Adaptive Treadmill-Assisted Virtual Reality-Based Gait Rehabilitation for Post-Stroke Physical Reconditioning—a Feasibility Study in Low-Resource Settings

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ABSTRACT
Objectives: Individuals with chronic stroke suffer from heterogeneous functional limitations, including cardiovascular dysfunction and gait disorders (associated with increased energy expenditure) besides psychological factors, e.g., motivation. To recondition their cardiovascular endurance and gait, rehabilitation exercises with gradually increasing exercise intensity suiting their individualized capabilities need to be offered. In principal accordance, here we (i) implemented an adaptive Virtual Reality (VR)-based treadmill-assisted platform sensitive to energy expenditure, (ii) investigated its safety and feasibility of use and (iii) examined the implications of gait exercise with this platform on cardiac and gait performance along with energy expenditure, clinical measures (to estimate physical reconditioning of subjects with stroke) and their views on community ambulation capabilities. Methods: Ten able-bodied subjects volunteered in a study to ensure its safety and feasibility of use. Nine subjects with chronic stroke underwent physical reconditioning over multiple exposures using our platform. We investigated the patients’ cardiac and gait performance prior and post exposure to our platform along with studying the clinical relevance of gait parameters in estimating their physical reconditioning. We collected the patients’ feedback. Results: We found statistical improvement in the gait parameters and reduction in energy expenditure during overground walk following ∼1 month of gait exercise with our platform. They reported that the VR-based tasks were motivating. Conclusion: Results show that this platform can pave the way towards implementing home-based individualized exercise platform that can monitor one’s cardiac and gait performance capabilities while offering an adaptive and progressive gait exercise environment within safety thresholds suiting one’s exercise capabilities.

INDEX TERMS
Physiology-sensitive, home-based, gait Rehabilitation, stroke, treadmill exercise.

I. INTRODUCTION
Neurological disorders, such as stroke is a leading cause of disability with a prevalence rate of 424 in 100,000 individuals in India [1]. Often, these patients suffer from functional disabilities, heterogeneous physical deconditioning along with deteriorated cardiac functioning [2], [3] and a sedentary lifestyle immediately following stroke [4]. A deconditioned patient requires reconditioning of his/her cardiac capacity and ambulation capabilities that can be achieved through individualized rehabilitation [5]. This needs to be done under the supervision of a clinician who can monitor one’s functional capability, cardiac capacity and gait performance thereby recommending an appropriate dosage of the gait rehabilitation exercise intensity to the patient along with feedback. Such gait rehabilitation is crucial since about 80% of these patients have been reported to suffer from gait-related disorders [6] along with more energy expenditure than able-bodied individuals [7] often accompanied with reduced cardiac capacity [2], [4]. However, given the low doctor-to-patient ratio [8], lack of rehabilitation facilities and patients being released early from rehabilitation clinics followed by home-based
exercise [9], particularly in developing countries like India, availing individualized rehabilitation services becomes difficult. Again, undergoing home-based exercises under clinician’s one-on-one supervision becomes difficult given the restricted healthcare resources, thereby limiting the rehabilitation outcomes [10]. Again, given the restricted healthcare resources, getting a clinician visiting the homes for delivering therapy sessions to patients is often costly causing the patients to miss the expert inputs on the exercise intensity suiting his / her exercise capability along with motivational feedback from the clinician [11]. This necessitates the use of a complementary technology-assisted rehabilitation platform that can be availed by the patient at his / her home [12] following a short stay at the rehabilitation clinic [13]. Again, it is preferred that this platform be capable of offering individualized gait exercise while varying the dosage of exercise intensity (based on the patient’s exercise capability) along with motivational feedback [14]. Additionally, exercise administered by this platform can be complemented with intermediate clinician-mediated assessments of rehabilitation outcomes, thereby reducing continuous demands on the restricted clinical resources. Thus, it is important to investigate the use of such technology-assisted gait exercise platforms that are capable of offering exercise based on one’s individualized capability along with motivational feedback.

Researchers have explored the use of technology-assisted solutions to offer rehabilitative gait exercises to these patients, along with presenting motivational feedback [15]–[24]. Specifically, investigators have used Virtual Reality (VR) coupled with a treadmill (having a limited footprint and making it suitable for home-based settings) while delivering individualized feedback [15] to the patient during exercise. Again, VR can help to project scenarios that can make the exercise engaging and interactive for a user [16]–[19]. In fact, Finley et al. have shown that the visual feedback offered by VR provides an optical flow that can induce changes in the gait performance (quantified in terms of gait parameters, e.g., Step Length, Step Symmetry, etc.) of such patients during treadmill-assisted walk [20]. Further, Jaffe et al. have reported positive implications of VR-based treadmill-assisted walking exercise on the gait performance of individuals with stroke [23], leading to improvement in their community ambulation [24]. These studies have shown the efficacy of the VR-based treadmill-assisted gait exercise platform to contribute towards gait rehabilitation of individuals suffering from stroke. Though promising, none of these platforms are sensitive to one’s individualized exercise capability and thus, in turn, could not decide an optimum dosage of exercise intensity suiting one’s capability, e.g., cardiac capacity and ambulation capacity. This is particularly critical for individuals with stroke since they possess diminished exercise ability along with deteriorated cardiac functioning [2], [4].

