A Low-Cost Adaptive Balance Training Platform for Stroke Patients: A Usability Study

Sunny Verma, Deepesh Kumar, Animesh Kumawat, Anirban Dutta, and Uttama Lahiri

***Abstract*— Stroke patients usually suffer from asymmetric posture due to hemi-paresis that can result in reduced postural controllability leading to a balance deficit. This deficit increases the risk of falls, which often makes them dependent on caregivers for community ambulation, thus deteriorating their quality of life. Conventional balance training involves rehabilitation exercises performed under physiotherapist's supervision, where the scarcity of trained professionals as well as the cost of clinic-based rehabilitation programs can deter stroke survivors from undergoing regular balance training. Thus, researchers have been exploring technology-assisted solutions, e.g., home-based virtual reality (VR) setup. In this paper, we developed a VR-based balance training (VBaT) platform, where VR-augmented user-interface using Nintendo Wii balance board was tested in a laboratory setting for its feasibility. The VBaT offered tasks of varying difficulties to the participants that adapted to individual performance capability during balance training. We performed a preliminary usability study with 7 stroke survivors (post-stroke period $>$ 6 months). Preliminary results indicate the potential of the VBaT system to cause improvement in overall average task performance over the course of training while using the VBaT. Thus the VBaT system is proposed to be a step toward an effective balance training platform for people with balance disorder.**

***Index Terms*— Stroke, balance, virtual reality, Wii balance board.**

I. Introduction

STROKE is one of the leading causes of adult disability and is often associated with impaired motor function. In India, the estimated prevalence rate of stroke is 84-262/100,000 in rural and 334-424/100,000 in urban areas [1]. Studies on stroke incidence have reported a 42% decrease in stroke incidence in developed countries and greater than 100% increase in stroke incidence in developing countries [2]. Up to 85% of stroke survivors face hemi-paresis immediately after stroke and around 55%-75% of stroke survivors continue to experience motor deficits with reduced balance [3].

Deficits in balance deficits post-stroke may be caused by several factors, e.g., loss of muscle strength, restricted joint movement, impaired proprioception and motor control [4]. In extreme cases, the weight bearing ability of stroke survivors can be reduced by up to 43% on the paretic side of the lower extremity thereby making them prone to falls during over-ground ambulation [5], [6]. In fact, incidence of falls can be up to 73% in the first year, post-stroke [7]. About 20-30% of individuals, who fall, suffer lacerations, hip fractures and head traumas [8]. As a result, stroke survivors often suffer from fear of falling, reduced self-confidence, and loss of functional independence which in turn adversely affects their participation in social activities [6].

Balance rehabilitation program during early stages after stroke incidence is often effective in improving balance and mobility skills while reducing fall-risk [9]. Post-stroke motor recovery relies on neuronal plasticity that allows different areas of the brain to take over functions of the affected zone, where the complexity of this reorganization strongly depends on the severity of the anatomical and functional lesion [10]. Rehabilitative systems must be designed with an aim to induce cortical reorganization that can contribute to functional recovery [3]. Conventional techniques used in balance rehabilitation have been reported to provide promising outcomes [6]. However, such conventional techniques often require one-on-one therapist's supervision and practice of repetitive tasks that become monotonous to the patient over time. This often leads to poor engagement and lack of interest among stroke survivors while undertaking rehabilitation exercises [11], [12]. Given the scarcity of adequately trained healthcare resources [6], high cost of one-on-one services in specialized health clinics [13], researchers have been trying to explore alternative technology-assisted solutions. We chose virtual reality (VR) based systems since these can offer an individualized, cost-effective, safe, interactive and repetitive practice environment with variations to stroke survivors [14]. Thus, VR-based systems are often motivating [12]. Additionally, VR-based exercise platforms can be easily programmed to incorporate physiotherapist's inputs in its design. Thus VR-based exercise platform can also serve as a complementary tool in the hands of the physiotherapist, with one therapist being able to administer exercise of many patients at the same time reducing the time spent on one-on-one sessions. Also, stroke survivors can use these cost-effectiveness platforms to exercise at their homes [6]. In recent years, the VR-based exercise modules coupled with peripheral devices have begun to gain widespread usage as augmented

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stroke rehabilitation tools [14]. This is because VR provides an interactive training environment by simulating real-world scenarios easily. Additionally, VR offers an avenue to interface the simulated world with peripheral devices, such as, balance board [15] for addressing balance disorders [11].

One's balance is mainly addressed using three main postural strategies while standing, namely, ankle, hip and step strategies [15]. All of these strategies have their own advantages. However, the ankle strategy is most commonly used to improve standing balance through muscle contraction of the ankle joint [16]. In ankle strategy, for stable weight shifting, the body's center of pressure (CoP) is controlled by ankle joint with head and hips moving in the same direction while staying within one's limits of stability (LOS) [4]. The LOS is defined as the maximal distance by which a subject can lean while maintaining balance without raising his feet from the ground surface [4]. The CoP has been commonly used as an index of postural stability while standing [17]. CoP is the point location of the vertical ground reaction force vector. It represents a weighted average of all the pressures over the surface of the area in contact with the ground [18]. Studies on upright posture use a measure of "body sway" to characterize the performance. For balanced body sway, the body's center of mass (CoM) is regulated in the gravitational environment. Body sway is often estimated from CoP measures derived from force plate data [19]. Researchers have reported the reliability of force plates, e.g., Nintendo Wii balance board (BB) to be used as a tool for assessing balance in clinical settings [20]. In this study, we integrated low-cost portable BB (from Nintendo) with a VR-based platform and made the user-interface interactive by providing real-time visual feedback of the CoP (measured by BB and recorded at the backend) through the dynamic virtual object (integrated with CoP and displayed at the front-end of a VR-based task).

