r| = 0.61$, $p = 0.006$). The kinematic metrics, including N_{ZC}-ACC, N_{ZC}-DRF and DDP of the VBBT, were strongly correlated with the ARAT ($|r| \geq 0.76$; $p < 0.001$), while PLR was moderately correlated with the ARAT ($|r| = 0.56$; $p = 0.013$). All four kinematic metrics of the VBBT were moderately or weakly correlated with the FMA-UE ($|r| \leq 0.48$). For the correlations between the BBT and VBBT, all metrics of the VBBT were strongly correlated with the BBT ($|r| \geq 0.75$, $p < 0.001$), except for PLR, which was moderately correlated with the BBT ($|r| = 0.52$, $p = 0.041$). To sum up, all the metrics of the VBBT were moderately to strongly correlated with the ARAT and the BBT, but weakly to moderately correlated with the FMA-UE. That is because the ARAT and the BBT are related to the International Classification of Functioning, Disability and Health (ICF) activity level (Santisteban et al. 2016). Whereas the FMA-UE is related to the ICF Body Function/Body Structure level (Santisteban et al. 2016). The results indicated that VBBT could be considered as an arm-specific measure of activity limitation as BBT and

Table 2 Spearman's rank correlation coefficients between the BBT/VBBT and clinical scales

Parameter	ARAT	FMA-UE	BBT
Score (BBT)	0.83***	0.66**	–
Score (VBBT)	0.84***	0.61**	0.85***
N_{ZC}-ACC	−0.76***	−0.48*	−0.91***
N_{ZC}-DRF	−0.79***	−0.45*	−0.88***
PLR	−0.56*	−0.23	−0.52*
DDP	−0.78***	−0.47*	−0.75***

ARAT Action Research Arm Test, *FMA-UE* Fugl-Meyer Assessment for Upper Extremity, *BBT* Box and Block Test, *VBBT* Virtual Box and Block Test, *N_{ZC}-ACC* the number of zero-crossings of the moving acceleration, *N_{ZC}-DRF* the number of zero-crossings of the derivative of releasing force, PLR the ratio of the path length and linear length, *DDP* the distance between the barrier partition and the drop position.

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

ARAT rather than an arm-specific measure of function and structure limitations as FMA-UE (Lin et al. 2010; Santisteban et al. 2016).

7.6 Test–retest reliability

The test–retest reliability was determined by calculating ICC separately for each measure. The results of the test–retest analysis on the BBT and VBBT for healthy subjects ($n = 95$) are shown in Table 3. VBBT score (ICC = 0.75, $p < 0.001$) exhibited better consistency than that of the BBT (ICC = 0.62, $p < 0.001$). The test–retest correlations were good for the N_{ZC}-ACC and N_{ZC}-DRF (ICCs = 0.78 and 0.80, respectively, $p < 0.001$) and were moderate for PLR and DDP (ICCs = 0.68 and 0.58, respectively, $p < 0.001$). The result suggested that the VBBT could be considered as a reliable tool for researchers or clinical practitioners as the BBT. Additionally, the VBBT performances exhibited some improvements between test and retest sessions, though all the subjects were given a familiarization session up to 15 min to minimize the learning effect (Davis and Purcell 2014; Little et al. 2015). In fact, most subjects finished the familiarization session within 3 min, since they thought they were fully familiarized with how to operate the haptic device. However, the test–retest results indicated that this was not the case. Therefore, more complex virtual tasks should be included in the familiarization session to reduce the learning effect in the VBBT assessment (Table 3).