From literature review, we find that after stroke, treadmill-assisted cardiac exercise programs can lead to one’s improved fitness and exercise capability [25]. For example, researchers have presented studies on Moderate-Intensity Continuous Exercise and High-Intensity Interval Training in which exercise protocols are individualized by a clinician based on one’s cardiac capacity while contributing to effective gait rehabilitation [26]–[29]. Though promising, these have not offered a progressive and adaptive exercise environment in which the dosage of exercise intensity is varied based on one’s cardiac capacity in real-time. Thus, the choice of optimum dosage of exercise intensity that can be individualized in real-time for a patient, still remains as inadequately explored [4]. For deciding the optimal dosage of rehabilitative exercise intensity, clinicians often refer to the guidelines recommended by the American College of Sports Medicine (ACSM) [30]. These guidelines suggest thresholds to decide the intensity of the exercise based on one’s metabolic energy consumption in terms of oxygen intake, heart rate, etc. Deciding the dosage of exercise intensity is crucial, particularly for individuals with stroke since their energy requirements have been reported to be 55–100% higher than that of their able-bodied counterparts [7]. Specifically, higher energy requirement often limits the capabilities of these patients and challenges their rehabilitation outcomes. This can be addressed if the technology-assisted gait exercise platform can offer individualized exercise (maintaining the safe exercise thresholds) based on the energy expenditure of the patients acquired in real-time during the exercise.

The energy expenditure can be defined as the cost of physical activity [4] and it is often expressed in terms of oxygen consumption or heart rate [31]. Thus, investigators have monitored the oxygen consumption and heart rate to estimate the energy expenditure of individuals with stroke during their walk [31], [32]. However, monitoring oxygen consumption during exercise requires a cumbersome setup [31], making it unsuitable for home-based rehabilitation. On the other hand, one’s heart rate (HR) can be monitored using portable solutions [33] that can be integrated with a treadmill in home-based settings. Researchers have explored treadmill-assisted gait exercise platforms that are sensitive to the user’s heart rate. For example, researchers have offered treadmill training to subjects with stroke in which some of them varied treadmill speed to achieve 45%-50% [34], while others varied speed to achieve 85% to 95% [35], [36] of one’s age-related maximum heart rate. Again, Pohl et al. have offered treadmill-assisted exercise to subjects with stroke while ensuring that the user’s heart rate settled to the respective resting-state heart rate [37]. Again of late, there had been advanced treadmills, available off-the-shelf, that can monitor one’s heart rate and vary the treadmill speed to maintain the user’s heart rate at a predefined level [38], [39]. Though one’s heart rate is an important indicator that needs to be considered during treadmill-assisted exercise, one’s walking speed while using the treadmill also offers important information on one’s exercise capability. This is because gait rehabilitation aims to improve one’s community ambulation that is related to one’s walking speed [40]. Thus, it would be interesting to explore the composite effect of one’s walking speed along with working and resting-state heart rates during treadmill-assisted gait...
exercise to study one’s energy expenditure, quantified in terms of a proxy index, namely Physiological Cost Index (PCI) [31].

Given that there are no existing studies that have used a treadmill-assisted gait exercise platform deciding the dosage of exercise intensity based on one’s PCI estimated in real-time during exercise, it might be interesting to explore the use of such an individualized gait exercise platform for individuals with stroke. Thus, we wanted to extend a treadmill-assisted gait exercise platform by making it adaptive to one’s individualized PCI. Additionally, we wanted to augment this platform with VR-based user interface to offer visual feedback to the user undergoing gait exercise. We hypothesized that such a gait exercise platform can recondition a patient’s exercise capability in terms of cardiac and gait performance to achieve improved community ambulation. The objectives of our research were three-fold, namely to (i) implement a novel PCI-sensitive Adaptive Response Technology (PCI-ART) offering VR-based treadmill-assisted gait exercise, (ii) investigate the safety and feasibility of use of this platform among able-bodied individuals before applying it to subjects with stroke and (iii) examine implications of undergoing gait exercise with this platform on the patients’ (a) cardiac and gait performance along with energy expenditure, (b) clinical measures estimating the physical reconditioning and (c) views on their community ambulation capabilities.

The rest of the paper is organized as follows: Section II presents our system design. Section III explains the experiments and procedures of this study. Section IV discusses the results. In Section V, we summarize our findings, limitations, and scope of future research.

II. MATERIALS AND METHODS
A. SYSTEM DESIGN
The PCI-ART platform comprised of 1) VR-based Task Presenter, 2) Gait Characterization Shoes, 3) Data Acquisition, 4) Adaptive Speed Engine, and 5) Speed Synching modules.

1) VR-BASED TASK PRESENTER MODULE
The VR-based Task Presenter module offered a Graphical User Interface (GUI) displaying a humanoid character (avatar henceforth) walking on a straight road (VirtualRoad henceforth) passing through different scenarios. The Fig. 2 gives a typical example. The idea of using a walking pathway in the VR environment was inspired by other research studies [16]–[19]. However, unlike these studies, which presented walking pathways running through city-like environments [16], [19], or laid out in a closed corridor [17], or open grounds [18], etc., here, we presented VirtualRoad as a straight pathway passing through a city outskirt environment. In fact, we wanted to reduce elements, such as for roads passing through a city [16], [19] that might be distracting, avoid closed spaces [17] that might restrict user’s view and also offer a pre-defined pathway for walking rather than presenting an open ground [18], etc. Since our target group comprised of subjects with stroke, we wanted to use a simplistic and controlled setting for VR-based gait exercise that could offer minimal distractions to reduce any possible cognitive burden during the exercise. One’s walking speed (while using a treadmill) was synchronized with the avatar’s walking speed through a Speed Synching Module (Section II.A.5). The VirtualRoad was separated from the surrounding VR scene by virtual objects, e.g., pillars, pyramids, spheres, etc. lying on both sides of the pathway. As the avatar walked forward on the VirtualRoad, these objects appeared to shift backward providing visual feedback (through establishing optical flow) that was synchronized with the treadmill. The idea was to offer a sense of presence [21] (in the VR environment) to the participant. Again, since our PCI-ART based treadmill setup was not a self-paced one (that depends only on one’s position and/or walking speed) with an option of reducing the walking speed on the part of the participant. The user’s gait-related and heart rate information were collected by a Task Computer via Gait Characterization Shoes and Data Acquisition modules. The Task Computer displayed a VR-based stimulus to the participant. An Adaptive Speed Engine varied the treadmill speed via the Speed Synching module. The following sections provide details on each module.
participant (as an effect of the optical flow [22]), the participant was expected to have a walking speed tuned to that of the treadmill speed as decided by the Adaptive Speed Engine module (Section II.A.4). We designed a database of ten VR-based templates displaying objects of different colors and shapes along with the VirtualRoad running through various scenarios (all environments showing different types of city outskirts). The different templates helped to offer variations in the user’s VR experience with the hope of overcoming any possible monotony during the treadmill-assisted walk (comprising of different walk trials). A countdown timer (center-top position of the screen) was meant to help the user to get an estimate of the time left for the specific walk trial.

