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A Novel Trunk Rehabilitation Robot Based Evaluation of Seated Balance Under Varying Seat Surface and Visual Conditions

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ABSTRACT Physical therapy involving the use of varying types of seating surface and visual input is recommended for individuals suffering from trunk instability. Some robots have been developed to assist in such therapy protocols, but none of them fully constrains the user's lower extremities to move with the seat, which is required to fully transfer the task of maintaining balance to the trunk. To fulfill this requirement, we have developed a robot that can provide a static, unstable or forced perturbation seating surface. The instability of seating surface is provided by having the robot follow movements in the user's center of pressure (COP) and forced perturbations are provided by moving the surface according to an operator's commands irrespective of the COP position. The system is also capable of providing visual feedback of the user's COP. This paper presents a study conducted using this novel robot aimed at evaluating the effect of the different seat modes on the balance of healthy subjects under different visual conditions (blindfold, eyes open and visual feedback). Various COP and trunk movement parameters were observed and the results indicate that the system can elicit similar responses in the unstable mode as the conventional devices, showing that it may be used as a controllable alternative to such devices for the training and objective evaluation of stroke survivors. The results under perturbation conditions showed deviations from the generally held notions about the use of visual feedback. Thus, revealing the need for further studies on the implications of using visual feedback under perturbation conditions. The observation of effects similar to conventional systems that may be beneficial for stroke survivors and the system's ability to help assess recovery progress show that the system holds promise for use as a trunk training and objective performance evaluation tool for stroke survivors.

INDEX TERMS Center of pressure (COP), rehabilitation robotics, seated balance, trunk rehabilitation, visual feedback.

I. INTRODUCTION

The human core consists of the abdominals in the front, paraspinals and gluteals in the back, the diaphragm on the top, and the pelvic floor and hip girdle musculature at the bottom [1]. These muscles work together to stabilize the spine, pelvis, and kinetic chain during movements of the body [2]. As a consequence of diseases such as stroke, the ability of this muscle complex to maintain balance can become impaired. This can have a strong negative impact on the ability of the patient to safely perform independent gait and the activities of daily living [3]–[10]. Due to these reasons, for stroke patients, initial therapy to develop gross trunk control is recommended in order to pave the way for recovery of other functions such as gait [11].

Similar to postural control in stance, seated postural control can be divided into three categories: static postural control, dynamic postural control and reactive postural control [12].

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During upright standing, the lower extremities, especially the ankles, play a vital role in maintaining a stable posture [13], whereas during sitting with the feet not supported on a fixed surface, the bulk of the work needed for posture maintenance is done by the trunk muscles [12]. Therefore, although the same underlying methodologies can be applied to both standing and sitting, the outcomes may be different due to the different muscle groups involved.

The general protocol for sitting posture rehabilitation [12] starts with the patient sitting on a stable firm surface with a conventional posture (hips and knees flexed at approximately 90 degrees and feet set hip-width apart) performing a rehabilitation activity. Once they have sufficiently mastered the activity, the difficulty level is increased. Difficulty can be set by altering/introducing several factors such as modifying the base of support (hands on thighs or across the chest, feet on ground or suspended), modifying the support surface (stable or unstable surface), and modification of sensory input (eyes open or closed). For patients with sufficient static and dynamic balance abilities, the challenge to reactive balance can be introduced by forcefully perturbing their balance. The patients can be assisted by the provision of augmented feedback to improve focus and to provide guidance in performing the balance tasks. In this regard, visual feedback of COP has been shown to have a beneficial effect on the sitting balance of chronic stroke survivors [14].

The performance of balance rehabilitation protocols may require extensive involvement of one or more therapists. This can add to therapists' workload and fatigue. Similar to other aspects of sensorimotor rehabilitation [15], sitting balance rehabilitation can benefit from the involvement of robotic systems that can be easily tuned to generate different exercise scenarios and provide augmented feedback. Furthermore, due to presence of integrated instrumentation, such systems can also provide continuous monitoring and evaluation of balance training exercises using balance indicators such as the position of center of pressure (COP). The incorporation of such systems in trunk rehabilitation cannot only reduce the therapist's workload; it may also reduce the patient's fatigue due to the integrated nature of training and evaluation afforded by them. Keeping in view these benefits, a number of robotic trunk rehabilitation systems have been developed recently [16], [17].

Notable among these is the Hunova developed by Movendo Inc. [17], which features instrumented seat and footrest that can determine the position of the user's COP and move according to its movements. The system has built-in stiffness that continually pushes the surfaces back to their neutral positions. This system's layout inhibits the amount of support and sensory feedback that the user can get from their lower extremities (LE) by making the footrest movable. However, the axes of rotation of the footrest are far removed from those of the seat. This means even when the seat and footrest are both free to move there will always be some flexion of the LE joints which will serve to provide proprioceptive feedback about the movements. Therefore, using this arrangement does not eliminate the proprioceptive feedback provided by the LE during postural control exercises.

In order to eliminate fully the proprioceptive feedback from the LE so that the sitting postural control duties have to be performed by the trunk, the LE must be constrained to move with the pelvis so that there is no movement of the joints as the pelvis is rotated [18]. Keeping this in view, we have recently developed a novel trunk rehabilitation robot that has the ability to generate seat motion in multiple degrees of freedom and has a footrest structure that is connected rigidly to the seat so that the feet have no motion relative to the pelvis [19], [20]. The system is also capable of generating visual biofeedback based on the position of the user's COP.

A review of previous studies on the use of COP based visual biofeedback during trunk rehabilitation on stable and unstable surfaces revealed that the inclusion of visual biofeedback improves balance related outcomes [14], [21]–[26]. However, these studies have mostly used stable or uncontrolled unstable platforms. As per our knowledge, there are no studies on the effect of visual biofeedback on the balance of a person sitting, with the LE constrained to have zero motion relative to the pelvis, on a robotically generated unstable seat with a stiffness field designed to bring the seat back to neutral position.