7.7 Motivation

The full version of the IMI includes 45 items and 7 subscales. Shorter versions have been used and found to be apparently reliable (Mihelj et al. 2012; Novak et al. 2014; Gorsic et al. 2017). To assess the intrinsic motivation of all the subjects, we designed a 7-item version to be administered at the end of all the assessments. The analysis of the IMI scores for the BBT and VBBT was performed using nonparametric tests. As shown in Fig. 6, the patients scored 3.7 ± 1.6 for the difference in performing the BBT and VBBT. Specifically, the patients gave higher scores for enjoyment in the VBBT than the BBT (6.0 ± 1.5 and 4.1 ± 0.9, respectively, $p = 0.016$) and gave higher scores for effort in the VBBT than the BBT (3.7 ± 1.8 and 1.7 ± 1.0, respectively, $p = 0.011$). There were no significant differences in scores for understandability (6.2 ± 1.5 and 6.9 ± 0.3, $p = 0.066$), attraction (6.6 ± 1.3 and 5.6 ± 1.1, $p = 0.151$), relaxation (4.6 ± 2.5 and 5.2 ± 2.5, $p = 0.180$) and tiredness (1.6 ± 1.1 and 1.3 ± 0.7, $p = 0.083$) between the VBBT and BBT. The results showed that most patients preferred to perform the assessment using the VBBT, due to the enjoyment of the immersive environment and effort needed for task performance, suggesting VBBT to be an effective, enjoyable, and motivating tool for promoting UE motor function assessment among post-stroke patients (Fig. 6).

8 Discussion

Although, commonly, the BBT has been considered to be an effective tool to evaluate manual dexterity, it is only used to reflect gross UE impairments in motor function due to its simplicity in measurement (counting the number of the correctly moved blocks in one minute). Based on the BBT, we developed a VBBT system with a haptic device to assess specific UE function of stroke patients. In the pilot study, we examined the clinical validity, reliability and patients' motivations for the VBBT; and we proved that the kinematic metrics N_{ZC}-ACC, N_{ZC}-DRF and DDP extracted from patients' performances can be used to reflect their UE motor function. The UE motor impairments were identified when their measurements fell outside of the normative ranges.

8.1 Kinematic metrics in the VBBT

Compared to conventional scales, robot-aided assessment tools boast the advantages of using kinematic metrics to

Table 3 Test–retest reliability for BBT and VBBT metrics in healthy subjects ($n = 95$)

	Test mean (SD)	Retest mean (SD)	ICC (95%CI)	SEM
Score (BBT)	72.20 (9.37)	73.74 (9.58)	0.62 (0.48–0.73)	5.85
Score (VBBT)	30.49 (7.92)	34.95 (10.57)	0.75 (0.65–0.83)	4.79
N_{ZC}-ACC	2.88 (1.24)	2.53 (1.09)	0.78 (0.68–0.84)	0.56
N_{ZC}-DRF	5.21 (1.84)	4.65 (1.79)	0.80 (0.71–0.86)	0.82
PLR	1.21 (0.16)	1.16 (0.15)	0.68 (0.56–0.78)	0.087
DDP	44.43 (17.00)	39.15 (15.83)	0.58 (0.43–0.70)	0.34