Additionally, the gait exercise platform was programmed to offer audio-visual feedback. For example, when a participant completed a walk trial and the Adaptive Speed Engine (Section II.A.4) decided to increase the treadmill speed then the PCI-ART platform delivered an audible motivational feedback “You are doing great! Keep it up”. Else, it delivered, “You can do better.” Added to displaying a walking avatar, the PCI-ART platform offered visual feedback on one’s performance. Specifically, the GUI displayed two baskets, namely ‘Initial basket’ and ‘Target basket’ (Fig. 2). Every time the Adaptive Speed Engine decided to increase the treadmill speed at the end of a walk trial, one colored disk flew from the ‘Initial basket’ to the ‘Target basket’ along with a monotone.

2) GAIT CHARACTERIZATION SHOES

In our present study, we have used in-house built instrumented shoes [41] to monitor one’s gait events, e.g., heel-strike, toe-off, etc. to quantify one’s gait in terms of gait parameters [42], [43]. This module comprised of a pair of shoes with six force-sensitive resistors (FSRs) placed below the insoles (Fig. 3). The FSRs were placed below the Toe (T_L (left leg) and T_R (right leg)) and Heel (H_L1 and H_L2 (left leg); H_R1 and H_R2 (right leg)). We chose these positions to i) record the heel-strike and toe-off events and ii) accommodate pathologic gait, e.g., foot inversion/eversion. We have validated the temporal and spatial gait parameters measured using the shoes with that measured using the standard camera-based technique (e.g., VICON [44]) and the paper-based setup [45] in our pilot study [41]. In our present study, we extracted different spatio-temporal gait parameters, e.g., Step Length, Single Support Time and Gait Stability Ratio (Section III.E) using the instrumented shoes.

3) DATA ACQUISITION MODULE

Apart from monitoring one’s gait, we were interested in measuring one’s heart rate (HR) using the Electrocardiogram (ECG) information. The Data Acquisition (DAQ) module was used to acquire one’s ECG data via BioPac MP150 (BioPac Systems Inc.) operated in the wireless mode. The ECG data was routed to a computer using a baud rate of 250000 bits/second.

The acquired ECG signal was processed using a bandpass filter (10 - 25 Hz) to extract the ‘R’ wave followed by measurement of the R-R interval. The HR in beats per minute (bpm) was computed from the R-R interval. The HR values were averaged for each walk trial (Section III.D.1) to compute the mean heart rate (HR_MEAN) during a walk trial. We validated the computed HR_MEAN with the heart rate value measured by the BioPac data acquisition software (mean absolute error = 0.26 beats/minute). Subsequently, the PCI was computed by dividing the difference in heart rate (i.e., heart rate during walk trial - heart rate at rest) by the average walking speed during walk trial.

4) ADAPTIVE SPEED ENGINE MODULE

The treadmill-assisted gait exercise platform used in this study comprised of a motorized treadmill (Fitness World 3100-Motorized Treadmill). The treadmill speed was varied using an in-house designed Adaptive Speed Engine (ASE) algorithm to offer individualized gait exercise that was adaptive to one’s energy expenditure. The responsibilities of the ASE module were two-fold, namely, (i) to maintain the exercise intensity within the safe exercise thresholds for the subject with stroke during exercise and (ii) to monitor the energy expenditure in terms of PCI and accordingly offer varying exercise intensity. The ACSM guidelines suggest offering exercise intensity within 55% to 90% of the age-predicted maximum heart rate (HR_MAX,AGE; Eq. 1) for able-bodied individuals [30]. However, considering that the PCI-ART platform was meant for subjects with stroke, we chose the lower threshold of exercise intensity as 50% of HR_MAX,AGE and the upper threshold of exercise intensity as 80% of HR_MAX,AGE (as a typical case). Subsequently, two HR threshold zones (HR_THRESH) were defined for subjects with stroke who were consumers and non-consumers of beta-blocker medicine [46] as given by Eqs. (2.1) and (2.2), respectively. Again, the ASE module was empowered to decide whether to maintain or increase the treadmill speed (based on the individualized PCI value) using a switching rationale while keeping an eye on the HR thresholds. For this, the ASE module compared the PCI of a current walk trial (PCI_k) with that during the previous walk trial (PCI_k-1). If there was a 10% reduction in one’s PCI value during PCI_k from that during PCI_k-1, then the ASE module increased the treadmill speed by 1 mpg.
speed by 10% (chosen taking inputs from the literature [37]) during PCI\(_k+1\) from what was there during the respective PCI\(_k\) thereby increasing the exercise intensity. Otherwise, the ASE module maintained the treadmill speed with the hope that the subject will adapt to the currently increased exercise intensity.

\[
HR_{MAX\_AGE}(\text{beats/minute}) = 220 - \text{Age(in years)} \quad (1)
\]

For those on Beta-Blocker medication:

\[
0.8 \times (0.85 \times HR_{MAX\_AGE}) > HR_{THRESH} \\
\geq 0.5 \times (0.85 \times HR_{MAX\_AGE}) \quad (2.1)
\]

For those not on Beta-Blocker medication:

\[
0.8 \times HR_{MAX\_AGE} > HR_{THRESH} \quad \geq 0.5 \times HR_{MAX\_AGE} \quad (2.2)
\]

To ensure the subject’s safety, the ASE module terminated the exercise (i.e., turned off the treadmill) when one’s heart rate exceeded the maximum limit of the \(HR_{THRESH}\). Please note that the thresholds for heart rate were chosen as per the guidelines suggested by the ACSM [30].