A powered seat surface can also be used to generate balance perturbations irrespective of the position of the user's COP. Current studies on reactive balance in sitting have used a variety of methods to generate perturbations. These include manually actuated platforms [27] and powered platforms with actuation along either mediolateral (ML) or anteroposterior (AP) direction [28] and have not used the posture that a person adopts while sitting on a normal seat. Until now, a study on the effect of perturbations in the ML, AP and diagonal directions on the balance of a person sitting in a conventional posture has not been conducted. Furthermore, the effect of visual biofeedback on the reactive balance of a person sitting in these conditions has also not yet been evaluated. Our trunk rehabilitation robot allows the user to sit in normal seating posture and provides rotational perturbations to the pelvis in both ML and AP directions so it can be used to evaluate postural responses to rotational perturbations under different visual conditions. A summary comparison of the current study with studies presented in the abovementioned literature is given in Table 1.

Therefore, in the presented work, we have utilized our trunk rehabilitation robot to carry out a study to evaluate three hypotheses. First, we hypothesized that using different types of seating surface, i.e. stable seat, unstable seat and forcefully perturbed seat, and different visual conditions, i.e. eyes closed, eyes open and visual feedback, will affect the performance of a postural maintenance task. Secondly, we hypothesized that the difficulty of postural maintenance task performance will increase as the user moves from the static seat to the unstable seat and then to the forcefully perturbed seat condition. Thirdly, we hypothesized that the difficulty of postural maintenance task will decrease as the user moves

TABLE 1. Summary comparison of current study with previous works.

Ref.	Objectives	Participants and Methods	Comments
[14]	To investigate the effects of visual feedback training in sitting position on sitting balance ability and visual perception of chronic stroke patients	Chronic stroke survivors received conventional therapy and visual feedback training using an instrumented static seat. Different visual feedback scenarios were used	Static seat with visual feedback of COP
[21]	To test if and to what extent chronic stroke survivors were able to learn the center of pressure control task and transfer the learned ability to a condition without visual feedback and with varied goals	Chronic stroke survivors were seated on a stool placed on top of a force platform. Their COP was measured and mapped to the coordinates of a cursor on the screen. They had to shift their weight to move the cursor to the target	Static seat with visual feedback of COP
[22]	To investigate the effects of trunk stabilization training using visual feedback on an unstable surface to improve balance and trunk stability of individuals with chronic stroke debility.	Chronic stroke survivors received therapeutic exercise and trunk stabilization training using visual feedback while sitting on a 50 cm diameter balance disc with a sensor to measure COP attached to its cover placed on a chair with armrests and no backrest.	Uncontrolled unstable surface with visual feedback of COP
[23]	To investigate the effect of visual biofeedback on seated postural trunk control in subjects with chronic low back pain, and to investigate the relationship between the postural control parameters and clinical tests.	Subjects with chronic low back pain sat on an unstable seat with attached footrest consisting of a hemispherical surface fitted under the seat and placed on a force plate. COP parameters collected were under three experimental conditions: eyes-open, visual biofeedback, and eyes-closed.	Uncontrolled unstable seat with eyes closed, eyes open and visual feedback of COP
[24]	To analyze the evolution of the spatial postural control during the use of a virtual motor rehabilitation system	Subjects with Parkinson's disease sat on a Nintendo Wii balance board (with legs hanging freely) that measured their COP position, and performed weight transferences according to various virtual environments.	Static seat with visual feedback of COP
[25]	To describe a rehabilitation protocol for the maintenance of balance in a short-sitting position following spinal cord and head injuries by use of a center-of-pressure– controlled video game–based tool.	Adults with varying types of spinal cord injury sat on an instrumented flexible mat placed on rigid or compliant (deflated Physio Gymnic Ball or Swisdisk) surfaces to measure COP position, which was used to play different videogames.	Static and uncontrolled unstable seat with visual feedback of COP
[26]	To investigate the dose-related effect of trunk control training using Trunk Stability Rehabilitation Robot Balance Trainer in chronic stroke patients with poor sitting balance.	Chronic stroke survivors sat on a static seat system with instrumentation in the seat and footrest to measure the position of COP that is displayed on the screen and used to play different games.	Static seat with visual feedback of COP
[27]	To investigate the electromyographic patterns of the trunk muscles during balance perturbations in a sitting position.	Healthy adults sat on a manually actuated platform with legs set straight in front of them resting on a wheeled dolly and received rotational perturbations in either the frontal or sagittal planes. Trials were conducted in blindfolded and eyes open conditions.	Manually actuated perturbations. No diagonal perturbation. Long sitting posture used. No visual feedback
[28]	To describe the muscle activation pattern of sitting subjects during various perturbations and to test whether somatosensory or vestibular stimulation elicited the responses.	Healthy adults sat with their legs set straight forward on a platform that could be translated (anterior-posterior) or rotated (in the sagittal plane) by two servomotors. The kinematic and EMG data were recorded under translational and rotational perturbations	Motorized translational perturbation in AP direction and rotation in sagittal plane. Long sitting posture. No visual feedback
This Study	To evaluate the effect of different seat modes (static, unstable and perturbation) on the balance of healthy subjects under different visual conditions (blindfold, eyes open and visual feedback).	Healthy adults sit in a normal seating posture on a robotically actuated seat that generates both unstable (tracking of COP movements) and perturbation (passive seat movement) seat conditions.	Robotic seat generates static, controlled unstable and 2DOF perturbation (diagonal perturbations included) conditions. Conventional posture for sitting on a seat. Visual COP feedback.

from eyes closed to eyes open and then to visual feedback conditions.