Different researchers have used computer-based games integrated with BB for addressing problems associated with one's balance [6], [11], [12], [15], [21]–[23]. For example, Gil-Gómez et al. [12] designed a BB and VR-based system (eBaVir) for balance rehabilitation in which they designed three games that a stroke survivor played in each session. However, their system did not offer participants with games of varying difficulty that can be adapted based on individual performance during balance training. Also, most of the pioneering research studies [6], [11], [21]–[23] used off-the-shelf games that were designed for use by healthy individuals to offer a gaming experience, mostly aimed towards entertainment and not for tasks addressing balance disorder. Additionally, these systems did not use any rule engine that could present tasks of varying challenges in a systematic, controlled and adaptive manner based on the user's performance capability, essential for effective rehabilitation.

In this study, we aimed at two objectives, namely, (1) Develop a VR-based Balance Training (VBaT) platform having a VR-based system augmented with a BB to offer balance rehabilitation exercises in an individualized and adaptive manner that suits one's performance capabilities and (2) Conduct a usability study, as a proof-of-concept application of the VBaT system, with an aim to understand the implications of such a system on the task performance of individuals having balance disorders. The VBaT system also featured an automated Heel Lift Detection module that detected one's incorrect posture (i.e., lifting of the heel from the BB surface) during balance training while using ankle strategy. Effective balance training using ankle strategy requires one's foot to remain in contact with the base of support [4]. The VBaT system offered participants a variety of VR-based balance tasks of varying levels of difficulty in a controlled and systematic manner. The tasks required a participant to shift his weight in different directions (North, East, West, etc.) using ankle strategy.

This paper is organized as follows: Section II describes the system design, Section III presents the experimental setup and the methodology used, Section IV discusses the results obtained in the usability study. Finally, Section V summarizes the research findings, and discusses the limitations of the current study as well as the direction for future research.

II. System Design

The VBaT system consisted of five modules, namely, (a) VR-based task (b) Heel Lift Detection (c) BB VR Handshake (d) Performance evaluation and (e) Task switching modules.

A. VR-Based Task Module

We developed VR-based tasks to quantitatively estimate one's balance capability during weight-shifting. Our tasks required participants to shift weight in different directions, similar to our day-to-day activities that often need us to shift our weight in different directions to perform reaching tasks. Additionally, practicing bipedal weight-shift exercises may be critical for hemi-paretic stroke survivors with asymmetric biped balance since they are particularly susceptible to falls during reaching tasks. Thus, we also designed tasks that needed effective use of both limbs to complete a task. Often physiotherapists recommend exercises for lower limb that last for about 20 minutes [11] consisting of static and dynamic balance, passive and active range of motion, stretching, gait training, muscle strengthening and activities of daily living exercises. Here we chose to focus on static balance exercises, where participants took part in VR-based balance training lasting for about 20 minutes. We used Vizard software toolkit (from WorldvizLlc.) to design realistic VR environments with variations so as to make the weight-shifting exercise interesting. The VR-based tasks required the participant to maneuver virtual objects in the VR environment (shown on the task computer monitor) using their CoP while standing on a balance board (BB). The raw CoP values (acquired at 30 Hz) were processed by a 5-point moving average filter. The position of virtual object (VR_{obj} henceforth) was determined from the filtered CoP data by using equation (1).

$$\begin{bmatrix} x \\ y \end{bmatrix}_{VR_{obj}} = \begin{bmatrix} CoP_x & 0 \\ 0 & CoP_y \end{bmatrix} \begin{bmatrix} \in_1 \\ \in_2 \end{bmatrix} \tag{1}$$

Where, $\in_1$ and $\in_2$ are constants used to scale the position of VR_{Obj}corresponding to the CoP position on the computer monitor in real-time. There was no perceptible visual lag

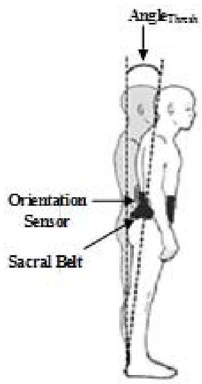


Fig. 1. Weight shifting using ankle strategy.

TABLE I
THRESHOLD ANGLES AND TIME OF WEIGHT SHIFTING

	Direction	$Angle_{Thresh}$ (degrees)	$Time_{Thresh}$ (sec)
DL1	North	3.38	12
	East	5.11	12
	West	5.11	12
	North-East	4.245	12
	North-West	4.245	12
DL2	North	5.29	12
	East	8.09	12
	West	8.09	12
	North-East	6.69	12
	North-West	6.69	12
DL3 & DL4	North	5.29	60/Template
	East	8.09	
	West	8.09	

Note: $Angle_{Thresh}$ –Threshold Angle; $Time_{Thresh}$ - Threshold Time

between the moving CoP (acquired at the backend) and the VR_{obj} during the VBaT task. Additionally, the VBaT system provided performance-based audio-visual feedback to the participants. The tasks were of four difficulty levels (DL1- DL4), with difficulty depending on the threshold angle of shifted weight from the vertical (e.g. $Angle_{Thresh}$ for North as shown in Fig. 1) and the threshold task completion time ($Time_{Thresh}$) (Table I) as obtained from a pilot study carried out with healthy participants (age-matched with our participant pool). The VR-based tasks (Fig. 2) were designed using Google Sketchup and imported to Vizard environment with scaling factors of $\in_1$ and $\in_2$ that were (2.45, 4.51), (1.72, 3.16), (0.26, 0.48), and (1.52, 2.72) for DL1, DL2, DL3 and DL4 respectively. In the pilot study, the participants were asked to perform tasks in each difficulty level by shifting weight while standing on the Balance Board. Each participant was asked to wear a Sacral Belt holding an android phone (with the orientation sensor application program) placed on the Sacrum. The $Angle_{Thresh}$ with the vertical was computed from the pitch angle for 'North' direction, roll for 'East' and 'West' directions and combination of roll and pitch angle for 'North-East' and 'North-West' directions as recorded by the orientation sensor application program.