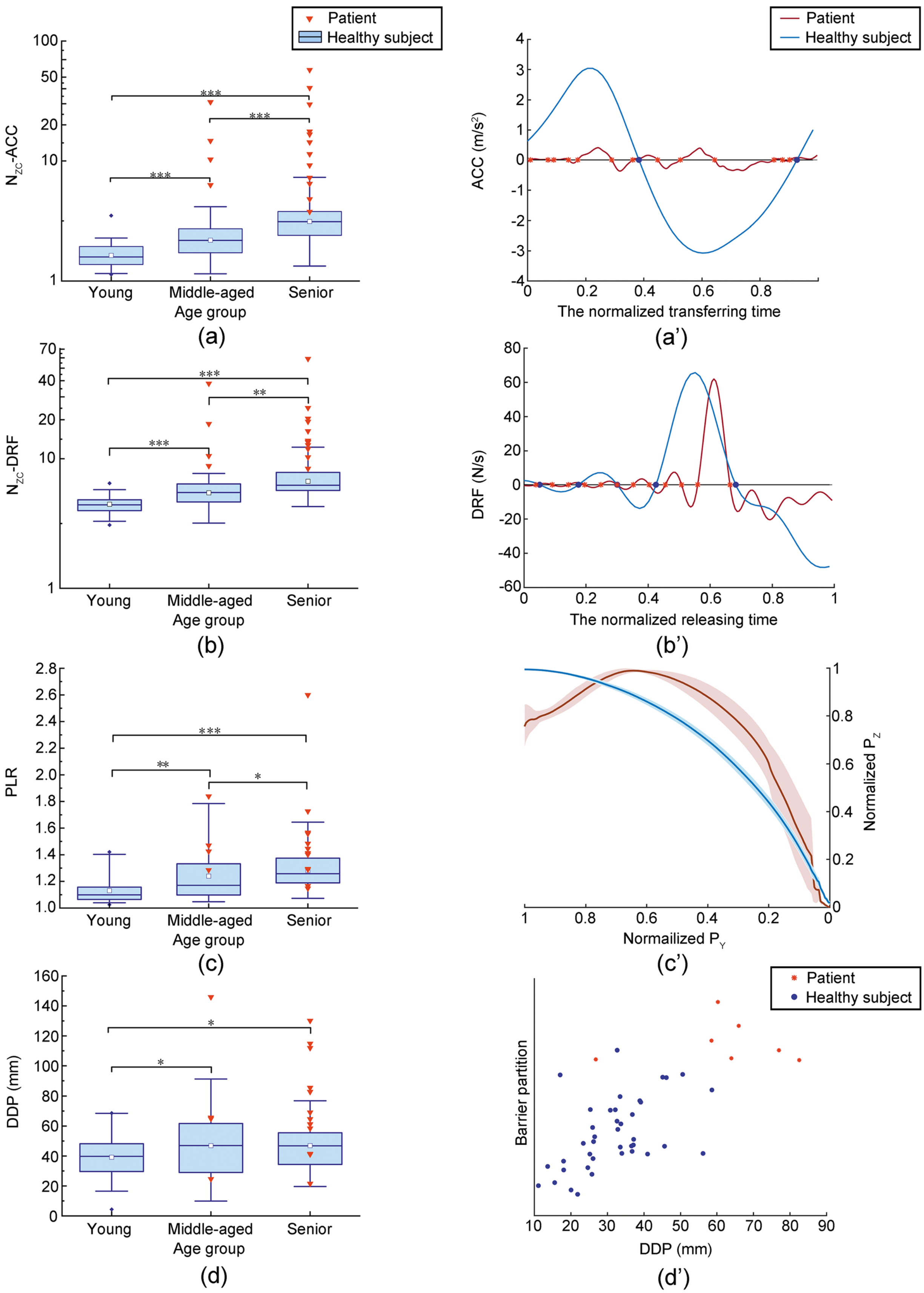
SD Standard Deviation, *ICC* Intraclass Correlation Coefficient, *CI* Confidence Interval, *SEM* Standard Error of Mean, *BBT* Box and Block Test, *VBBT* Virtual Box and Block Test, N_{ZC}*-ACC* the number of zero-crossings of the moving acceleration, N_{ZC}*-DRF* the number of zero-crossings of the derivative of releasing force, *PLR* the ratio of the path length and linear length, *DDP* the distance between the barrier partition and the drop position characterize impairments more sensitively with high resolution (Schwarz et al. 2019). They have been applied to identify abnormal movement patterns (Bjoern et al. 2017; Shull et al. 2014). The BBT performance involves several movement patterns including grasping, moving and releasing blocks (Hebert and Justin Lewicke 2014; Mathiowetz et al. 1985). To further improve the test, we proposed relevant kinematic metrics collected by the haptic device to quantify the VBBT performance. Specifically, we used N_{ZC}-ACC as an indicator to characterize the smoothness of the UE motion, while participants were moving blocks. Due to the decreased ability of neuroregulation and muscle control, stroke patients usually exhibit tremors in their movements that cause more submovements and poorer smoothness in the execution of tasks (Germanotta et al. 2015; Nordin et al., 2014; Rohrer et al. 2002). Clinical evidence has indicated that stroke patients moved more smoothly when they gradually recovered their motor function as rehabilitation proceeds (Krebs 1998). Actually, N_{ZC}-ACC, the number of peaks in the velocity profile, which has been considered as one of the key variables for characterizing kinematic movements in UE tasks (Kantak et al. 2017; Krebs et al. 2014; Mazzoleni et al. 2014). When a stroke has damaged the cortex related to motor function, the communication between the neurons and the muscles may be abnormal, causing spasticity (Pandyan et al. 2005). The spasticity is characterized by extreme stiffness in the muscles, tendons and joints, and it often occurs in UE after stroke (Mochizuki et al. 2019; Wilson et al. 1999). As a result, most stroke patients involuntarily keep their hands clenched, which significantly limits their hand movements, especially for opening their hands and releasing objects (Qin et al. 2019). We used N_{ZC}-DRF, the number of zero-crossings of derivative of releasing force, to examine stability of fingers during the grasp-to-release movement. The results of clinical validity showed that the N_{ZC}-DRF was strongly correlated with the BBT and the ARAT, both of which were involved in the grasping and releasing tasks (Lin et al. 2010; Mathiowetz et al. 1985; Yozbatiran et al. 2008). Comparing to healthy people who tend to follow a trajectory similar to the shortest path between the start and the target, neurologically affected patients move in a path that is less optimal for their feedforward control is disrupted (Graaf et al. 1991). Usually, PLR, the ratio of the path length and linear length of a trajectory, is considered as an indicator of motion efficiency (Saandeep et al. 2013; Semrau et al. 2017; Zollo et al. 2011). However, the PLR performed by patients in the VBBT showed weak or moderate correlation with clinical scales. We extrapolated that it was because the transferring movement was blocked by a barrier partition that the optimal path was not a linear profile. Therefore, the PLR may not be appropriate for representing motion efficiency in the VBBT. Instead, we designed a kinematic metric, DDP, to demonstrate motion efficiency in the VBBT performance. Patients with high motion efficiency tended to drop the blocks immediately when they transferred them over the barrier partition. The result of clinical validity indicated that the DDP exhibited a strong correlation with the clinical scales.