II. MATERIALS AND METHODS

A. TRUNK REHABILITATION ROBOT

The trunk rehabilitation robot, shown in Figure 1, is composed of a chair with an instrumented seat and removable articulated back support. The instrumented seat is used to determine the position of the user's COP, which is then displayed on a screen placed in front of the user at eye level. There is a footrest structure attached to the seat that can be moved out of the way while getting on or off the apparatus. The length of the footrest support can be adjusted so that the user's thighs are always lying flat on the seat surface and the hip and knees are flexed at approximately 90 degrees. The footrest structure is designed to move the feet with the seat, which also has restraints to hold the pelvis in place, so that there is no relative motion between the feet and the

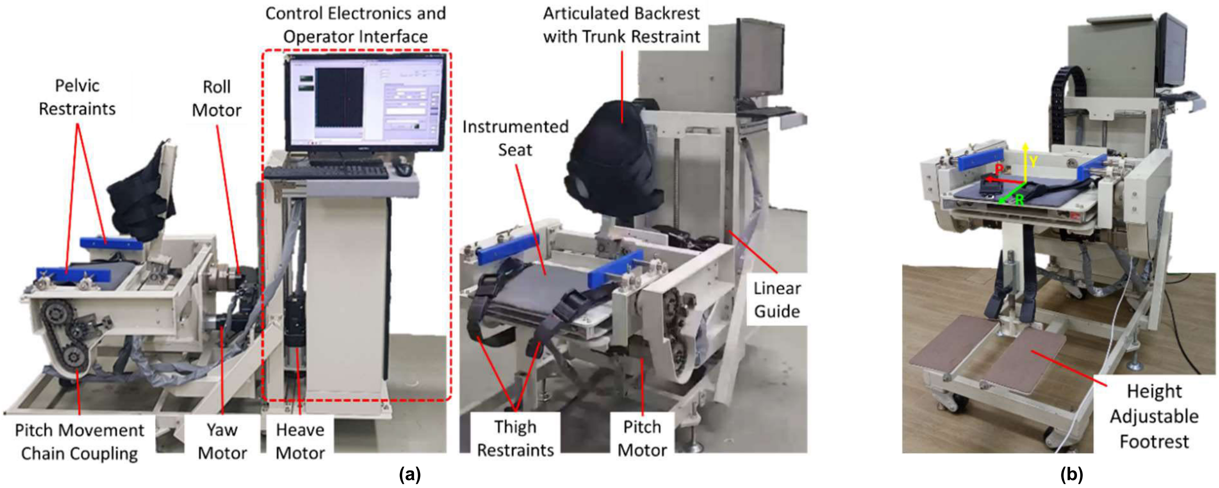


FIGURE 1. The trunk rehabilitation robot. (a) The complete robotic system and (b) the system configuration used in the presented study (notice that the trunk restraint has been removed as it is not required for healthy users) (The colored arrows show the axes of rotation for pitch (red), roll (green) and yaw (yellow) movements).

pelvis. A trunk restraint is also provided on the back support for the safety of patients who may lose their balance during system use. For healthy subjects, this support is not necessary so it has been removed in the system configuration used in the presented study (Figure 1(b)). The seat is mounted on an actuation mechanism with 4 degrees of freedom. The seat can be rotated about the horizontal axes to generate movements corresponding to the ML ($\pm 15^\circ$) and AP ($-15^\circ \sim +45^\circ$) movements of the trunk. Rotation about the vertical axis ($\pm 45^\circ$) helps with wheelchair access while translation along this axis ($0 \sim 450$mm) allows us to adjust the seat height. Thus the seat can be used in three different modes, static (seat does not move), unstable (seat moves with the movement of the COP giving the user a feeling that they are sitting on a wobble board), and perturbation (seat moves according to operator commands irrespective of the COP position to generate forced rotational movements of the user's pelvis). The unstable motion is achieved by using the admittance control methodology [19] to move the seat according to the position of the user's COP. The controller is designed to have a certain amount of stiffness so the seat always tends to return to its neutral position.

The COP is calculated using the forces gauged by four compression load cells placed one at each corner of the seat and interfaced with the PC, where a software running in the LabVIEW development environment (LabVIEW 2015, National Instruments) calculates the position of the user's COP referred to the center of the seat surface. The COP position is calculated using equations (1) and (2) where, F_1, F_2, F_3 and F_4 are the forces measured by the four load cells, and L and W are the length (along X-axis) and width (along Y-axis) of the seat surface, respectively [29]. The X_{COP} value is the COP position in the ML direction and the Y_{COP} value is the COP position in the AP direction. The calibrated COP position is used to generate the visual feedback and is communicated to the motor control software that runs the motors either according to the operator's commands or according to the admittance control scheme with stiffness that works to track the COP position [19], [20]. The system is actuated using AC servomotors (Yaskawa, Japan) with electrically actuated mechanical brakes. The system has been designed so that the rotational axes intersect at the center of the top surface of the seat. The data flow between the different system modules is shown in Figure 2.

$$X_{COP} = \frac{(F_1 + F_2 - F_3 - F_4) \times \left({}^{L}\!/_{2}\right)}{F_1 + F_2 + F_3 + F_4} \tag{1}$$

$$Y_{COP} = \frac{(F_2 + F_3 - F_1 - F_4) \times \left({}^{W}\!/_{2}\right)}{F_1 + F_2 + F_3 + F_4} \tag{2}$$

The display provided to the subject contains the visual feedback GUI shown in Figure 3(a) that shows the current position of the COP and presents a target that the user has to achieve. In this display, the current COP position is shown by the light blue colored solid square while the target is shown by the square outline that is colored red when the COP is outside the target region and turns green when the COP is inside it. In the presented study, the user is supposed to maintain a balanced upright posture. Therefore, the target represents the position of the user's COP while they sit with a balanced upright posture. The GUI is displayed on a LED monitor placed in front of the subject at eye level at a distance of 1m from them, as shown in Figure 3(b).