5) SPEED SYNCHING MODULE

The Speed Synching Module (Fig. 4) comprised of two sub-modules, namely (i) Speed Tracker and (ii) Speed Modulator. The Speed Tracker measured the treadmill speed and communicated this information in real-time to the VR-based Avatar during the task trial snapshot of typical VR environment.

Computer that in turn, sent the updated speed information to the Speed Modulator. Subsequently, the Speed Modulator (comprising of an in-house built microcontroller and relay-based circuit) communicated the updated speed information to the treadmill console in real-time.

III. EXPERIMENTAL SETUP AND PROCEDURE

In our present work, we implemented a novel PCI-ART (VR-based treadmill-assisted gait exercise) platform. Subsequently, we wanted to investigate the safety and feasibility of the use of this platform among able-bodied subjects before applying it to subjects with stroke. Following this, we recruited subjects with stroke and wanted to examine the implications of undergoing gait exercise while using this platform on their (a) cardiac and gait performance along with energy expenditure, (b) clinical measures to estimate the patients’ views on their community ambulation capabilities. For this, we conducted a study in two phases, namely Phase 1 and Phase 2. The Phase 1 of the study involved able-bodied subjects and the Phase 2 involved subjects with stroke.

A. PARTICIPANTS

Our study had 19 male volunteers comprising of 10 able-bodied subjects (Group\(_{\text{Healthy, henceforth}}\) (H1-H10, Mean(SD) = 38.4(±8.7) years) and 9 hemiplegic subjects with stroke (Group\(_{\text{Stroke, henceforth}}\) (P1-P9, Mean(SD) = 48.3(±13.4) years; Table 1). The participants belonging to the Group\(_{\text{Stroke}}\) were recruited through clinician’s referral. The study was reviewed and approved (Approval No: IEC/2014-152/UL/003) by the Institutional Ethics Committee. The participants (belonging to Group\(_{\text{Healthy}}\) and Group\(_{\text{Stroke}}\)) were enrolled while following the inclusion/exclusion criteria.

B. INCLUSION/EXCLUSION CRITERIA

The inclusion/exclusion criteria for the participants belonging to Group\(_{\text{Healthy}}\) and Group\(_{\text{Stroke}}\) were (i) age between 18 and 90 years, (ii) has not undergone major surgery in the recent past and (iii) able to provide informed consent along with ability to understand experimenter’s instructions. Again, for the Group\(_{\text{Stroke}}\), we enrolled the participants who were (i) able to walk 10 m without external support (to exclude cases

TABLE 1. Participant characteristics.

| ID  | Age (years) | Gender | Post-strokeperiod (years) | BMI (kg/m\(^2\)) | Affected Side |
|-----|-------------|--------|---------------------------|------------------|--------------|
| P1  | 36-40       | Male   | 1.5                       | 29.05            | R            |
| P2  | 51-55       | Male   | 1.5                       | 23.81            | R            |
| P3  | 41-45       | Male   | 2                         | 24.02            | R            |
| P4  | 46-50       | Male   | 2                         | 23.32            | L            |
| P5  | 41-45       | Male   | 2.5                       | 21.63            | R            |
| P6  | 71-75       | Male   | 6                         | 27.47            | L            |
| P7  | 36-40       | Male   | 1                         | 29.40            | R            |
| P8  | 21-25       | Male   | 10                        | 20.06            | R            |
| P9  | 35-40       | Male   | 1                         | 28.95            | R            |

Note: BMI - Body Mass Index; R - Right Side; L - Left Side.
with severe biomechanical limitations) and (ii) not in acute phase (6 months after onset of stroke) of stroke. Further, we excluded subjects with stroke who have received any spasticity treatment in the recent past. Also, we ensured that none of the subjects with stroke underwent any treadmill-assisted therapeutic exercise during the last six months. All the participants were clinically examined by a physiotherapist in our team while checking their medical records. Specifically, the physiotherapist in our team ensured that the participants did not have any symptoms of severe cardiovascular illness (as suggested by the ACSM screening guidelines).

C. EXPERIMENTAL SETUP

In this work, the participants were asked to perform an overground and treadmill-assisted walk.

1) SETUP FOR OVERGROUND WALK

The setup comprised of (i) 10 m long pathway (marked with ‘START’ and ‘END’), (ii) BioPac MP150, (iii) Data Logger computer and (iv) Gait Characterization Shoes.

2) SETUP FOR TREADMILL-ASSISTED WALK

This setup comprised of (i) Task Computer presenting the VR-based tasks and hosting the ASE module, (ii) Treadmill with the safety harness, (iii) DAQ module along with BioPac MP150, (iv) Speed Synching module and (v) Gait Characterization Shoes (Fig. 5).

D. PROCEDURE

In the present research, we carried out our study in two phases. The experimental procedures followed in both these phases are discussed below.

1) PROCEDURE FOR PHASE 1: SAFETY AND FEASIBILITY TESTING WITH ABLE-BODIED SUBJECTS

The Phase 1 of our study involved able-bodied subjects. The idea was to investigate the safety and feasibility of using the PCI-ART platform for gait exercise. For this, we involved the GroupHealthy before applying it to the GroupStroke. Once a participant arrived at the study room, he was asked to relax for 5 minutes. The experimenter demonstrated the overground walk, treadmill-assisted tasks and showed the Gait Characterization Shoes to the participant. The Phase 1 required a commitment of ~30 mins from each participant. The participants were told that they were free to discontinue from the study if they felt uncomfortable. Then the signing of the consent form was administered. After this, the experimenter helped the participant to wear the shoes. Also, the ECG sensors (Ag-AgCl light-weight sticky sensors) were pasted on the participant’s body below the neck, one towards the right arm (RA) and other towards the left arm (LA) locations [47]. The third electrode was placed near the fourth interspace of the rib-cage on the left side of the body [47]. After recording the baseline measure of the heart rate (resting-state), the participant was asked to perform overground walk (PreH henceforth) followed by using the PCI-ART platform (i.e., the treadmill-assisted gait exercise which was adaptive to one’s individualized PCI value) that in turn was followed by the overground walk (PostH case henceforth). The exercise using the PCI-ART platform lasted for ~10 minutes having 10 walk trials each being ~1 minute long. The participant’s PCI and HR were evaluated for each walk trial and the ASE module either increased / maintained the exercise intensity by increasing / maintaining the treadmill speed for the next walk trial. During the overground walk, the participants were asked to use their self-selected comfortable walking speed, similar to that in other studies [48], [49] with the hope of taking precaution against any possible voluntary speed modulation, particularly for GroupHealthy.