8.2 Identification of motor function impairments in the VBBT

Kinematic metrics facilitate the understanding of motor function impairment caused by neurological disorders (Kanzler et al. 2020). Therefore, it is possible to find significant differences in the kinematic measurements between stroke patients and healthy people (Mesquita et al. 2019). Clinical evidences have suggested that, compared to the conventional assessment from therapists' subjective scores, the metrics extracted from robotic devices are able to characterize impairments with smaller samples required in resource demanding clinical trials (Burridge et al. 2019; Lamers et al. 2014; Vergnault and Pichon 2017). Although the robotic measurements, especially for novel metrics, are effective in assessing UE motor function, they are still inhibited by insufficient clinical routine (Santisteban et al. 2016). How to identify the impairment of UE motor function for stroke patients by using the kinematic metrics in the VBBT performance? Semrau et al. reported an effective approach that can identify the motor-functional deficits of stroke patients by robotic devices (Semrau et al. 2013). They first determined a normative range for each metric by 95% confidence interval (CI) for double-sided measurements (2.5%-97.5%) from the performances of healthy subjects in robot-aided tasks. The abnormal movements of stroke patients could be quantitatively identified when their kinematic measurements fell outside of the normative range. The similar approach was also used to identify motor functional deficits in previous studies (Hawe et al. 2020; Liu et al. 2019; Semrau et al. 2017). According to these studies, we determined a normative range for each kinematic metric in the VBBT. Specific deficiencies in the patients' UE function were identified when their measurements fell outside of the normative ranges.

8.3 VBBT versus conventional BBT

We compared a basic performance (the number of moved blocks) in the VBBT with that in conventional BBT. The result indicated that subjects' performances in the VBBT presented a stronger age-related correlation than that in the BBT. This is probably because the senior participants were unfamiliar with the use of electronic equipment (Chou et al. 2022). Based on it, we divided the subjects into three groups (young, middle-aged and senior) to characterize the subjects' performances; and we found significant differences between any two groups. Therefore, it is strongly suggested


Patient
Healthy subject
N_{ZC}-ACC
Young
Middle-aged
Senior
Age group
(a)
ACC (m/s²)
The normalized transferring time
(a')
N_{ZC}-DRF
(b)
DRF (N/s)
The normalized releasing time
(b')
PLR
(c)
Normalized P_Z
Normalized P_Y
(c')
DDP (mm)
(d)
Barrier partition
(d')

