The Use of Virtual Reality in Stable Sitting Trunk Rehabilitation for Stroke Patients: A Pilot Study

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ABSTRACT

INTRODUCTION: Virtual reality (VR) holds promise for stroke rehabilitation. However, many existing VR systems require users to stand while playing, posing a potential falling risk for stroke patients. This study investigated the effects of a custom-developed VR system that focuses on trunk rehabilitation in a stable sitting position on muscle activities, postural control, and physiological cost compared to conventional trunk exercises in stroke patients. MATERIALS AND METHODS: A cross-sectional observational pilot study was conducted involving 12 paretic stroke subjects performing four exercises: two Conventional Trunk Exercises (CTE) and two VR-based Trunk Exercises (VRTE) using customized Tilt-Maze (self-paced) or Catch-Mole (game-paced) games. Muscle activity was measured using electromyography (EMG). Postural control data in the Anterior-Posterior (AP) and Medio-Lateral (ML) axes was recorded using a force plate, while the physiological cost was measured via a heart rate sensor during the exercises. RESULTS: The results indicated low muscle activity and light-intensity cardiovascular responses in all CTE and VRTE exercises. Game-paced VRTE recorded slightly higher Center of Pressure (CoP) velocity in the AP and ML axes versus CTE (AP: 4.40±1.80 vs. 4.02±1.20 cm/s; ML: 6.40±2.54 vs. 5.42±2.21 cm/s). In contrast, the self-paced VRTE showed an insignificant impact on postural control than both CTE and game-paced VRTE. CONCLUSION: The game-paced VRTE induced comparable effects on muscular activation, postural control, and physiological cost to that of CTE in stroke patients. The findings suggest the stable-sitting VR system as a supplementary approach to the existing trunk rehabilitation protocols for stroke patients.

INTRODUCTION

Balance impairment is a common clinical consequence of stroke, with estimates indicating that up to 80% of stroke survivors experience certain degree of balance dysfunction.1 The deterioration of balance ability will significantly compromise the activities of daily living (ADL), induces greater fatigue, and increases the risk of falling for these individuals.2,3 Balance issues in stroke survivors also substantially contribute to healthcare costs.10-11 However, trunk rehabilitation of stroke patients is strenuous as the monotonous nature of conventional therapy could inadvertently lead to patient attrition in healthcare costs.4

Keywords
Virtual reality, sitting position, postural control, muscle activity, stroke rehabilitation.

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Addressing this challenge, Virtual Reality (VR) emerges as a promising alternative to enhance patient engagement and training intensity. Commercialized VR gaming systems, like Nintendo Wii™ Balance Board, positively impacted balance function, range of motion, and ADLs in stroke rehabilitation. Recent observational studies have also revealed that VR can effectively challenge stability limits but results in low activation of balance-related muscles. The therapeutic applicability of VR solutions for balance rehabilitation is hindered by the absence of reliable calibration for different impairment levels, especially for patients with difficulty standing or maintaining balance. This concern is especially pertinent for stroke survivors, as studies have identified distinctive challenges in standing positions, including exaggerated postural sway and an increased risk of falling.

In addition, findings from a recent review suggest VR-based trunk exercises can improve trunk functions in both subacute and chronic stroke patients. However, these VR-based exercises often overlook the crucial dynamic and coordination aspects of trunk movement. The studies apply a range of trunk training strategies, such as simulated driving or canoeing, which fail to promote meaningful trunk movement, thereby limiting the potential of trunk rehabilitation.

Therefore, there is a demand for a VR solution tailored to trunk rehabilitation in a seated posture, specifically designed for stroke survivors with standing disabilities. To the best of knowledge, there are no studies focusing on the effects of VR in stable-sitting trunk rehabilitation currently. Consequently, this study aimed to bridge this research gap by investigating the impact of a custom-developed stable sitting VR system on muscular activation, postural control, and physiological cost in stroke survivors compared to conventional therapy. We hypothesized that the VR-based trunk exercises (VRTE) would demonstrate comparable outcomes to the conventional trunk exercises (CTE).

METHODS
Participants
This within-participant, repeated measures cross-sectional pilot study involved 12 stroke patients (9 males and 3 females) undergoing standard rehabilitation. The pilot sample size was determined based on the recommendation by Julious. The participants were recruited voluntarily from the rehabilitation unit of Advanced Medical & Dental Institute (AMDI), Universiti Sains Malaysia (USM), based on the following inclusion criteria: (1) age 18 and above; (2) experiencing paretic status from a single stroke; and (3) capable of maintaining a stable sitting position. In addition, those who have the following criteria were excluded from the study: (1) suffering from comorbidities that could potentially interfere with the experiment; (2) epilepsy within recent years; or (3) having an implanted pacemaker.