2) PROCEDURE FOR PHASE 2: USABILITY BY SUBJECTS WITH STROKE

In Phase 2, the subjects with stroke were recruited from a neighboring hospital. The experimental protocol was similar to that used in the Phase 1. However, each subject with stroke was offered with nine exposures to our PCI-ART platform on different days spread over ~1 month with nearly 3 days / week (every alternate day) leaving holidays and weekends. Once the participant arrived at the study room, he was asked to relax for 5 minutes. The experimenter demonstrated the overground walk, treadmill-assisted tasks and showed the Gait Characterization Shoes to the participant. Our study required a commitment of ~45 minutes on the first day.
followed by ~30 minutes on subsequent days. The participants were told that they were free to discontinue from the study if they felt uncomfortable. Subsequently, the inclusion/exclusion criteria were administered. Also, the baseline clinical measures (e.g., 10m walk [45] and Timed Up and Go (TUG) [45]) were recorded for each subjects with stroke. Then the signing of the consent form was administered. After this, the experimenter helped the participant to wear the shoes. Also, the ECG sensors (Ag-AgCl light-weight sticky sensors) were pasted on the participant’s body. The placement of the ECG sensor was similar to that discussed for Phase 1. During each session (held on different days), after recording the baseline measure of the heart rate (resting-state), the participants were asked to perform overground walk (Pre case henceforth for the first session) followed by using the PCI-ART platform. Each patient was exposed to this gait exercise platform for 9 sessions, with each session (n<sup>th</sup> say) being followed by the overground walk the next session, i.e., preceding the n + 1<sup>th</sup> session (Post<sub>S</sub> case henceforth for n = 9) to account for the fatigue due to treadmill-based gait exercise. Subsequently, the clinical gait measures were recorded (during the Post<sub>S</sub> case). Finally, the experimenter collected feedback from each participant using the User Satisfaction Evaluation Questionnaire (USEQ) [50]. Similar to Phase 1, the participants were asked to use their self-selected comfortable speed during the overground walk.

**E. EXTRATION OF GAIT PARAMETERS**

As we wanted to examine implications of using the PCI-ART platform on the gait performance of the user, the gait events recorded by the Gait Characterization Shoes (during one’s overground walk) were used to compute the gait-related indices, e.g., Step Length, Gait Stability Ratio and Single Support Time.

1) COMPUTATION OF STEP LENGTH

In our present research, we wanted to study one’s Step Length (quantified using the instrumented shoes) prior to (Pre case) and post (Post case) exposure to the PCI-ART platform since Step Length can be indicative of functional (gait) recovery after stroke. The Step Length was computed using the information on the distance covered between two successive contra-lateral heel strikes [45]. Here, we have used Step Time and Walking Speed to compute the Step Length. The Step Time was measured from the time interval between two successive heel-strike events of the contralateral legs using the Gait Characterization Shoes. The Walking Speed (during the overground walk) was computed using the information on the time taken (walk duration) by an individual to cover the 10m pathway. The walk duration was measured by the therapist in our team with the help of a stopwatch based on one’s walking between the ‘START’ and ‘END’ lines drawn at the beginning and the end of the 10 m pathway. This measurement was validated using a camera-based setup that was synchronized with the Gait Characterization Shoes with three foot taps on the floor at the ‘START’ line by each participant before starting the overground walk [42]. The Step Length was computed using Eq. (3) [52].

\[
\text{Step Length} = \frac{\text{Walking speed} \times \text{Step time}}{} \tag{3}
\]

2) COMPUTATION OF GAIT STABILITY RATIO

The Gait Stability Ratio (GSR) can be a cardinal indicator of investigating one’s dynamic stability during walk [53]. The GSR takes into account changes in one’s Walking Speed and Step Length [53]. The GSR was computed as the ratio of cadence (steps/sec) (recorded by the Gait Characterization Shoes) to the Walking Speed (m/sec) (Eq. (4)).

\[
\text{Gait Stability Ratio} = \frac{\text{Cadence}}{\text{Walking Speed}} \tag{4}
\]

3) COMPUTATION OF SINGLE SUPPORT TIME

The Single Support Time (SST) can indicate one’s postural control demands during walking [54] that is often adversely affected after stroke [41]. The single (limb) support time is the duration for which only one of the legs supports an individual’s body during gait [45]. Alternatively, the SST for one leg can be measured from the swing time of the other leg [55]. We have considered the alternate approach. The %Single Support Time (%SST<sub>L</sub> and %SST<sub>R</sub>) was calculated as a percentage of the total gait cycle time (Gait Cycle Time<sub>L</sub> and Gait Cycle Time<sub>R</sub>) for left and right legs using Eqs. (5) and (6), respectively.

\[
\%\text{SST}_L = \frac{(\text{Swing Time}_L)}{\text{Gait Cycle Time}_L} \times 100 \tag{5}
\]

\[
\%\text{SST}_R = \frac{(\text{Swing Time}_R)}{\text{Gait Cycle Time}_R} \times 100 \tag{6}
\]

**F. STATISTICAL ANALYSIS**

We wanted to carry out a comparative analysis of the cardiac and gait performance (quantified using the Gait Characterization Shoes) of the subjects with stroke between prior (Pre<sub>S</sub> case) and after (Post<sub>S</sub> case) repeated exposures to the PCI-ART platform. Given a limited sample size, we opted for a non-parametric statistical test, e.g., Wilcoxon signed-rank test [56] to explore the statistical difference (if any) of these measures between the Pre<sub>S</sub> and Post<sub>S</sub> cases.