1) Design of VR-based Tasks of Difficulty Level 1 (DL1): Fig. 2(a) shows an example of the Graphical User Interface (GUI) of VR-based task of

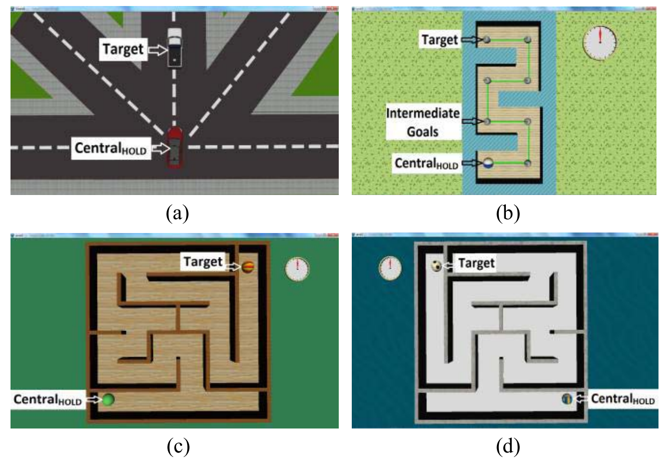


Fig. 2. (a) GUI of DL1& DL2 task; (b) GUI of DL3 task; (c) GUI of DL4 task ($Template_{Right}$◁; (d) GUI of DL4 task ($Template_{Left}$◁.

DL1. We created a database of 30 unique combinations of VR-based environments and virtual objects related to tasks of daily living and entertainment. The task required participants to shift their weight in different directions from the central hold state (i.e., $Central_{Hold}$ (standing straight (upright) without shifting weight while balancing on both legs), namely, 'North', 'East', 'West', 'North-east', and 'North-west' to move the virtual object (i.e. Test object (VR_{Obj})) in the VR environment to a predefined target position, with various target images (chosen randomly from a database). Also, the task required the participant to hold the VR_{Obj} at the target position for one second. The tasks were kept fairly easy, in which the participant had to shift weight by a minimum $Angle_{Thresh}$ (Table I). The task in DL1 began with target object presented at the end (target position) of one of the virtual paths pointing in one of the 5 directions (Fig. 2(a) shows target position towards 'North'). The participant was asked to shift his weight to move the VR_{Obj} towards the Target object. Once the VR_{Obj} travelled a certain minimum threshold distance (in VR environment) from $Central_{Hold}$ position (equivalent to the minimum $Angle_{Thresh}$ (Table I)), the VR_{Obj} was programmed to automatically shoot towards the Target position. The participant was also expected to hold the shifted weight for 1 sec with the VR_{Obj} remaining at/near the Target position for 1 sec. If the participant could achieve that, then the VBaT generated a 'ting' sound as audio feedback. The participant was expected to complete the task within a $Time_{Thresh}$ (Table I), or else the VR_{Obj} was relocated back to the $Central_{Hold}$ position with the participant's performance score for that specific direction being marked as zero. Likewise, the participant was asked to execute the tasks for the remaining 4 directions that were randomly presented. The VBaT system delivered audio-visual feedback, such as, "Well done! You are doing great" if the task completion was successful and "Keep trying, you can do better" otherwise.

2) Design of VR-based Tasks of Difficulty Level 2 (DL2): The tasks belonging to DL2 were similar to those in DL1. However, these tasks required a greater $Angle_{Thresh}$ thereby requiring the participant to move the CoP by a greater amount. This means that these tasks required greater weight-shifting, hence increasing the difficulty level.

3) Design of VR-based Tasks of Difficulty Level 3 (DL3): Fig. 2(b) shows an example of the GUI for a task belonging to DL3. The task required the participant to shift weight starting from $\mathrm{Central_{Hold}}$ position towards 'North', 'East' and 'West' directions (with intermediate $\mathrm{Central_{Hold}}$ after each of the 7 segments of the maze-like path) to maneuver the $\mathrm{VR_{Obj}}$ in the task environment. The task required a participant to (i) plan and (ii) dynamically shift weight to maneuver the $\mathrm{VR_{obj}}$ from a start position to a target position while moving through intermediate goal points in the maze-like path. However, after reaching each intermediate goal point (at the end of each segment of the path), the $\mathrm{VR_{obj}}$ was programmed to be stationary at that position (with $\mathrm{VR_{obj}}$ being disintegrated from the CoP) until one returned back to the stable $\mathrm{Central_{Hold}}$ position. The $\mathrm{Angle_{Thresh}}$ used for DL3 was same as that of DL2 (Table I). Unlike DL1 and DL2, for tasks in DL3, the participants were not presented with any target location by the VBaT system. Specifically, here the participant was expected to look at the maze-like path displayed on the computer screen and having intermediate goals at the end of each segment. Subsequently, based on the goal position, he was expected to decide the direction in which he would need to shift his weight to complete the task within the allotted $\mathrm{Time_{Thresh}}$. A timer was added in the environment (Fig. 2(b)) for the participants to keep track of their time.