◂**Fig. 5** The kinematic metrics in the VBBT. **a** N_{ZC}-ACC in different age groups. **a'** Two typical curves of ACC vs. normalized time in one trial performed by a healthy subject and a patient, respectively. **b** N_{ZC}-DRF in different age groups. **b'** Two typical curves of DRF vs. normalized time in one trial performed by a healthy subject and a patient, respectively. **c** PLRs in different age groups. **c'** Two typical curves of PLRs vs. normalized Y position (PY) performed by a healthy subject and a patient, respectively. **d** DDPs in different age groups. **d'** Two typical scatter plots of the distance between the barrier partition performed by a healthy subject and a patient, respectively. $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

that the normative ranges in the VBBT should be determined in accordance with patients' ages. Moreover, the quantitative performances in the VBBT showed a better reliability than that in the BBT. We speculated that the block always appeared in the same location between trails in the VBBT while the block in the BBT was grabbed in completely random location (Mathiowetz et al. 1985). The consistency of the block location helps subjects perform more stably in the VBBT. The BBT is a task-oriented assessment that is also concerned with patients' motivation. IMI scores indicated that the VBBT allows more motivation for patients compared to conventional BBT. Most of them approved their motivation due to the enjoyment of the immersive environment and effort needed for task performance.

8.4 Our VBBT versus previously reported VBBTs

Several studies virtualized the BBT assessment by using motion-tracking devices, such as LMC (Alvarez-Rodríguez et al. 2020; Gieser et al. 2016; Oña et al. 2020), Kinect (Cho et al. 2015), and Oculus Touch Controller (Everard et al. 2022). Almost all the reported results indicated that the number of moved blocks in the VBBT was less than that in the BBT, which were consistent with our study. This is most likely due to the difference between the virtual environment and physical world. For the VBBT assessment by the aid of LMC and Kinect, the number of moved blocks that researchers analyzed only reflected gross motor function rather than specific deficiencies in patients' UE motor function. In the study on the controller-aided VBBT assessment, kinematic metrics such as average velocity, peak velocity and SPARC were analyzed to identify some specific deficiencies in motor function. But subjects' ability to grasp was not characterized since the data of interactive force could not be collected by using the controller device. Most motion-tracking devices cannot collect force data. So, they failed to provide tactile sensory stimulation in the VBBT assessment (Arlati et al. 2021; Voinescu et al. 2021). Actually, multi-sensory feedback is important for virtual rehabilitation therapy since it augments the immersion in VR environment (Arlati et al. 2021). In this paper, we used a haptic device to allow tactile and gravity perception during the VBBT performance. In addition, the haptic device can collect force data, which could be used to characterize patients' ability to grasp and release objects.

8.5 Limitations and future work

There are still some limitations in the current study. The first limitation refers to the "floor effect" of the VBBT. The patients could operate the device and perform the virtual task only if their UE function reached Brunnstrom stage IV or later. In fact, most patients tend to conduct rehabilitation at home when they have recovered major function of the UE. For some patients who are unable to independently operate the device, we strongly suggest that patients should be provided some arm supports during the VBBT performance. Secondly, there are several non-negligible differences in the performance between the VBBT with a haptic device and the BBT. Most obviously, users pick up and move blocks by pincher grasp with a handle of the haptic device in the VBBT. However, they perform BBT involved in three-finger grasp or other grasp types besides pincher grasp (Feix et al. 2015). Also, the BBT refers to a larger operation space than the VBBT that could limit users' movement to some extent. In addition, the haptic device is costly though they improve the assessment of UE motor function in the VBBT, which makes it impossible to make commercially available for some patients. However, this does not mean that every patient must buy it. Patients can rent the device from the rehabilitation unit. When they regain motor function and can maintain recovery, they can return the device to the rehabilitation unit.

As it is a pilot study to examine the validity of a noncommercial system, the sample size of 16 post-stroke patients is an appropriate and acceptable size to perform the preliminary evaluation for the assumed relation between stroke and the hemiplegic UE for the VBBT. Future studies may strive to collect a larger sample size for validating the responsiveness of the VBBT. Additionally, the selected subjects were limited to adults with a minimum age of 18 years old, and users' performance of the VBBT might be different at the age below 18 years. Therefore, further studies are necessary to assess the performance of patients with lower ages in the VBBT and to establish the normative ranges for them. Moreover, we will establish normative ranges for non-dominant hands to assess UE function of patients with other diseases (e.g., Parkinson's disease, Multiple sclerosis, etc.). In the future, we will design a virtual task in which virtual objects with different masses and textures to explore whether the inertia of objects will influence task performance in virtual environment.