**IV. RESULTS**

We aimed to investigate the safety and feasibility of the use of the PCI-ART platform by the able-bodied subjects before applying it to the subjects with stroke. Thereafter, we aimed to examine the implications of the PCI-ART platform on the cardiac performance, gait performance, energy expenditure and clinical measures to estimate the physical reconditioning of the subjects with stroke. Further, we also studied the patients’ views on their own community ambulation capabilities. We discuss our findings in the following sections.

**A. SAFETY AND FEASIBILITY TESTING OF THE PCI-ART PLATFORM WITH ABLE-BODIED SUBJECTS**

In Phase 1 of our study, the able-bodied subjects were exposed to the PCI-ART platform to investigate the safety
TABLE 2. Pre-to-post comparative analysis of cardiac and gait performance during phase 1 for GROUPhealthy.

| Parameter                  | Group Pre<sub>SToke</sub> | Group Post<sub>SToke</sub> |
|----------------------------|---------------------------|-----------------------------|
| Speed (km/h)               | 3.81                      | 4.12                        |
| HR (bpm)                   | 96.32                     | 104.35                      |
| PCI (beats/meter)          | 0.15                      | 0.28                        |
| Step Length (meter)        | 0.62                      | 0.66                        |
| %SST (%)                   | 40.54                     | 41.20                       |
| GSR (steps/m)              | 1.76                      | 1.67                        |

FIGURE 6. Comparative analysis of physiological cost index during Pre<sub>SToke</sub> and Post<sub>SToke</sub> cases for subjects with stroke. Note: Pre exposure- Pre<sub>SToke</sub> case; Post exposure- Post<sub>SToke</sub> case; * - (p-value < 0.05).

1) IMPLICATIONS OF GAIT EXERCISE WITH THE PCI-ART PLATFORM ON THE CARDIAC AND GAIT PERFORMANCE

In this study, we investigated the implications of repeated exposures to our novel PCI-ART gait exercise platform on the cardiac output (quantified in terms of Physiological Cost Index) and gait parameters (quantified in terms of Step Length, Single Support Time and Gait Stability Ratio).

a: COMPARATIVE ANALYSIS OF THE PHYSIOLOGICAL COST INDEX

Literature indicates that the Physiological Cost Index (PCI) (Section II.A.3) can be used as a proxy index to measure one's energy expenditure [31] during exercise with its reduction being crucial for the exercise to be effective [57]. In our present study, we computed the group average PCI for the GroupStroke during both the Pre<sub>SToke</sub> and Post<sub>SToke</sub> cases. From Fig. 6 we can see that there was a group average Pre<sub>SToke</sub>-to-Post<sub>SToke</sub> reduction of 0.43 beats/meter in the PCI value for the GroupStroke. Such a reduction in the group average PCI value from the Pre<sub>SToke</sub> case to Post<sub>SToke</sub> case can be attributed to a group average reduction in HR (9 bpm) along with an increment in the group average Walking Speed (0.3 m/s). We conducted a dependent sample Wilcoxon signed rank test [56] on the PCI values. Results indicate significant (p-value < 0.05) Pre<sub>SToke</sub>-to-Post<sub>SToke</sub> reduction in the PCI values inferring improvement in the energy expenditure leading to improvement in overground gait efficiency.

b: COMPARATIVE ANALYSIS OF THE GAIT PARAMETERS

We wanted to investigate the implications of undergoing gait exercise with our PCI-ART platform on the gait performance of the subjects with stroke. We examined some of the gait parameters, e.g., Step Length, Single Support Time and Gait Stability Ratio, since these parameters can offer cardinal measures of one’s gait performance. For example, an increase in one’s Step Length can be an indicator of functional (gait) recovery [51]. Again, the Single Support Time (SST) can be an indicator of one’s postural control demands during
walking [54]. Also, one can expect that the SST for the Affected (AL) and Unaffected (UAL) legs can be widely different particularly for asymmetric hemiplegic gait, deteriorating one’s postural control [54], depending on the extent of the disorder. Further reduction in Gait Stability Ratio can be indicative of improved dynamic stability [53] while walking. Our findings indicated PreS -to- PostS case increment in the group average Step Length (∼25%) (Fig. 7). In fact, detailed analysis revealed that the increment in the Step Length was bilateral, but different for the AL (Δ% = ∼24%) and UAL (Δ% = ∼18%). Again, the variability in the group average Step Length decreased by ∼24% from the PreS case to the PostS case, thereby inferring improved (functional) gait [51], important for gait rehabilitation. Results of a dependent sample non-parametric statistical test, e.g., Wilcoxon signed-rank test, showed a statistical increase (p-value < 0.05) in the group average Step Length post-exposure to the PCI-ART assisted gait exercise platform.

As far as gait stability was concerned, our findings showed an overall group average PreS -to- PostS case improvement in the gait stability quantified through a reduction (∼22%) in the Gait Stability Ratio (GSR; Section III.E.2) after multiple exposures to the PCI-ART assisted gait exercise platform (Fig. 8). Such an observation can infer improvement in the gait stability[53] of the subjects with stroke, a critical indicator of reconditioning of gait performance after stroke. The reduction in GSR value was found to be statistically significant (p-value < 0.05) using the dependent sample Wilcoxon signed-rank test.