4) Design of VR-Based Tasks of Difficulty Level 4 (DL4): Figs. 2(c) and 2(d) show examples of GUI used for tasks belonging to DL4. Similar to DL3, the task of DL4 required a participant to plan and shift his weight so as to maneuver a $\mathrm{VR_{Obj}}$ along the maze-like path. However, unlike DL3, in DL4 task, (i) the maze-like path was more complex and (ii) there were no intermediate goals to achieve. In fact, here the participant's CoP was integrated to the $\mathrm{VR_{Obj}}$ throughout the task requiring the participant to maintain his shifted weight while not returning back to the stable $\mathrm{Central_{Hold}}$ position in which case the $\mathrm{VR_{obj}}$ would trace back and delay the task completion. Here, we designed two templates for each task, namely, (a) one with start position at the bottom left corner (corresponding to $\mathrm{Central_{Hold}}$) and target position at top right corner ($\mathrm{Template_{Right}}$) and (b) another with start position at bottom right corner (corresponding to $\mathrm{Central_{Hold}}$) and target position at the top left corner ($\mathrm{Template_{Left}}$). For $\mathrm{Template_{Right}}$, the participant was required to move the $\mathrm{VR_{Obj}}$ using a path having combination of 'North', 'East' and 'North-East' directions with the target position being displaced towards 'North-East' from $\mathrm{Central_{Hold}}$ position. For $\mathrm{Template_{Left}}$, the participant was required to move the $\mathrm{VR_{Obj}}$ using a path having combination of 'North', 'West' and 'North-West' directions with the target position being displaced towards 'North-West' from $\mathrm{Central_{Hold}}$ position. A participant was asked to interact with both the templates (offered randomly) to complete a task in DL4 within a specified time (Table I).A timer was added (Figs. 2(c) and 2(d)) for the participants to keep track of their time. For DL4, the $\mathrm{Angle_{Thresh}}$ was similar to DL2 and DL3 (Table I) and width of the maze-like path was lesser than DL3.

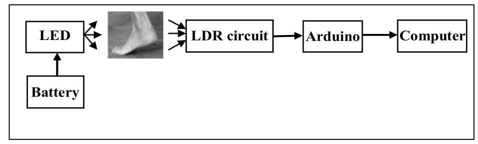


Fig. 3. Block schematic of Heel Lift Detection module.

B. Heel Lift Detection Module

We aimed to capture one's capability to shift weight using CoP displacement while standing on BB and maneuvering the CoP by using ankle strategy and not by a heel-to-toe weight-shift strategy by lifting heel above the ground surface. Therefore, we designed a Heel Lift Detection (HLD) module to penalize the user for each lift of heel while performing the task. The HLD module consisted of a 5 watt LED source, a light dependent resistor (LDR) and an Arduino board. While standing erect, one's heels will be in contact with the BB surface and therefore the heels will obstruct the light from the light source to fall on the detector, resulting in a high resistance of the LDR. However, if the user lifts his heel from the BB surface, the light from the source will fall on the detector, thereby reducing the resistance of the LDR. The LDR output was processed by the microcontroller of the Arduino board (Fig. 3) which was interfaced with the task computer executing the VR-based tasks.

C. Handshaking Module Integrating BB With VR Platform

We interfaced the Nintendo Wii BB with our task computer executing the VR-based tasks, with a Bluetooth dongle and a licensed version of BlueSoleil 10.0.483.0 software. A customized Matlab-based code [24] was used to interface the BB with the VR environment that accessed data from BB at 30 Hz. The data consisted of the force values from the Back Left (R_1), Back Right (R_2), Front Left (R_3) and Front Right (R_4) pressure sensors of the BB. These values were used to compute the x and y coordinates of the CoP measure ($\mathrm{CoP_x}$, $\mathrm{CoP_Y}$) (eqs. 2 and 3).

$$\mathrm{CoP_x}(\text{in cm}) = 26.05 * (R_2 + R_4 - -R_1 - -R_3) / (R_1 + R_2 + R_3 + R_4) \tag{2}$$

$$\mathrm{CoP_Y}(\text{in cm}) = 16.75 * (R_1 - R_3 + R_2 - R_4) / (R_1 + R_2 + R_3 + R_4) \tag{3}$$

The constants '26.05' and '16.75' in eqs. (2) and (3) represent the physical dimension of the BB.

D. Performance Evaluation Module

Previous research studies [14], [25] have reported that one's balance assessment can be made using different metrics e.g., CoP sway distance, sway angle, sway area, sway velocity, etc. While our participants performed VR-based tasks, the VBaT system computed their performance scores for the tasks of varying difficulties using different performance metrics. Here we chose sway distance quantified as length of sway trajectory, and sway angle quantified as deviation of the direction of shifted weight from the direction of target for tasks belonging to different difficulty levels. Additionally, we used three other performance metrics namely, ability to hold shifted weight (a measure of postural stability), task completion time, and ability to shift weight without lifting heel. The threshold values for different performance metrics were decided based on a pilot study and the feedback from a physiotherapist in our team.

1) Performance Evaluation Criteria for Tasks of DL1: For task of DL1, the score in each of the five directions was evaluated based on four performance metrics, namely, (i) P_{S1}: measure of the length of trajectory (T_L) of participant's CoP while standing on the BB before reaching the $\text{Angle}_{\text{Thresh}}$ of weight shifting, (ii) P_{S2}: measure of deviation (D_A) of participant's shifted weight from the instructed straight path between the start and the target positions, (iii) P_{S3}: measure of one's ability to hold his weight at the target position for Hold time (H_T) of 1 second, and (iv) P_{S4}: penalizing factor to discourage the participant from lifting his heel while shifting weight.

The first metric (P_{S1}) evaluated the participant's CoP trajectory within the $\text{Angle}_{\text{Thresh}}$with one's sway in random directions while shifting weight was penalized as follows,

$$P_{S1} = \begin{cases} 100; & if T_L \le D_{TH} \\ 100 - \propto * \left(\dfrac{T_L - D_{TH}}{D_{TH}}\right) * 100; & if D_{TH} < T_L < 3 * D_{TH} \\ 0; & T_L \ge 3 * D_{TH} \end{cases}$$

where, D_{TH} (Threshold distance) = 1.8 * the length of the straight line path between the start and the target positions in each direction. The factor α (=½) was considered in order to reduce the penalty on the task performance score. The value of $D_{TH}$was decided based on the pilot study with healthy participants. In this pilot study, we computed the length of participant's CoP trajectory to reach the target position in different directions. Then the value of D_{TH} was computed by averaging the distance travelled by the participants' CoP in different directions. It was found to be 1.8 $*$ the length of the straight line path between the start and target positions. The value of α was decided based on trial and error.