The study was approved by the Human Research Ethics Committee of USM (JEPeM) (JEPeM Code: USM/JEPeM/22120824). The Medical Device Authority (MDA), Ministry of Health Malaysia, had also granted an exemption from registration of medical devices for the custom-developed stable sitting VR system in this study under protocol number FS-GMD-20230308-4. All participants provided informed consent.

Experimental Setup

Figure 1 displays the experimental setup, featuring a custom-developed NEAR3 Force Plate (USM, Penang, Malaysia), a game-operating desktop (PC #1), and another desktop (PC #2) for continuous data recording. The force plate was positioned approximately 1 m from a monitor displaying the game interface. The force plate functions both as a controller input for participants to engage with the game via trunk movements and as a tool for measuring ground reaction forces and the Center of Pressure (CoP) during various activities.

Figure 1: The experimental setup shows a stroke participant sitting on the NEAR3 force plate facing the monitor display.
Figure 2 showcases the connection between real-world trunk movements and their virtual representation within the VR game environment. In Figure 2A, the lateral trunk flexion performed by the participant is illustrated, while Figure 2B displays the corresponding CoP changes recorded by the force plate. The CoP is represented as a green dot; rightward flexion moves the CoP positively in the Medio-Lateral (ML) axis, leftward flexion moves it negatively; forward flexion shifts the CoP positively in the Anterior-Posterior (AP) axis, while arching backward moves it negatively. Subsequently, the acquired CoP data are utilized to map the movement of the mallet in the game interface, as depicted in Figure 2C.

**Intervention**

Prior to the experiment, the participants’ demographic and clinical data were collected to ensure the inclusion criteria were met. Electromyography (EMG) data were collected using a Shimmer3 EMG Unit (Shimmer, Dublin, Ireland). Following the SENIAM guidelines, the electrode patches were positioned bilaterally over the lumbar erector spinae, and a reference electrode was placed on spinous processes C7. Participants were then instructed to perform the Reference Voluntary Contraction (RVC) procedure to establish baseline values. To ensure maximal trunk movement and minimize compensation of other body parts during the exercise, participants were seated securely on the force plate, with their palms placed on their laps and their feet were gently supported onto the ground or a footrest. Additionally, participants were instructed to avoid touching the seat’s backrest during the exercise. The sequence of exercises was randomized. For CTE, participants performed two stable-sitting core exercises, trunk flexion-extension, and trunk sagittal inclination, with three repetitions each. Trunk flexion-extension exercise involves alternately curling and arching the trunk in frontal direction, while sagittal trunk inclination exercise involves lateral flexion and extension. For VRTE, participants engaged in two custom-developed non-immersive VR games, Catch-The-Mole and Tilt-The-Maze. As described in Table I, Tilt-The-Maze presented a self-paced VR game where players navigate a rolling ball through a maze by tilting the platform through trunk movements. In contrast, Catch-The-Mole adopted a game-paced approach, requiring players to react quickly to the appearance of moles at nine different positions and tapping them with a virtual mallet controlled via trunk movements.

Prior to VRTE, participants were subjected to calibration tasks in which they were asked to sit still for 10 seconds to map their static CoP to the game’s centre position. Subsequently, participants performed maximal frontal, backward, and lateral trunk excursions to establish the game boundaries. A practice session and a detailed explanation of the exercises were provided to reduce the learning effect during the actual assessment sessions. Both games amounted to roughly 5 minutes of gameplay time, with sufficient rest intervals between each exercise to prevent fatigue. Concurrently, the participant’s Heart Rate (HR) was measured continuously using a wrist-worn Polar Verity Sense heart rate monitor (Polar Electro, Kempele, Finland) throughout the exercise.