A comparative analysis of %SST (Section III.E.3) for the Affected and Unaffected legs (AL and UAL, respectively) of the subjects with stroke showed a greater unequal distribution of %SST between the AL and UAL during the PreS case as compared to that at the PostS case (Fig. 9). Specifically, we could see a reduction in the inequality between the %SST for the AL and UAL from the PreS case (∼6%) to the PostS case (∼3.7%) inferring improved gait symmetry and postural control [23] while indicating an improvement in gait performance. A dependent sample Wilcoxon signed-rank test revealed that there was a group average PreS -to- PostS case improvement in %SST on the AL (∼9.5%) which was significantly (p-value < 0.05) more than that (∼0.3%) on the UAL (p-value > 0.05).

2) CLINICAL RELEVANCE OF THE GAIT PARAMETERS

To assess the clinical relevance of the physical reconditioning after exposure to our PCI-ART platform, we investigated two of the clinical measures, namely the 10 m walk test [45] and Timed Up and Go (TUG) test [45] quantifying functional gait

TABLE 3. Pearson correlation for clinical measures and gait parameters; TUG:- Timed Up and Go Test; 10MWT:- 10 Meter Walk Test; GSR:- Gait Stability Ratio; SL:- Step Length; SST_AL/UAL:- Single Support Time (AL/UAL); WS:- Walking Speed.

| Clinical Test | GSR | SL | SST_AL | SST_UAL | WS |
|---------------|-----|----|--------|---------|----|
| PreS Case     | TUG | -0.84 | -0.54 | -0.67 | -0.83 |
|               | 10MWT | -0.92 | -0.66 | -0.59 | -0.95 |
| PostS Case    | TUG | -0.91 | -0.23 | -0.41 | -0.94 |
|               | 10MWT | -0.96 | -0.25 | -0.41 | -0.96 |
Step Length were considerably correlated with the scores seen from Table 3 that both the Gait Stability Ratio and the TUG test during each of performance) with the scores of the 10 m Walk Test and of each of the gait-related indices (quantifying the gait ability [58]. For this, we computed the Pearson Correlation TABLE 4. Participant’s feedback.

| ID | Question                                      | Rating |
|----|-----------------------------------------------|--------|
| Q1 | Were you comfortable in wearing the shoes?    | 5      |
| Q2 | Were you comfortable during the treadmill-assisted exercise? | 4.8    |
| Q3 | Did you realize any alteration in your manner of walk? | 4.9    |

ability [58]. For this, we computed the Pearson Correlation [56] of each of the gait-related indices (quantifying the gait performance) with the scores of the 10 m Walk Test and TUG test during each of \( \text{PreS} \) and \( \text{PostS} \) cases. It can be seen from Table 3 that both the Gait Stability Ratio and the Step Length were considerably correlated with the scores of the 10 m Walk Test and TUG test during both the \( \text{PreS} \) and \( \text{PostS} \) cases. However, that was not the case with the %Single Support Time while considering the contribution of both the AL and UAL. Additionally, given the fact that one’s gait speed is a critical outcome variable after stroke and a strong predictor of physical function with regard to community ambulation [59], we found that the 10 m walk test and TUG scores were strongly correlated with the Walking Speed of \( \text{Group}_{\text{Post}} \) during \( \text{PreS} \) and \( \text{PostS} \) cases (Table 3).

In fact, further analysis on Walking Speed revealed that the group average Walking Speed increased from 0.8 m/s (for \( \text{PreS} \) case) to 1.1 m/s (for \( \text{PostS} \) case) inferring improvement in their community ambulation. In short, we can say that both the Gait Stability Ratio and the Step Length (as measured by the Gait Characterization Shoes) can offer useful insights to one’s gait-related physical reconditioning after multiple exposures to the PCI-ART platform.

3) VIEWS OF SUBJECTS WITH STROKE ON THE USABILITY OF PCI-ART PLATFORM AND ITS CONTRIBUTION TOWARDS THEIR COMMUNITY AMBULATION CAPABILITIES

After completion of the study, the experimenter collected the views on the usability of the PCI-ART platform from subjects with stroke and their perception on the contribution of this platform towards their physical reconditioning in terms of their community ambulation capabilities. For this, we conducted a small survey comprising of three questions (Q1-Q3) adopted from the User Satisfaction Evaluation Questionnaire [50]. The participants were asked to respond to each question using a 1-5 scale (1: ’not at all’ and 5: ’very much’). Table 4 indicates the average rating by the \( \text{Group}_{\text{PostS}} \) for each question. In response to Q1, all our subjects with stroke expressed that they were comfortable with the instrumented shoes while walking. In response to Q2, most of them (except P3 and P6) mentioned that they did not feel any inconvenience during exercise and expressed that they felt safe with the safety harness. Specifically, P3 said that he felt the harness to be a bit heavy, although he agreed that he felt safe with the harness while using the treadmill. Again, P6 mentioned that though the safety harness was provided to him during the treadmill-assisted walk, yet he had a fear that he might fall during walking. Additionally, all of the participants expressed that they felt motivated to continue with the gait exercise using the PCI-ART platform since the exercise environment offered them with audio feedback. The visual feedback offered by PCI-ART helped them to gauge their gait performance. Also, they mentioned that they can carry on with the gait exercise using the PCI-ART platform even without the clinician’s continuous intervention. Even some of them commented that if such platforms are available at their homes, they can carry out gait exercise using such platforms at their homes without the need to commute long distances for coming to the clinic. Concerning Q3, all of the subjects with stroke (except P6) were very positive in reporting their notion on the improvement in their community ambulation ability. For example, P1, P2, P4, P6, and P7 commented that they felt more confident while crossing the street leading to the clinic. Though the gait performance of P6 (eldest in the \( \text{Group}_{\text{PostS}} \)) had improved considerably (since he started coming to the study center on his own after five exposures and expressed that he was confident in traveling alone), yet he wanted to have more exposure to our PCI-ART platform hoping that his gait performance can improve further. The same was true for P3, P5, P8 and P9 who told that they could make better use of their affected leg (than before) during their community ambulation. Also, after exposure to the PCI-ART platform, the patients reported that they were feeling less tired in general while walking that can be inferred in terms of reduced energy expenditure during community ambulation. To summarize, we can say that our PCI-ART gait exercise platform can be acceptable by the target users and has the capability of contributing to post-stroke physical reconditioning and improvement in community ambulation.