B. PARTICIPANTS

A total of 11 young healthy people (10 male and 1 female) took part in this study. They were aged 28.91±5.19 years, weighed 75±14.80 kg, and were 1.70±0.06 m tall. None of the participants suffered from any neurological, musculoskeletal or vestibular disorders, and did not suffer from any uncorrected vision defects that may impede their use of the visual feedback. They had no prior experience of

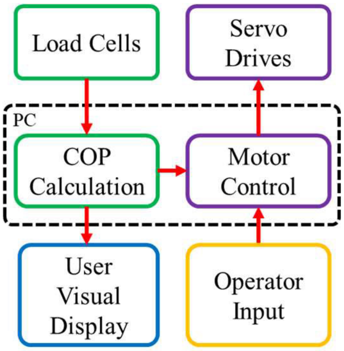
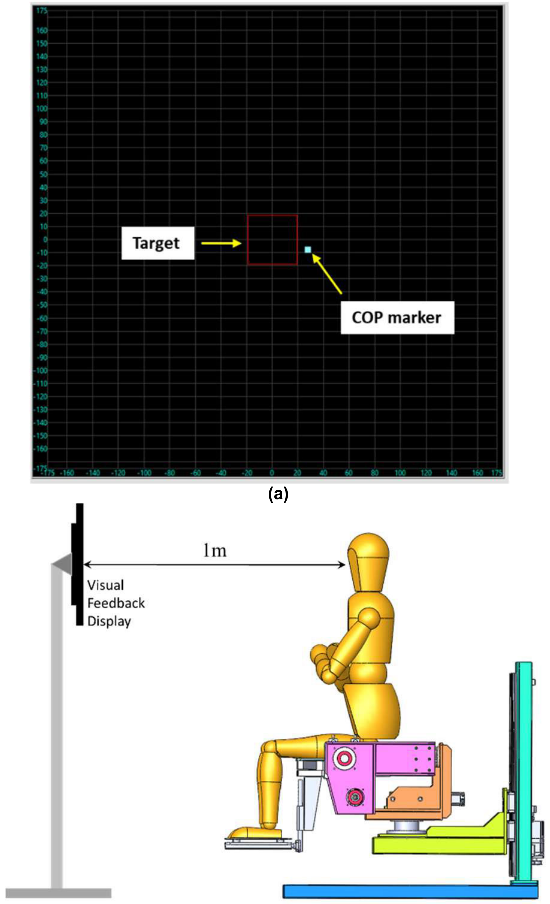


FIGURE 2. System block diagram.



(a)

(b)

FIGURE 3. (a) The graphical display used to provide visual feedback of the COP position to the user. (b) Layout Schematic of the experimental setup.

performing trunk-balancing exercises on unstable surfaces or under forced perturbation. All subjects gave their informed consent for inclusion before they participated in the study and the study was conducted in accordance with the Declaration of Helsinki

C. PROTOCOL

The participants took part in trials designed to evaluate the effect of the different seat modes on their balance under different visual conditions. Prior to the start of trials, the participants were given a detailed description of the protocol and were given a few minutes to accustom themselves to the system, the different movement modes and the visual feedback. At this point, it was also confirmed that they could see the visual display easily and clearly. Once accustomed, each participant rested for a while before starting the testing protocol. The protocol was designed so that each of the three seat modes (static, unstable and perturbation) was tested under three visual conditions (blindfold, eyes open and visual feedback). The blindfold was used to ensure complete blockage of visual input. For the eyes open trials, the subjects were asked to focus on a black circle set against a white background that appeared on the screen placed in front of them. In the trials with visual feedback, the participants were asked to keep their COP (light blue cursor described in the previous section) inside the target area. Prior to start of every trial the participant was asked to assume the exercise posture; sitting upright with a balanced posture and with the arms crossed across the chest, and the system was calibrated so that the position of their COP coincided with the target position set at the center of the screen. Considering the different seat and visual conditions, a total of nine trial conditions were used, which are:

1. SB: Static (S) seat with blindfold (B).
2. SE: Static seat (S) with eyes open (E).
3. SV: Static seat (S) with visual feedback (V).
4. UB: Unstable seat (U) with blindfold (B).
5. UE: Unstable seat (U) with eyes open (E).
6. UV: Unstable seat (U) with visual feedback (V).
7. PB: Perturbation seat (P) with blindfold (B).
8. PE: Perturbation seat (P) with eyes open (E).
9. PV: Perturbation seat (P) with visual feedback (V).

The trials were conducted in random order in two sets with each trial condition appearing once in each set in random order. In order to avoid any fatigue effects, there was a break of one minute between trials and a longer break of up to 5 minutes between sets. Furthermore, the subjects were asked to inform the researchers if they felt any tiredness or fatigue; however, none of the participants did so. Each trial lasted for a total of 55 seconds and the experimental data for a span of 40 seconds recorded after the first 10 seconds was used for analysis. In the unstable seat mode, the system stiffness was set at a low level to generate an adequately high level of difficulty for the participants [30]. For trials with forced perturbation of the seat, a total of eight perturbations, one in each of the cardinal directions (right, left, forward, backward, front right diagonal, front left diagonal, rear right diagonal, and rear left diagonal), were provided in random order. Each perturbation involved a 10-degree tilt of the seat carried out at a rate of 10 degrees/second. Once tilted, the seat was held in position for 3 seconds, and then returned to the level position, after which the next perturbation was given.

D. DATA COLLECTION AND ANALYSIS

The two dimensional position of the participant's COP obtained using the sensors built in to the seat was recorded

TABLE 2. Descriptive statistics of COP parameters.

Trial Parameter	SB	SE	SV	UB	UE	UV	PB	PE	PV
CPLD (mm)	3.96 ±3.51	4.66 ±3.92	2.10 ±1.01	31.66 ±18.41	18.34 ±10.73	13.29 ±5.61	47.22 ±13.60	43.72 ±12.75	45.02 ±10.48
CMLE (mm)	3.56 ±2.54	5.50 ±3.57	1.23 ±0.63	29.10 ±20.05	21.79 ±18.35	9.66 ±4.51	34.32 ±9.70	30.78 ±6.27	28.92 ±6.36
CAPE (mm)	12.25 ±20.51	9.73 ±9.37	2.33 ±1.40	18.24 ±13.19	12.77 ±10.78	5.96 ±2.96	30.79 ±8.14	30.79 ±11.88	20.24 ±9.23

TABLE 3. Descriptive statistics of trunk movement parameters.