<table>
<thead>
<tr>
<th>Game</th>
<th>Tilt-The-Maze</th>
<th>Catch-The-Mole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Game description</td>
<td>Players navigate a rolling ball through a set of mazes to reach a target by tilting the maze using trunk movements</td>
<td>Players react to the appearance of moles in nine different positions by moving the hammer to hit the moles</td>
</tr>
<tr>
<td>Pace of the game</td>
<td>Self-paced. Players dictate their own pace of movement</td>
<td>Game-paced. The player must react to a target. Speed increases with player success</td>
</tr>
<tr>
<td>Type of movement required</td>
<td>Trunk movement in the AP and ML axes</td>
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**Figure 1**

A participant performing a lateral trunk flexion on the force plate. (B) The green dot represents the CoP on the force plate, shifting directionally with trunk movement. (C) Mapping of acquired CoP data to control the movement of the mallet in the VR game interface.
Outcome Measures

Muscle Activation

The mean EMG amplitude of the erector spinae muscles was recorded at a sampling rate of 1024 Hz using a Shimmer3 EMG unit. The erector spinae muscle is selected as the targeted muscle group for investigation due to its importance to trunk control and movement. Subsequently, a 20 Hz fourth-order high-pass Butterworth filter was applied to process the raw EMG signal, followed by a low-pass cut-off of 511 Hz. Line noises were then removed using a multi-taper estimate of sinusoidal components. Then, the signal was rectified by taking the absolute value of the filtered signal. Finally, a fourth-order, zero-phase-lag low-pass Butterworth filter with a cut-off frequency of 10 Hz was applied to obtain a smoothed linear envelope. The maximum value from the three RVC trials was selected as the 100% RVC value for EMG normalization.

Postural Control

CoP data in the AP and ML axes were recorded using the custom-developed force plate at sampling rate of 80Hz. Given that this study exclusively focused on trunk movements executed in a stable sitting position, CoP movements were assessed as a surrogate measure to evaluate postural control changes, including the speed and range of trunk movement during the stable sitting trunk exercises. The range of CoP excursion in the AP and ML axes (CoP Range_AP, CoP Range_ML) indicates the maximum range of trunk motion during the exercise, and the velocity of CoP displacement (CoP Velocity_AP, CoP Velocity_ML) reflects the velocity of trunk movement. The CoP range and velocity were derived based on the equations outlined in a previous study.

Physiological Cost

A wrist-worn Polar heart rate monitor was used to record participants’ HR. The raw data is collected using the Polar software development kit (SDK). The data was then computed as a percentage of the predicted maximum HR (%HRmax=220 - age), corresponding to the physiological expenditure during the exercises.

Statistical Analysis

Statistical Package for the Social Sciences (SPSS) v27.0 for Windows (SPSS, Chicago, IL) was applied to conduct statistical analyses. Boxplots were first used to identify any outliers in the data. Next, the normality of the data was assessed using the Shapiro-Wilk test. A one-way repeated measures Analysis of Variance (ANOVA) was performed for normally distributed data. Besides, the sphericity assumption was evaluated using Mauchly’s test of sphericity, and violations of this assumption were adjusted using the Greenhouse-Geisser correction. Partial eta-squared ($\eta^2$) was calculated to measure the effect size for each main effect and interaction. Additionally, post-hoc pairwise comparisons were conducted using Bonferroni corrections to examine specific differences between different exercises. The statistical significance level was set at $\alpha=0.05$.

RESULTS

Demographic and Clinical Characteristics of Participants

All stroke patients successfully completed both CTE and VRTE sessions without any adverse effects. Table II presents the demographic and clinical characteristics of the participants. This study included 12 stroke patients with a mean age of 46 years old. Table III demonstrates the descriptive statistics and ANOVA results for EMG, postural control, and physiological cost. For conventional exercises, trunk flexion-extension exercise does not involve motion in ML axis; while trunk sagittal inclination exercise does not involve motion AP axis. Therefore, data points for these cases are represented with a dash (“-”) to denote the absence of values. ANOVA results in Table III revealed significant differences in CoP Range_ML, CoP Velocity_ML, and CoP Velocity_AP between exercises. To interpret these observed differences, post-hoc tests with Bonferroni corrections were conducted. The results are visually presented in Figure 3, with asterisk (*) brackets highlighting statistically significant differences.
differences in CoP Range

Table III displays ANOVA results revealing significant CoP Parameters in the ML Axis Postural Control movements during the exercises.

such as gameplay strategies adopted and compensatory strategies for the accuracy. Accordingly, the difference in mean EMG amplitude in both the left (F[2.09, 20.92] =1.144, p=0.346, partial η²=0.098) and right erector spinae muscle (F[1.60, 16.00]=1.090, p=0.346, partial η²=0.098) were statistically insignificant. This finding suggests that the CTE and VRTE engage the erector spinae muscle at a similar level, potentially influenced by factors such as gameplay strategies adopted and compensatory movements during the exercises.