The second metric (P_{S2}) evaluated the quality of participant's weight shifting (in terms of deviation (D_A)) from the instructed direction (defined by $\theta_x = 0^0$ for East; 45^0 for North-East; 90^0 for North; 135^0 for North-West; and 180^0 for West) with a tolerance range (θ_{RANGE}) of $\pm 22.5^0$ around the instructed direction.

$$P_{S2} = 100 - \propto * \left(\frac{abs(\theta_x - D_A)}{\theta_{RANGE}}\right) * 100; \quad \text{Here,} \ \alpha = 1/2.$$

The third metric (P_{S3}) was considered to encourage a participant to make a stable weight shifting.

$$P_{S3} = \begin{cases} 100; & if H_T > 1s \\ 0; & if \ H_T < 1s \end{cases}$$

The fourth metric (P_{S4}) was used to penalize a participant for lifting heel during weight shifting.

$$P_{S4} = \begin{cases} -100; & for\ heel\ lifting \\ 0; & otherwise \end{cases}$$

Therefore, the weighted performance score (P_S^x) for each of the five directions (x = East; North-East; North; North-West; West) was calculated as

$$P_S^x = 0.5 P_{S1}^x + 0.25 P_{S2}^x + 0.25 P_{S3}^x + 0.2 P_{S4}^x$$

The range of values of P_S^x was 0-100. If P_S^x was negative, then it was rounded off to zero. Here we wanted to quantify the participant's performance in terms of (a) reduced swaying, (b) reduced deviation from the instructed direction, (c) increased ability to hold the posture and (d) heel lift/no heel lift. As advised by the therapist, we gave more weight (0.5) to (a), and less to (b) and (c). We wanted to understand whether the VBaT system can contribute to improved balance in participants. An important indicator to such an improvement, particularly at the initial stages of balance rehabilitation, is the ability to shift weight while maintaining a controlled profile of CoP trajectory (captured through P_{S1}). Subsequently, on achieving the requisite weight shift, one needs to work on the finer aspects, namely, remaining close to the target location (captured through P_{S2}) and hold the shifted weight (captured through P_{S3}). Thus, as suggested by the therapist, more weight was assigned to P_{S1} than P_{S2} and P_{S3}.Additionally, a penalty factor (0.2) was used to discourage a participant from lifting his heel while shifting weight. The penalty factor was decided based on trial and error with healthy participants.

The final performance score (P_s) for DL1 was computed from the average of the performance scores for all the directions as follows:

$$P_S = \frac{1}{5} \sum_x P_S^x$$

2) Performance Evaluation Criteria for Tasks of DL2: For tasks of DL2, we used the same metrics (described in section II.D.1) for computing the participant's performance score.

3) Performance Evaluation Criteria for Tasks of DL3: For the tasks of DL3, a participant was expected to maneuver a VR_{obj} along a maze-like path consisting of a combination of 7 different straight segments (3 segments pointing upwards from 'south' to 'North' and 2 each towards right and left i.e., 'East' and 'West' directions). In this task, the score was evaluated by using three performance metrics, namely (i) P_{S5}: measure of the length of trajectory (T_L) of participant's CoP while standing on the BB and before reaching the $\text{Angle}_{\text{Thresh}}$ of weight shifting (ii) P_{S6}: measure of the time taken to complete the task, and (iii) P_{S7}: penalizing factor used to discourage the participant from lifting his heel while shifting weight towards the target position.

The first metric (P_{S5}) was evaluated for each segment of the path. The other two metrics were calculated for the entire path consisting of 7 segments. Thus, P_{S5_i}(i = 1 to 7) was calculated similar to P_{S1} (section II.D.1) and subsequently, the mean value of P_{S5} was calculated, by using

$$P_{S5} = \frac{1}{7} \sum_{i=1}^{7} P_{S5_i}$$

The second metric (P_{S6}) was computed as

$$P_{S6} = \begin{cases} 100; & if\ T_{CT} \le T_{TH} \\ 100 - \alpha * \left(\frac{T_{CT} - T_{TH}}{T_{TH}}\right) * 100; & if\ T_{TH} < T_{CT} < 3 * T_{TH} \\ 0; & if\ T_{CT} \ge 3 * T_{TH} \end{cases}$$

where, T_{TH} (=20 seconds) was the minimum threshold time to complete a task and achieve maximum score; T_{CT} was the time taken by the participant to complete the task; and α =½. The value of T_{TH} was decided based on the average time taken by the healthy participants to complete the task.

To make this level more challenging, the penalty due to one's lifting of heel from the BB during weight-shifting was designed to be proportional to the amount of time the participant lifted his heel (T_{Lift}) during the task. Thus, P_{S7} was calculated as

$$P_{S7} = \frac{T_{Lift}}{T_{CT}} \times 100 \tag{4}$$

he final weighted performance score (Ps) for a task of DL3 was calculated as

$$P_S = 0.7P_{S5} + 0.3P_{S6} - P_{S7}$$

If P_S was negative, then it was rounded off to zero. For a task of DL3, we looked into the patient's maneuvering capability, maneuvering speed and task completion capability without lifting heel. As suggested by the therapist, we provided increased weight (0.7) to the maneuvering capability and reduced weight (0.3) to the maneuvering speed, since ability to do a task properly is more critical than the speed, particularly at early stages of rehabilitation. Additionally, an increased penalty factor (P_{S7}) was given for lifting heel, since a participant was expected to have received practice in doing a task without heel lifting, while interacting with previous tasks of DL1 and DL2.