Trial Parameter	SB	SE	SV	UB	UE	UV	PB	PE	PV
TTPLD (degrees)	0.48 ±0.29	0.45 ±0.25	0.49 ±0.29	2.71 ±1.01	1.80 ±0.56	2.22 ±0.87	5.92 ±1.99	5.93 ±1.97	6.40 ±1.88
TMLAR (mG)	3.70 ±0.23	3.57 ±0.21	3.62 ±0.19	5.87 ±1.17	4.61 ±0.72	4.33 ±0.65	14.84 ±3.62	13.44 ±2.52	15.03 ±3.02
TAPAR (mG)	3.00 ±0.17	2.97 ±0.25	2.93 ±0.07	4.99 ±0.95	3.83 ±0.49	3.67 ±0.58	23.40 ±3.90	22.27 ±3.46	24.58 ±4.18

during all trials. An inertial measurement unit (IMU) (MyoMOTION, Noraxon, USA) positioned at the thoracic spine was also worn by the participants to measure the trunk accelerations. The COP and IMU data recording was synchronized using a synchronizing device (MyoSYNC, Noraxon, USA). The mean values of the data obtained from the two trials under each condition were calculated and used for further analysis.

From the COP data, Planar Deviation (CPLD) (3), and the ML and AP Excursions (CMLE and CAPE) (4) and (5) were calculated. These parameters were calculated using a specially made program running in MATLAB (Mathworks, USA).

$$\mathrm{CPLD} = \sqrt{\sigma^2 COP_{ML} + \sigma^2 COP_{AP}} \tag{3}$$

$$\mathrm{CMLE} = \frac{\sum |COP_{ML}(i)|}{n} \tag{4}$$

$$\mathrm{CAPE} = \frac{\sum |COP_{AP}(i)|}{n} \tag{5}$$

The CPLD is the square root of the sum of variances of COP in both the ML and AP directions. This shows the overall spread of the COP movements. CMLE and CAPE are the means of the absolute values of the COP in both the ML and AP directions. All of these parameters are commonly used measures for evaluating postural stability and higher values of these parameters mean higher level of postural instability [31], [32].

From the trunk movement data obtained from the IMU, the trunk linear accelerations referred to the earth frame of reference were calculated using the proprietary software provided with the sensors (MR 3.14, Noraxon, USA). The RMS values of these accelerations were calculated for the ML and AP directions (TMLAR and TAPAR) using equations (6) and (7), with the help of a purpose made code in MATLAB. The trunk acceleration can be correlated with trunk muscle activation as it has been observed that greater trunk accelerations are accompanied by greater trunk muscle activations [33]. The planar deviation of the trunk tilts (TTPLD) was also calculated, using equation (8).

$$\mathrm{TMLAR} = \sqrt{\frac{\sum (Trunk\ Acceleration_{ML}(i))^2}{n}} \tag{6}$$

$$\mathrm{TAPAR} = \sqrt{\frac{\sum (Trunk\ Acceleration_{AP}(i))^2}{n}} \tag{7}$$

$$\mathrm{TTPLD} = \sqrt{\sigma^2 Trunk\ Tilt_{ML} + \sigma^2 Trunk\ Tilt_{AP}} \tag{8}$$

The results obtained for the abovementioned parameters were statistically analyzed through a 2-way analysis of variance (2-way ANOVA) using SPSS 20 (IBM Corp., USA) to determine the effects of seat and visual modes on them. The factors for this analysis were seat mode (Levels: static (S), unstable (U) and perturbation (P)) and visual status (Levels: blindfold (B), eyes open (E) and visual feedback (V)). Greenhouse-Geisser corrections were applied where Mauchly's test of sphericity was violated and post hoc tests were conducted using the Bonferroni correction method.

III. RESULTS

The means and standard deviations of the COP and trunk movement parameters obtained for the different trial conditions are shown in Tables 2 and 3, respectively. The statokinesigram of one subject under all the trial conditions is shown in Figure 4. The AP movements are

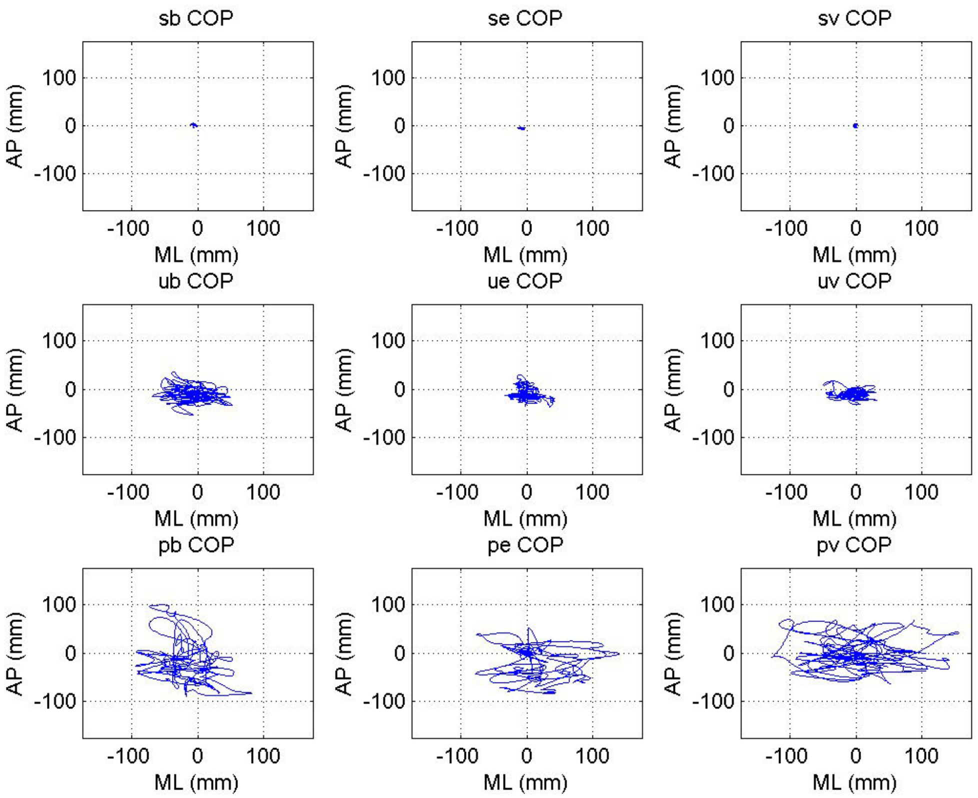


FIGURE 4. Statokinesigram of one subject under all trial conditions.