Muscle Activation

Referring to Table III, the mean EMG amplitude for the erector spinae muscle ranged from 23.08±15.32 to 33.67±27.68%RVC. The muscle activation levels for all CTE and VRTE exercises were relatively low, and the high standard deviations observed indicates substantial variability. Due to the sphericity assumption violation for both the EMG of left and right erector spinae, the Greenhouse-Geisser correction was applied to compensate for the accuracy. Accordingly, the difference in mean EMG amplitude in both the left (F[2.09, 20.92] =1.144, p=0.346, partial η²=0.098) and right erector spinae muscle (F[1.60, 16.00]=1.090, p=0.346, partial η²=0.098) were statistically insignificant. This finding suggests that the CTE and VRTE engage the erector spinae at a similar level, potentially influenced by factors such as gameplay strategies adopted and compensatory movements during the exercises.

Postural Control

CoP Parameters in the ML Axis

Table III displays ANOVA results revealing significant differences in CoP RangeML (F[2, 22]=14.050, p<0.001, partial η²=0.561) and CoP VelocityML (F[2, 22]=42.351, p<0.001, partial η²=0.794). Post-hoc comparisons illustrated in Figure 3A indicated a lower range of CoP during the self-paced Tilt-The-Maze game (11.50±4.18 cm) than in the CTE (17.10±5.50 cm; p=0.003) and game-paced Catch-The-Mole (17.51±4.87 cm; p=0.002). Figure 3B highlights that the Catch-The-Mole game achieved a higher CoP VelocityML (6.40±2.54 cm/s) than the Tilt-The-Maze game (2.32±0.99 cm/s; p<0.001) and CTE (5.42±2.21 cm/s), although the result was insignificant. Regardless, the Tilt-The-Maze game showed significantly lower CoP VelocityML than all other exercises (all pairwise comparisons p<0.05). Notably, the effect sizes for the CoP velocity and range in the ML axis were particularly compelling, with η² values of 0.794 and 0.561, respectively.

CoP Parameters in the AP axis

Additionally, Table III also shows that the changes in CoP RangeAP were statistically insignificant (F[2, 22]=0.473, p=0.630, partial η²=0.041), but the CoP VelocityAP was significantly different (F[2, 22]=17.950, p<0.05, partial η² =0.620). Figure 3C shows that the Tilt-The-Maze game promoted significantly lower CoP VelocityAP (2.04±0.71 cm/s) than both CTE (4.02±1.20; p<0.001) and Catch-The-Mole game (4.40±1.80; p<0.001).

Physiological Cost

Table III also shows that there is insignificant changes in the HR between different exercises (F[3, 30]=1.451, p=0.248, partial η²=0.127), indicating consistent exercise intensity across all exercises. The participants recorded an

Table II: Demographic and clinical characteristics of the participants.

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<td>Age (year), mean (SD)</td>
<td>46.33 (9.74)</td>
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<td>Gender, n females (%)</td>
<td>3 (25%)</td>
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<td>Time since stroke (months), mean (SD)</td>
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<td>Weight (kg), mean (SD)</td>
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Table III: Descriptive outcome measures and ANOVA results.

| Muscle Activation                          |  |  |
|--------------------------------------------|--------------------------|
| Conventional trunk exercise                | Virtual reality trunk exercise | ANOVA |
| Trunk flexion-extension                   | Tilt-The-Maze             | Catch-The-Mole     | F-Stat | p-value | Effect size (η²) |
| Sagittal trunk inclination                 |                           |                   |        |         |                |
| CoP velocity ML (cm/s)                    | 11.50 (4.18)             | 17.51 (4.87)      | 42.351 (df = [2,22]) | p < 0.001 | 0.794 |
| CoP range ML (cm)                         | 17.10 (5.50)             | 14.050 (df = [2,22]) | p < 0.05 | 0.561 |
| CoP velocity AP (cm/s)                    | 2.04 (0.71)              | 4.02 (1.20)       | 42.351 (df = [2,22]) | p < 0.001 | 0.794 |
| CoP range AP (cm)                         | 14.09 (3.88)             | 13.52 (3.98)      | 4.02 (1.20)       | p < 0.05 | 0.561 |
| Physiological cost                        |                           |                   | 42.351 (df = [2,22]) | p < 0.001 | 0.794 |
| Heart rate (%HRmax)                       | 45.71 (8.47)             | 47.22 (9.15)      | 47.39 (10.14)     | 47.82 (9.47) | 0.248 |