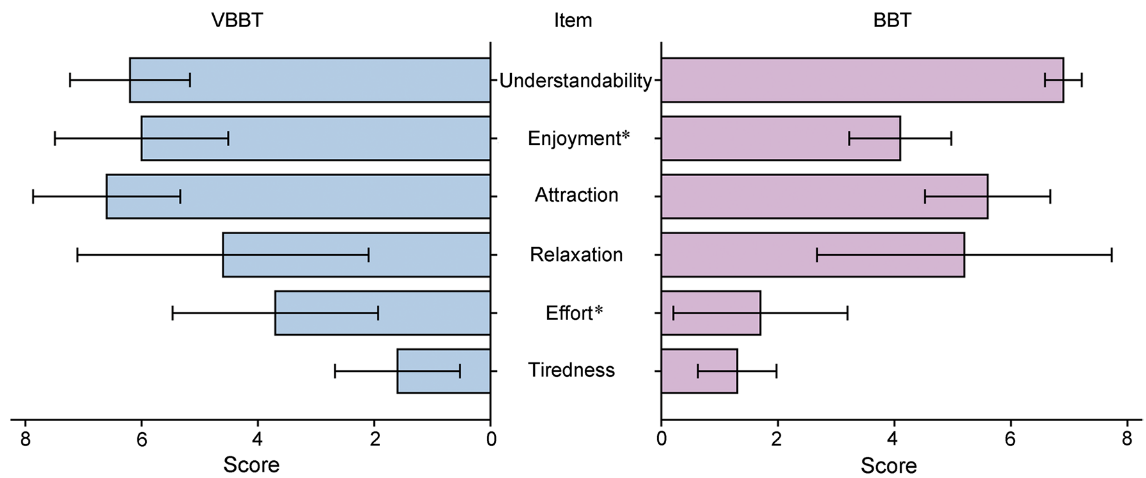


Fig. 6 The scores of the patients' motivation between the VBBT and BBT

9 Conclusion

We designed the VBBT with a haptic device to improve the BBT for assessing UE motor function in post-stroke patients. The performances of healthy subjects were collected to establish normative ranges in different age groups. Deficiencies in a patient's UE motor function could be determined when his/her measurements were not within the normative ranges. The validity and test–retest reliability were examined to indicate that the VBBT is an effective and reliable task-oriented assessment. Besides the number of transferred blocks, the VBBT can provide clinically validated kinematic metrics, including N_{ZC}-ACC, N_{ZC}-DRF and DDP, to reflect patients' specific impairments in UE function, including the motion smoothness, hand dexterity and motion efficiency. Additionally, the patients showed a significantly higher score of the motivation to complete the VBBT than the BBT due to the enjoyment and completion effort, which would facilitate the enthusiasm for participation in unsupervised assessment for home-based rehabilitation.

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Authors' contribution YD contributed to designing and conducting the experiment, analyzing the experimental data, and drafting this manuscript. XL contributed to leading this work, securing the funding, guiding the experiment and drafting and editing the manuscript. MT contributing to programing the virtual task, conducting the experiment and interpreting the data. HH contributed to analyzing and interpreting the data. DC, ZW and RA contributed to conducting the experiment. YF contributed to leading this work, securing the funding, editing and approving the final manuscript.

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Data availability All the data and materials in the current study are available from the corresponding author on reasonable request.

Code availability The custom code in the current study is available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

Consent to participate A signed informed consent statement was received from each participant. This study was registered on Chinese Clinical Trials Registry (ChiCTR2100042355 at http://www.chictr.org.cn/).

Consent for publication All the authors contributed to this article and consent to the publication of this research work.

Ethics approval The current study adhered to the tenets of the Declaration of Helsinki, and ethical approval was approved by Beihang University (BM20180017).

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