4) Performance Evaluation Criteria for Tasks of DL4: Each task of DL4 consisted of two mirror templates ($Template_{Left}$ and $Template_{Right}$). These tasks were designed to understand how effectively one can use both of his limbs while executing tasks. The participant was required to complete both the templates within a specified duration (Table I). The score was calculated based on the difference in the time taken by the participant to complete both the templates. Thus, if T1 and T2 were the times taken by the participant to complete $Template_{Left}$ and $Template_{Right}$ respectively, then the first performance metric, P_{S8} was computed as

$$P_{S8} = \begin{cases} 100 - \alpha * \left(\frac{T2 - T1}{T1}\right) * 100; & if\ T1 < T2 \\ 100 - \alpha * \left(\frac{T1 - T2}{T2}\right) * 100; & if\ T1 > T2 \end{cases}$$

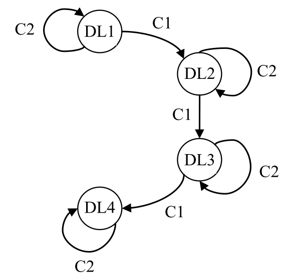


Fig. 4. State machine based Task Switching Rationale.

Here, α = 1/2 . We also considered the penalty of P_{S7} (see section II.D.3)for one's heel lifting. Thus the overall performance score (P_s) for a task of DL4 was

$$P_S = P_{S8} - P_{S7}$$

E. Task Switching Module

The VBaT system was designed to be adaptive to one's performance score in a task. A participant's performance was considered 'Adequate' (condition: C1) if his score was $\ge$ 70%, otherwise the performance was considered 'Inadequate' (condition: C2). Here, the threshold for the performance score was taken as 70% as an initial approximation since, literature indicates 70% as the average initial exercise performance for robot-assisted rehabilitation tasks [26], for outpatient clinics [27], technology-assisted skill learning [28], etc. This threshold can be easily adjusted based on the study requirement. The VBaT system offered tasks of varying difficulty based on the performance using a state machine representation (Fig. 4). For 'Adequate' performance, the VBaT offered the participant with a task of higher difficulty whereas for 'Inadequate' performance, the VBaT offered tasks of the same difficulty with a hope that the participants might improve their performance with practice.

III. Experiment and Methods

A. Participants

The study was carried out after informed consent at a local civil hospital where the stroke survivors were undergoing treatment. In the present usability study, seven stroke survivors (S1-S7) (mean (SD) = 40.57years(17.728)) who had experienced ischemic stroke participated. Table II shows the participants' characteristics. The inclusion criteria were (1) post-stroke period > 6 months (2) ability to follow instructions (3) ability to walk with/without orthopedic aids (4) Berg Balance score (BBS) > 40 that was measured by a physiotherapist in our team.

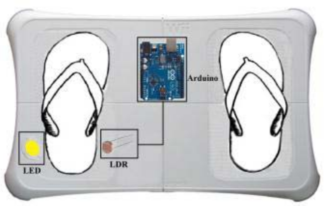
B. Experimental Setup

The experimental setup consisted of a BB and task computer (PC) with a 2D computer monitor and executing VR-based tasks (Fig. 5(b)). The participant was asked to stand on the BB (at a distance of approximately 150 cm from PC (Fig. 5(b))) fitted with slippers and Heel Lift Detection module set on the paretic side(as indicated by the therapist) to capture the heel lifting on the affected side (Left position

TABLE II
PARTICIPANT CHARACTERISTICS

	Age	Sex	Hemiplegic Side	Post Stroke period	BBS
S1	33	F	Left	1.5 years	46
S2	20	M	Left	11 months	49
S3	43	M	Right	9 years	50
S4	70	M	Right	3 years	50
S5	21	M	Right	13 months	53
S6	45	F	Left	4 years	51
S7	52	M	Right	2 years	51

Note: F-Female, M- Male



(a)

(b)

Fig. 5. (a) Balance board with HLD module for monitoring lifting of heel (Paretic side only); (b) Experimental setup.

shown in Fig. 5(a) as a typical case). Though the slippers attached to the BB surface restricted the movement of the participants on the BB, yet, we used this setup since, without the slippers, the stroke survivors were changing their position continuously on the BB leading to fluctuation in the CoP values.

C. Procedure

Our study required a commitment of approximately forty minutes from each participant for completion of a session with twenty minutes of interaction with the VBaT system. After the participant arrived in the experiment room, they were asked to sit down on a chair and relax for approximately 5 minutes. Then the physiotherapist in our team assessed the participant's balance using BBS measure and also checked medical records to match the inclusion criteria. Also the participant was told that the task would require him to do weight shifting without lifting his heels from the BB. Then, the experimenter explained the experimental setup to the participant and demonstrated the VR-based tasks (one in each difficulty level).Once the participant was ready, he was asked to stand on the BB. When the participant was ready to start interacting with the VBaT system, the experimenter started the VR-based tasks. After the participant completed the exercise lasting for 20 minutes, he was given a questionnaire regarding the VBaT system. The study followed institutional research ethics.

D. Statistical Analysis

While our participants interacted with the VBaT, we measured their performance score (%) and task completion time (seconds). Since our sample size was limited and data was not normally distributed, we used non-parametric dependent sample paired Wilcoxon signed-rank test [29] to check for the statistical significance. Here we have used Wilcoxon signed-rank test keeping the first and last attempt as between subject factor and DL1, DL2, DL3 and DL4 as within subject factor. We were interested to know whether the participants had significant improvement in performance while interacting with the VBaT system.