shown on the vertical axis with the anterior movement shown along the positive axis, and the ML movements are shown along the horizontal axis with movements to the subject's right side shown along the positive axis [34]. The outputs of the two way repeated measures ANOVA for the COP and trunk movement parameters are shown in Tables 4 and 5, respectively. For all parameters with statistically significant interaction, multiple comparison post-hoc tests were conducted after the application of Bonferroni correction.

TABLE 4. Results of the two-way repeated measures ANOVA of COP parameters.

Parameter	Factor	F	P-value
CPLD	Seat Mode	78.062	<0.001
	Visual Mode	14.308	<0.001
	Interaction	6.579	<0.001
CMLE	Seat Mode	40.263	<0.001
	Visual Mode	9.984	0.001
	Interaction	5.162	0.002
CAPE	Seat Mode	17.804	<0.001
	Visual Mode	13.400	0.003
	Interaction	0.329	0.704

TABLE 5. Results of the two-way repeated measures ANOVA of trunk movement parameters.

Parameter	Factor	F	P-value
TTPLD	Seat Mode	75.850	<0.001
	Visual Mode	2.570	0.102
	Interaction	2.842	0.036
TMLAR	Seat Mode	119.151	<0.001
	Visual Mode	23.344	<0.001
	Interaction	10.139	<0.001
TAPAR	Seat Mode	291.180	<0.001
	Visual Mode	15.763	<0.001
	Interaction	17.360	<0.001

For all COP parameters except CAPE, simple main effects were tested for post-hoc analysis due to the statistically significant interaction of seat and visual modes. No statistically significant interaction between seat mode and visual mode on CAPE led to post-hoc analysis of seat mode (S, U and P) and visual mode (B, E and V) separately. The results of these post-hoc tests are presented in Figure 5.

For all trunk movement parameters, simple main effects were tested for post-hoc analysis due to the statistically significant interaction of seat and visual modes. The results of these post-hoc tests are presented in Figure 6.

IV. DISCUSSION

We have developed a novel trunk rehabilitation robot [19], [20] that can generate seat motion in multiple degrees of freedom and has a footrest structure that is connected