Note: Values are presented as means, with standard deviations (SD) in brackets; For conventional exercises that do not invo

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Postural Control

CoP Parameters in the ML Axis

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Additionally, Table III also shows that the changes in CoP RangeAP were statistically insignificant (F[2, 22]=0.473, p=0.630, partial η²=0.041), but the CoP VelocityAP was significantly different (F[2, 22]=17.950, p<0.05, partial η² =0.620). Figure 3C shows that the Tilt-The-Maze game promoted significantly lower CoP VelocityAP (2.04±0.71 cm/s) than both CTE (4.02±1.20; p<0.001) and Catch-The-Mole game (4.40±1.80; p<0.001).

Physiological Cost

Table III also shows that there is insignificant changes in the HR between different exercises (F[3, 30]=1.451, p=0.248, partial η²=0.127), indicating consistent exercise intensity across all exercises. The participants recorded an
HRmax range of 45.71–47.82%, suggesting a uniform low-intensity cardiovascular response during CTE and VRTE exercises. From a clinical perspective, this finding implies that introducing VR-based exercises does not increase cardiovascular demand, therefore it could be a safe adjunct to conventional rehabilitation practices.

**DISCUSSION**

**Muscle Activation**

The EMG values in this study were measured in the form of %RVC due to the inability of stroke patients to perform Maximal Voluntary Isometric Contraction (MVIC) tasks. Muscle activity levels greater than 50% of MVIC were categorized as challenging for healthy individuals. The findings indicate that CTE and VRTE resulted in relatively low muscle activity (23.08±15.32 to 33.67±27.6), with insignificant differences in mean EMG amplitude among exercises. This suggests that the level of muscle activation in the erector spinae muscles was comparable between the CTE and VRTE. The mean EMG amplitude was hypothesized to be higher in VRTE since previous studies also observed that muscle activities tend to be more intense when the participants were engaged. However, the mean EMG amplitude between CTE and VRTE was insignificantly different, possibly due to participants adopting strategies to gain higher scores, such as maintaining a central position in the game to react faster to the targets. This strategic adaptation could compromise trunk muscle excursions and reduce overall muscle activation. Additionally, participants may engage in undesirable compensatory movements during VR-based exercises, causing the intended muscles to be less active.

The notably high standard deviations in the EMG amplitude for both erector spinae muscles (14.02–27.68% RVC) may be ascribed to the heterogeneity of the recruited participants, as the severity and extent of impairments vary widely among stroke patients. These findings are aligned with earlier research suggesting fewer synergies in neuropathological conditions linked to stroke severity. Moreover, Transcranial Magnetic Stimulation (TMS) findings suggest that cortical stroke lesions lead to impaired contralesional trunk muscle activation. These factors could account for the high variability observed in this study.

**Postural Control**

As shown in Figure 2, the Tilt-The-Maze game exhibited a significantly lower CoP Range_{ML} and CoP Velocity in both AP and ML axes than other exercises (all pairwise<0.05). In addition, the effect sizes for the CoP velocity and range in the ML axis were high, with \( \eta^2 \) values of 0.794 and 0.561, respectively. These effect sizes highlight the strong influence of the type of exercise on postural control metrics in the ML axis, suggesting that Tilt-The-Maze leads to a reduced range and speed of trunk movement compared to other exercises.

The observed findings can be attributed to the game’s self-paced design and goal. This game entails tilting the maze using CoP adjustments to guide a rolling ball towards the target. Participants only need to perform slight
trunk movements to tilt the maze, and the ball will roll according to the gravity mechanism of the game. The self-paced nature of the game also allows participants to control their movement and avoid making large trunk movements or quick responses to achieve the goal. Conversely, the Catch-The-Mole game yielded significantly higher CoP Velocity in both AP and ML axes than Tilt-The-Maze, as well as higher than CTE, albeit insignificantly. This indicates that the Catch-The-Mole game involves faster trunk movements, mainly when reacting to the game targets.

This game-paced approach offers potential benefits in training trunk movement speed and responsiveness in stroke patients. For example, the elevated velocity during the game may lead to increased repetition, aligning with previous studies showcasing VR’s immersive capability to enhance patients’ motivation, resulting in higher repetition than conventional exercises. Higher repetition enhances the intensity of rehabilitation, contributing to sensorimotor pathway recovery and improving clinical outcomes in stroke patients.