E. Post-Study Survey

At the end of the study, the experimenter conducted a post-study survey with a questionnaire. In this, the participants were asked questions, e.g., (i) Did you face any difficulty in understanding the tasks? (ii) Did you find the tasks interesting? (iii) Do you want to play again? and (iv) Do you think that you can benefit by using such a system. The participants responded to these questions either with a 'Yes' or 'No'. Questions (i) and (ii) were asked to know the users' thoughts on the specific tasks used in the VBaT (useful for the task design). Question (iii) was asked so as to understand the users' motivation to interact with the VBaT again. Question (iv) was asked to get the user's views on the potential of the VBaT system to serve as a possible rehabilitation platform. The survey was carried out to understand the overall qualitative aspect of the VBaT system without going for participant-specific quantitative measures.

IV. RESULTS AND DISCUSSION

We conducted a usability study with the VBaT system. The aim was to understand whether VR-based tasks (integrated with Wii BB) were capable of improving participants' performance in the tasks offered by the VBaT system. Additionally, this study examined whether the VBaT system was acceptable to stroke survivors.

A. Acceptability of the VBaT System

After the participants finished interacting with the VBaT system, the experimenter conducted a post-study survey. From the participants' responses, we found that the participants did not face any difficulty in understanding the tasks as well as interacting with the VBaT system. Also, the participants reported that they found the VR-based tasks interesting. When asked about the possibilities of their future participation with the VBaT system, all of them expressed their interest in participating again. Also, all of them were very positive about the usefulness of exercising with such a system. Thus, this finding shows that the VBaT system has a potential to be accepted by the target group of participants.

B. Effects of the VBaT System on Participant's Performance

We recorded various performance measures, like performance score, task completion time, and number of tasks completed in each difficulty level while the participants were interacting with the VBaT system. During the experiment, aid

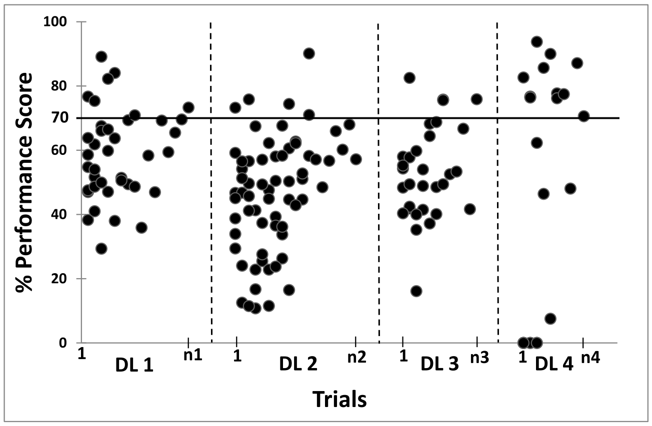


Fig. 6. Participants' %performance score in all trials for each difficulty level.

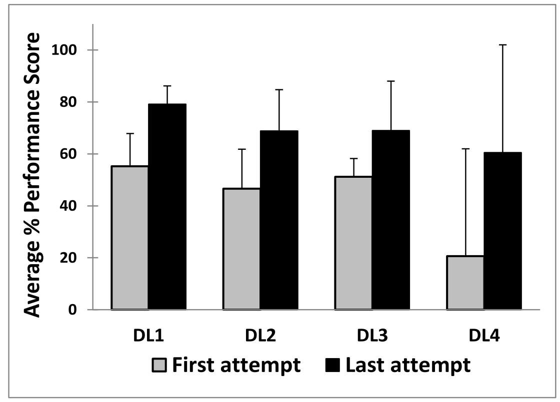


Fig. 7. Average performance scores of participants in their First and Last attempts for each difficulty level.

TABLE III
HIGHEST DIFFICULTY LEVEL TASK PLAYED BY THE PARTICIPANTS

Participant	S1	S2	S3	S4	S5	S6	S7
Difficulty Level	DL2	DL2	DL4	DL3	DL4	DL4	DL4

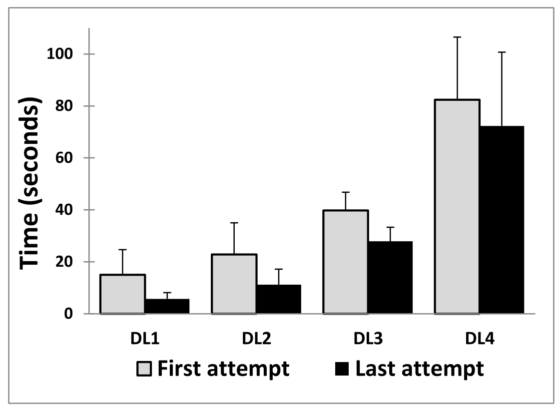


Fig. 8. Average interaction time of the participants in their First and Last attempts for each difficulty level.

in the form of therapist's support for preventing the participant from falling (as and when required) was allowed. Most of the participants, including S1 and S4, needed therapist's assistance to step on the Balance Board. Additionally, participants S1 and S4 took therapist's assistance while shifting their weight towards their affected side during the first few initial tasks offered by the VBaT. As the session progressed, they could complete the tasks independently without any external assistance.

1) Effects of the VBaT System on Participants' Performance Score (%): Fig. 6 shows the % performance scores achieved by the participants in all of their attempts for tasks of each difficulty level. The participants achieved an overall average performance score of 51.52%. Furthermore, when looking at the distribution, number of tasks offered by the VBaT during the 20 min. exercise duration was higher for DL1 and DL2 as compared to that for DL3 and DL4.This was because, the participants needed more number of trials to achieve 'Adequate' performance for DL1 and DL2 possibly due to their poor balance. Again, the number of tasks offered to the participants in DL4 was much less compared to that in the other difficulty levels (Fig. 6). Table III indicates that all the participants (except S3, S5-S7) did not reach DL4. This was because some of the participants took more time for practicing with more trials of DL1 and DL2 before reaching to tasks of DL3 and DL4.