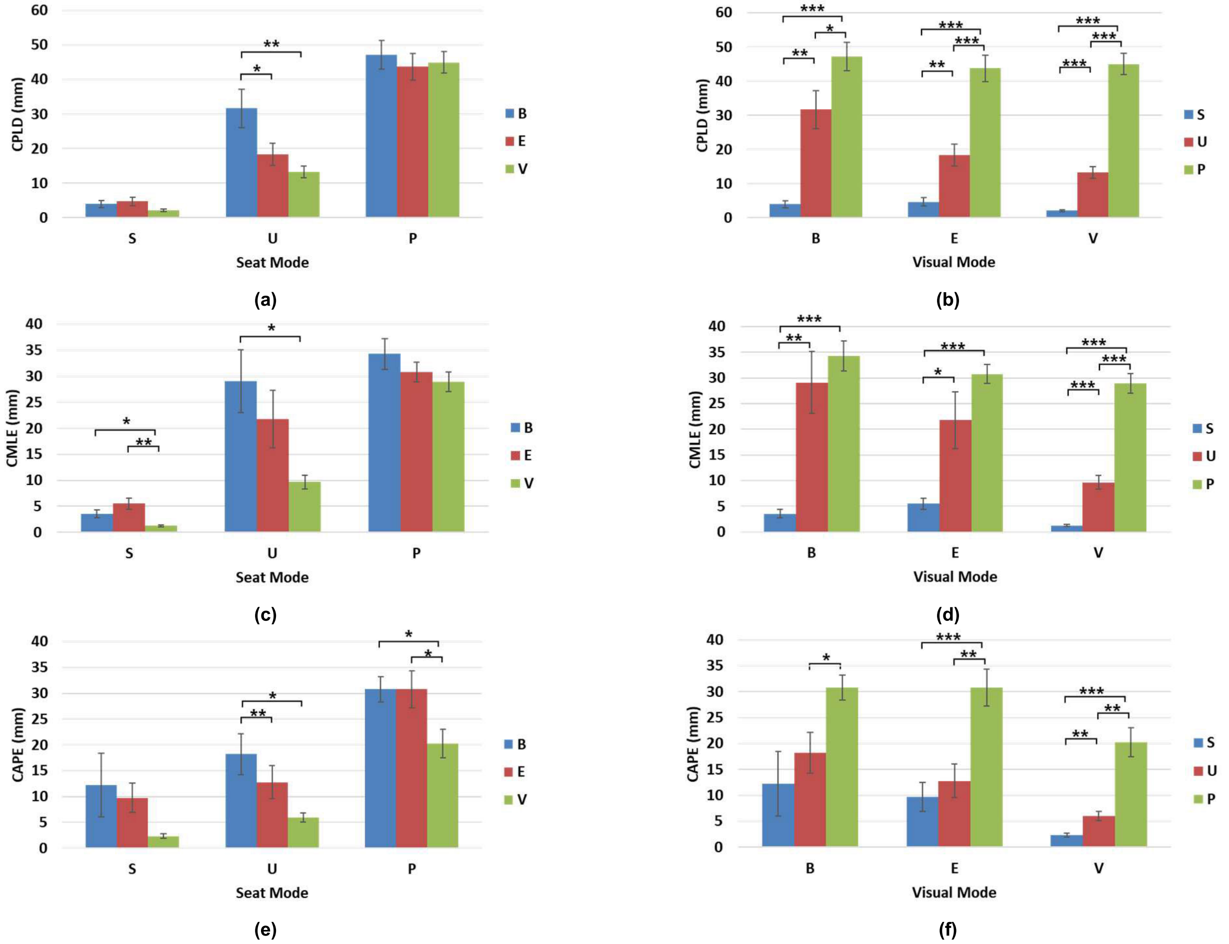
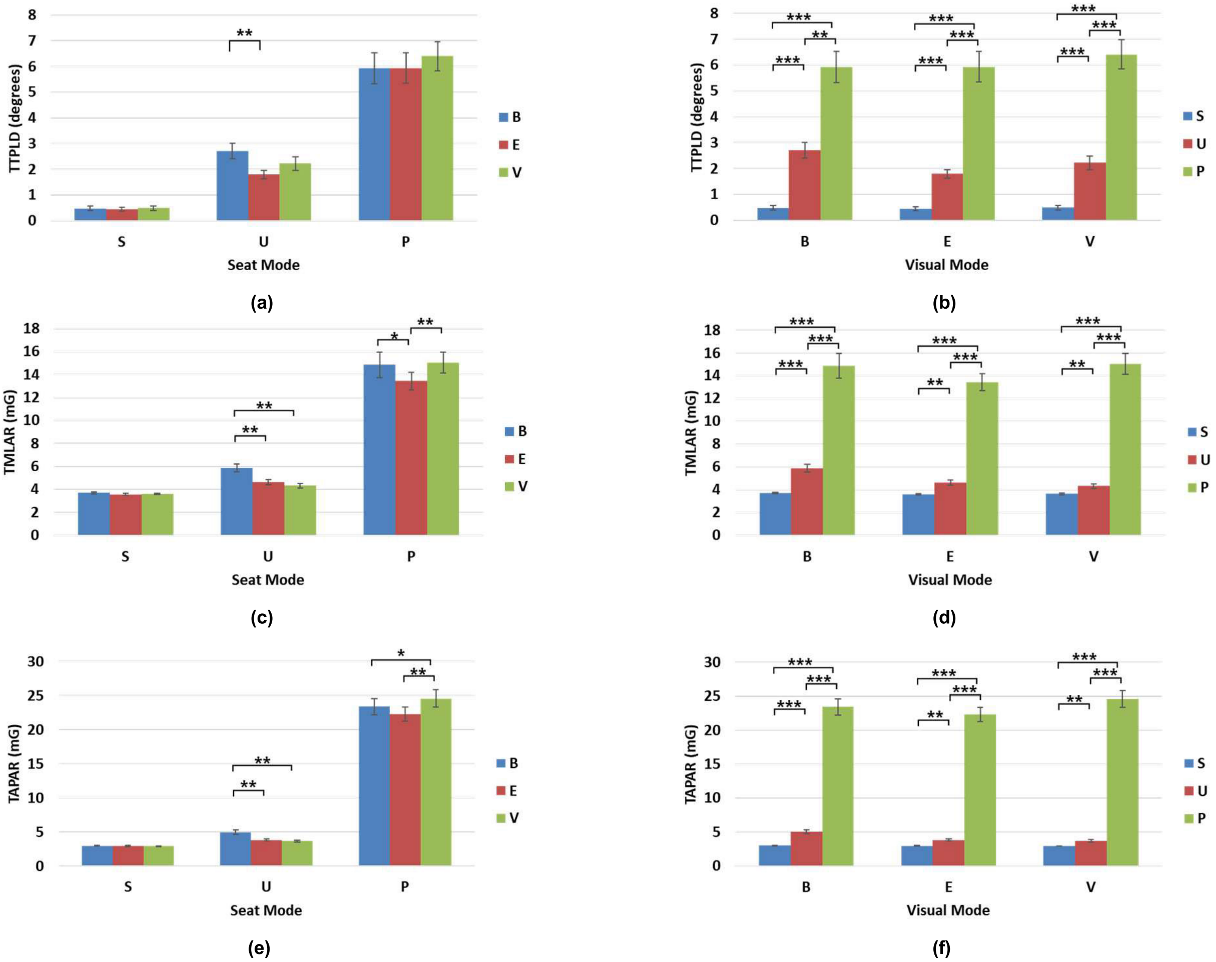


FIGURE 5. 2-way RMANOVA output of COP parameters. Post-hoc results of CPLD (a) and (b), CMLE (c) and (d), and CAPE (e) and (f) exhibit the statistically significant differences under different trial conditions. Here * is p-value < 0.05, ** is p-value < 0.01, and *** is p-value < 0.001.

rigidly to the seat in order to limit fully the proprioceptive feedback from the LE so that the sensory and control duties all have to be performed by the trunk [18]. In the presented study, we have used this robot to evaluate the effects of different seat modes and visual modes on the various COP and trunk movement parameters derived from data recorded during the performance of a simple upright balance maintenance task under different trial conditions. For all the observed parameters, higher values represent a decrease in the quality of balance [31], [32], [35]. Overall, it is observed that majority of the parameters showed statistically significant variations between different trial conditions. This indicates that, similar previous works [21]–[24], the seat mode and visual status both have a strong relationship with the quality of seated postural control. This is in line with our first hypothesis that difficulty of the task of seated postural control is affected by the variation in seat and visual modes.