The observed changes in postural responses among participants engaged in VRTE could be attributed to the immersive nature of VR environments. The VR system in this study utilized multisensory feedback mechanisms, such as the representation of the patient’s trunk movements through a game avatar, the display of scores achieved, and auditory and visual cues signalling goal accomplishment. The feedback mechanisms might boost patient engagement and participation in trunk exercises. This encouragement to exert greater effort is a likely key factor for the accelerated and more extensive trunk movements recorded during the Catch-The-Mole game.

**Physiological Cost**

HR is an objective and reliable measure of physical activity energy expenditure. In this study, the mean HR between CTE and VRTE exercises was insignificantly different. Participants’ HR remained around 45%, indicating a relatively low-intensity cardiovascular response compared to the recommended range (55–64%). The observed results indicate a slightly lower intensity compared to previous studies, which demonstrated moderate activity levels through custom-made VR games in chronic stroke patients. It is important to note that the present research solely focused on games in stable sitting positions, which may result in lower HR responses than standing positions.

Despite anticipating higher HR due to the rapid trunk movements in the fast-paced Catch-The-Mole game, the brief exercise duration could have depreciated the overall HR. However, it is worth mentioning that the total training volume is essential in health improvement. A recent study revealed that low-intensity, high-duration exercises enhanced motor recovery in stroke patients. Hence, emphasizing lower-intensity, longer-duration training using the VR system could be a promising alternative rehabilitation strategy for stroke patients, offering effective outcomes while minimizing injury risks.

**Implications for Rehabilitation**

This pilot study demonstrates the potential of VR systems in improving trunk rehabilitation for stroke patients, especially when performed in a stable sitting position. Findings indicate that game-paced VRTE can produce comparable effects on muscle activation, postural control, and physiological cost to conventional exercises. This suggests the potential of incorporating VR-based exercises into existing rehabilitation programs.

Stroke patients typically recover the ability to sit before they can stand during the early phases of rehabilitation. Therefore, the use VR-based trunk rehabilitation in a seated position early on could offer a safer and more accessible entry point for the patients. In addition, a significant concern for stroke survivors with severe impairments is the increased risk of falls. By enabling exercises in a stable sitting position through the use of our custom-developed VR system, the risk of falls could be mitigated. Furthermore, sustaining patient engagement and motivation is a major challenge in rehabilitation. The immersive nature of VR rehabilitation could enhance patient adherence to treatment plans. By integrating VR technology into existing protocols, physiotherapists may encourage more consistent patient participation in
rehabilitation, potentially leading to better outcomes due to the higher consistency and intensity of therapy sessions.\textsuperscript{41,42} 

**LIMITATIONS**

This study has several limitations that warrant discussion. Firstly, the relatively small sample size in this study may limit the generalizability of the results. A more extensive longitudinal study could provide an in-depth understanding of the long-term efficacy of VR in stroke patients. Secondly, this study was conducted during the coronavirus-2019 (COVID-19) pandemic. The reduced physical contact and interaction time might have limited the outcomes observed. Finally, trunk activation assessment using EMG was restricted to erector spinae muscles. Future studies should offer a holistic view of trunk muscle activation, including other trunk muscles, such as the external oblique, rectus abdominis, and multifidi. These limitations suggest that the results should be interpreted with caution, and further research is needed to confirm these findings in a larger, more diverse population.

**CONCLUSION**

The proposed trunk rehabilitation in stable sitting position using the custom-developed VR system demonstrated comparable postural control, muscular activation, and physiological cost to conventional trunk rehabilitation exercises. It was found that game-paced VRTE can promote a higher velocity in both AP and ML axes versus CTE (AP: 4.40±1.80 vs. 4.02±1.20 cm/s; ML: 6.40±2.54 vs. 5.42±2.21 cm/s). In contrast, the impact of self-paced VRTE on postural control is less significant than both CTE and game-paced VRTE. The findings suggest that the stable-seated VR system could supplement the existing treatments, providing additional practice time or repetitions for stroke patients with varying levels of disability, particularly when standing posture might pose a risk.

**FUNDING**

This work was supported by CREST (T06C2-19) and Universiti Sains Malaysia (304/PMEKANIK/6050419C121).

**CONFLICT OF INTEREST**

No competing financial interests exist.

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