Fig. 7 shows the comparative analysis of average performance score (%) for the First and Last attempts in tasks of each difficulty level. The participants showed an improvement of $\Delta\% = 59.72\%$ in overall average performance score from First to Last attempts. Though the participants could not achieve 'Adequate' performance score, on an average, in their First as well as their Last attempts, except in DL1 (easiest level), yet we see an improving trend in their performance score from First to Last attempts in tasks of all difficulty levels. Again, we see greater % performance score in the First attempt of DL3 compared to that of DL2.A possible reason might be that the participants were offered more practice during DL1 and DL2 tasks by the VBaT before progressing to DL3 tasks which were also challenging to them. However, tasks ofDL4 were the most challenging to the participants causing least performance score on the First attempt that improved with practice during the Last attempt. In short, the VBaT system contributed to the improvement in performance score of the participants possibly due to practice effect with increased exposure to more number of task trials. A dependent sample Wilcoxon signed-rank test was carried out on the average performance (%) of the participants and the result showed a significant improvement (p-value < 0.05) in performance from the First to the Last attempts.

2) Effects of the VBaT System on Average Interaction Time: Fig. 8 shows the average interaction time of the participants during their First and Last attempts in tasks of each difficulty level. Here, we see an improvement in terms of lesser interaction time in their Last attempt as compared to their First attempt. The magnitude of improvement reduced with tasks of increased difficulty, possibly implying the necessity of increased exposure (i.e., more practice). A dependent sample Wilcoxon signed-rank test carried out on average interaction time of the participants for the First and Last attempts in tasks of all the difficulty levels showed a significant improvement (p-value < 0.05).

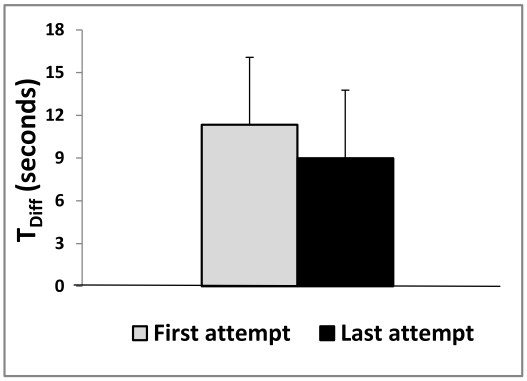


Fig. 9. Average T_{Diff} on First and Last attempts for DL4 tasks.

To maintain appropriate biped balance, one needs to use both the limbs effectively to shift one's body weight in a controlled manner while performing the biped task. Since tasks of DL4 were designed to leverage participant's ability to use both the limbs effectively, we carried out a comparative analysis of the difference in time taken (T_{Diff}) between $Template_{Left}$ and $Template_{Right}$ for the participants. Reduced T_{Diff} implies improved usage of both limbs for the task. To understand the effects of practice with the VBaT on T_{Diff}, we analyzed our data to find the variation in T_{Diff} from First to Last attempts (Fig. 9). Results indicate an improvement of 20.76% in terms of reduction in T_{Diff} from the First to the Last attempts. Thus we can say that the participants (though exposed to lesser number of tasks of DL4) had shown some improvement in the average % performance score along with reduced T_{Diff} from the First to Last attempts.

V. Conclusion

In our present study, we designed an adaptive VBaT system which used VR-based user interface augmented with Wii BB and Heel Lift Detection module for balance training in an individualized manner. The main contribution of our present work is the design of the VBaT system that can adaptively offer practice to stroke patients for balance-related tasks. A usability study was carried out with 7 stroke survivors. The idea was to understand whether the VBaT system can have effects on the balance and can contribute to the improvement in performance through practice. The adaptive VBaT system offered tasks of different difficulty levels to the participants based on their performance. Results indicate that the VBaT offered the participants with a large number of tasks in lower difficulty levels that were needed for their practice before achieving 'Adequate' performance and move to the tasks of higher difficulty levels. The VBaT system also helped the participants to decrease their average interaction time (by varying amounts) with repetitive practice which implies improvement in the speed of task execution.

One's performance measure in VR-based tasks offered by the VBaT system depended on different aspects of balance related to weight shifting, e.g., quality of CoP trajectory, ability to hold shifted weight while using ankle strategy, is novel as compared to the existing off-the-shelf games [6], [11], [21]–[23]. In fact, most of the existing off-the-shelf tasks are designed from a gaming perspective aimed towards entertainment instead of rehabilitation. Also, the rule engine used in the VBaT ensures that users can repeatedly practice specific movements in a variety of environments and in a controlled manner to achieve adequate performance and be prepared for interacting with tasks of greater challenge, a feature not available with off-the-shelf games.

Though the results of the preliminary usability study indicate that the VBaT system has potential to contribute to improved balance in stroke survivors, an essential component in daily living, our study had some limitations, e.g., limited sample size, semi-structured post-study survey and limited duration of exposure to the VBaT. However, this being a proof-of-concept study, we wanted to understand whether an adaptive VBaT system has a potential to improve balance in stroke survivors. Nevertheless, these findings cannot be generalized due to limited sample size. Thus, a more in-depth longitudinal study incorporating larger participant pool is required before such a platform can be deployed in clinical settings. Also, in future, we plan to design more structured post-study survey. Again questions on the transferability of the balance capability from the simulated VR-based environment to real-life daily living for the participants remain to be addressed in future. In addition, questions on the optimum duration of exposure of the participants to the VBaT system also remain.

In future, we plan to have a randomized and controlled study with a larger cohort of stroke-surviving participants for a longer duration. Additionally, we plan to increase our database of VR-based tasks. Since the VBaT system is easy to implement in a home-based setup, we also plan to have a home-based longitudinal study in future.

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