The CPLD represents how widely spread the COP movements are. A greater spread means lesser control of balance [31]. CPLD showed highly to very highly significant levels of increase as the seat modes changed from static to unstable and then to perturbation. This represents a strong relationship between seat mode and quality of balance. Similar trends were also shown by CMLE and CAPE. COP excursions (CMLE and CAPE) are a commonly used index of postural stability whose higher values show a decrease in stability [32]. These results are in line with our second hypothesis and with other existing reports that show the relationship of quality of balance with instability of uncontrolled sitting surface [36]. The trunk movement parameters also show similar trends for highly significant increase with the variation of seat modes. The increase in TTPLD shows greater spread of trunk tilts, which is related to higher levels of postural instability [37]. Similarly, the trunk accelerations (TMLAR and TAPAR) have exhibited increase with the variation in seat mode. Higher RMS trunk accelerations are also related with postural instability [35]. These trends show that as we move from the static to the unstable seat and then to the perturbation seat, the level of instability increases, with the perturbation mode showing the highest level of instability. These similarities also indicate that the trunk rehabilitation robot used in this study can elicit similar responses form the users as the conventionally used uncontrolled unstable



(a) (b) (c) (d) (e) (f)

FIGURE 6. 2-way RMANOVA output of trunk movement parameters. Post-hoc results of TTPLD (a) and (b), TMLAR (c) and (d), and TAPAR (e) and (f) exhibit the statistically significant differences under different trial conditions. Here * is p-value < 0.05, ** is p-value < 0.01, and *** is p-value < 0.001.

seating surfaces. However, the robot provides much easier methods for control of instability and adjustability for a wide range of users.

With the change in visual mode from blindfold to eyes open and then to visual feedback, all COP parameters show significant amounts of reduction. However, in general the relationships with change in visual mode are relatively less significant than those with the seat mode. On the other hand, the trunk movement parameters show a mixed trend of variations. Moving from the blindfold to the eyes open condition, the trunk accelerations show significant reductions. The TTPLD also shows a reduction but that is not statistically significant. This trend is similar to other previously reported work [35]. However, as we move from the eyes open to the visual feedback mode; all the trunk movement parameters show significant increase. This trend is contrary to our expectation that the provision of visual feedback will reduce the instability related variations in these parameters. From the pairwise comparisons, it is apparent that under the static and unstable seat modes the trunk accelerations reduce with the change in visual mode. However, significant increases in acceleration occur between the eyes open and visual feedback modes under the perturbation seat mode. These results indicate that the presentation of a COP target to the subjects may cause them to move more rapidly towards the stable postural position (target). This high acceleration movement may in turn cause them to overshoot the target, thus generating the increased level of TTPLD. This movement trend is also apparent from the statokinesigram where the subject's COP seems to oscillate around the stable central position (Figure 4). This overshoot may be reduced by the use of a more elaborate visual feedback methodology that encourages the subject to slow down as they near the target position. However, the increased acceleration may even prove to be beneficial for the intended purpose of this system as higher trunk accelerations are associated with greater muscle activations in the trunk [33] and muscle activation can be correlated with trunk control [38]. The increased level of COP and trunk movement may also be useful as it may help in improving the trunk range of motion of stroke survivors. The extent and pattern of variations in muscle activations under different visual feedback strategies requires further study. Furthermore, the TAPAR in general has a higher mean value than the TMLAR; this may be due to the difference in ways the body responds to external perturbations [28]. An in-depth evaluation of the body's kinematic and muscle activity responses to the perturbations produced by the trunk rehabilitation robot is needed to understand fully its effects on the user.

The system is designed with the aim of allowing both training and evaluation of patients. For evaluation, similar to the currently reported study, the system can generate different seat conditions and the balance performance of patients under these conditions can be evaluated using COP outcomes. COP measures have been shown to be highly reliable objective measures of trunk control and a high correlation between COP outcomes and the trunk impairment scale (TIS) has been shown for stroke patients [39]. Therefore, the trunk rehabilitation robot with built-in COP measurement capability can also be used to assess the recovery progress of the patients.

The current study utilized only one level of instability and one level of perturbation. Future studies with multiple levels may be useful to elucidate further the mechanisms through which the body responds to these stimuli. Similarly, evaluation with multiple feedback schemes may enable us to devise a feedback methodology that provides the best augmentation experience for the user. As mentioned above, evaluation of the muscle activation levels and patterns is also necessary to understand fully the implications of using this system with its various operation modes. Such studies will be undertaken in the future to better our understanding of the users' response to the system. The current study involved only healthy subjects. Future studies with pathological subjects such as stroke patients are warranted to evaluate the system's effects on those subject groups and to determine the implications of using this system as a device for therapist assistance in both training and objective assessment of patients during physical rehabilitation.

V. CONCLUSION

In this study, a novel trunk rehabilitation robot was used to generate static, unstable and perturbation seat surfaces in order to evaluate their effect on the balance of healthy subjects. Furthermore, three visual modes; blindfold, eyes open and visual feedback, were applied for each seat condition. The results indicate that the system can elicit similar responses in the unstable mode as the conventional devices, and that further studies of the implications of using the perturbation mode with the provision of visual feedback of COP position are required. Various parameters from the recorded COP data and trunk movement data captured using a body worn IMU sensor were calculated and analyzed. The COP parameters showed variation trends that concurred with the already established knowledge related to conventional (uncontrolled) unstable seating surface generation devices. This shows that the developed trunk rehabilitation robot capable of generating an unstable surface with a stiffness field may be used as a controllable substitute for such devices during balance training and evaluation. As for the perturbation mode, the COP parameters generally showed expected trends, however the CPLD measure showed reduced stability in the perturbation with visual feedback mode. Similar deviations from expectation were shown by the trunk movement parameters, indicating that the participants faced difficulty in performing the postural control task under the visual feedback with seat perturbation trials. These outcomes with the visual feedback mode may be attributed to the subjects producing a more vigorous response when given a target and continuous feedback of their own status. Such a response can reduce the subject's stability but it may increase muscle activation, which may be beneficial for stroke rehabilitation. Thus, the observation of such behavior under visual feedback conditions reveals the requirement for further studies to evaluate its causes and to explore the implications for stroke rehabilitation of using visual feedback of COP with seat perturbation. However, the observation of effects similar to conventional systems that may be beneficial for stroke survivors and the system's ability to help assess recovery progress show that the system holds promise for use as a trunk training and objective performance evaluation tool for stroke survivors.

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