V. DISCUSSION AND CONCLUSION

In our present work, we have implemented a novel PCI-sensitive Adaptive Response Technology (PCI-ART) platform that was tested with able-bodied subjects (Phase 1 of our study) before applying it to the subjects with stroke (Phase 2 of our study). In Phase 1, we investigated the safety and feasibility of the use of the PCI-ART platform by able-bodied subjects. Our findings of Phase 1 indicated the feasibility of our platform to be used by a user. In Phase 2, we examined the implications of gait exercise with the PCI-ART platform offering individualized dosage of exercise intensity on the cardiac and gait performance of the subjects with stroke. We also investigated the gait-related clinical measures of the subjects with stroke undergoing gait exercise using the PCI-ART platform to estimate the clinical relevance of the physical reconditioning offered by this platform. Lastly, we examined the patients’ views on the usability of the PCI-ART platform along with their perception on the contribution of this platform towards their physical reconditioning in terms of their community ambulation capabilities. The results of Phase 2 of our study revealed that the PCI-ART platform offering adaptive and progressive gait exercise with dosage of exercise intensity being individualized to one’s cardiac capacity was (a) acceptable by the subjects with stroke and (b) capable...
of bringing in improvement in their cardiac (quantified in terms of PCI) and gait (quantified in terms of gait parameters) performance.

The PCI-ART platform offered varying exercise intensities by changing the treadmill speed. However, unlike the traditional self-paced treadmill that automatically adjusts speed to match one’s Walking Speed in real time [60], the PCI-ART platform either maintained or increased the treadmill speed based on one’s Walking Speed along with monitoring the energy expenditure, quantified by PCI. The traditional self-paced treadmill have been shown to affect one’s spatiotemporal gait parameters [61], while the PCI-ART platform can have implications on both the spatiotemporal gait parameters and the energy consumption while undergoing gait exercise. Also with walking ability being adversely affected along with reduced motivation to do exercise, the subjects with stroke might tend to walk slowly with their self-selected Walking Speed thereby operating in their comfort zone while using self-paced treadmill that can restrict the rehabilitation outcomes. This is true since literature indicates that walking at faster speed can be beneficial for achieving improved rehabilitation outcomes compared to the self-selected Walking Speed [62]. The PCI-ART platform was designed to promote increased Walking Speed based on one’s ability thereby pushing the subject with stroke beyond his / her comfort zone while ensuring safety to the patient during gait exercise. Again, with regard to the protocol of exposure and the intensity of gait exercise, High Intensity Interval Treadmill training offers burst of high intensity gait exercises with intermediate rest periods. Such training has been shown to contribute to the improvement in one’s gait performance and aerobic capacity. In fact, Munari et al. showed that the High Intensity Interval Treadmill training can improve the gait performance in terms of spatio-temporal gait-related indices and peak Oxygen consumption [28]. Though powerful, this does not offer adaptive and progressive gait exercise based on one’s exercise capability that can be crucial for subjects with stroke who often suffer from limited cardiac capacity [2], [4] and adversely affected gait [3]. In contrast the PCI-ART platform can offer adaptive and progressive gait exercise while varying the dosage of exercise intensity based on the cardiac capacity and gait ability of the subject with stroke. Further, literature indicates that treadmill-based gait exercise coupled with VR-based feedback can contribute towards improvement in one’s gait performance in terms of gait-related clinical measures [18] and community ambulation [24]. This was in line with our findings while the subjects with stroke used the VR-enabled PCI-ART platform.

Though the results are encouraging, our present study had certain limitations. One of the limitations was the small sample strength of subjects with stroke (with a rather lower mean age of ~48 years except (P6), unlike individuals ≥65 years constituting ~3/4th of all the strokes [63]) and the exposure duration being restricted to ~1 month. This was due to the unavailability of subjects with stroke over the duration of nearly one month. Another limitation of our study was not being able to enrol all participates in Phase 2 of our study. In fact, on asking the participants from Phase 1 for continuing their participation for eight more exposures, most of them told that they cannot continue for one month. Again, our subjects with stroke had heterogeneous characteristics in terms of varied post-stroke periods, ambulation and cardiac capabilities, thereby requiring different dosage of exercise intensities. This was because these participants were enrolled purely based on convenience sampling (as available through referral). While most of the subjects with stroke in our study were below 65 years, in future we plan to include elderly patients as well in our studies. For this, our platform needs to be extended to monitor other important vitals, such as blood pressure, blood oxygen level, etc. Although the blood pressure of the subjects with stroke was checked by the therapist in our team during clinical examination before enrolling in our study, our PCI-ART platform did not keep a record of the blood pressure data. This is important particularly for in-home rehabilitation programs after stroke. Additionally, the elderly individuals with stroke demonstrate increased risk of fall and related injuries [64]. Thus the participants should be screened using Falls Efficacy Scale (FES) [65] before exposing them to such a platform. Further, only male subjects with stroke volunteered in our study. Females did not volunteer because of demographic limitations. Added to this, while enrolling participants, we took care that the participants did not possess any severe physical limitations that can affect their walking ability at higher speeds. For this, we enrolled only those subjects with stroke who could walk independently without any external support. Also, the VR-based GUI of the PCI-ART platform offered some audio-visual feedback to the participants. Since the PCI-ART platform has access to the gait performance and cardiac measures of the user, in future, we plan to extend it to offer other audio-visual information on the various measures to the user and records on their progressive improvement to the caregivers. Further, our current study was conducted as a proof-of-concept study and not as a full-fledged home-based clinical study. In future, we plan to conduct longitudinal home-based studies involving both able-bodied subjects and those with stroke while offering them with increased number of exposures to the PCI-ART platform. Subsequently, we plan to conduct full-fledged survey comprising of USEQ [50] and quality of life (SS QoL) [66], check measures using FES [65] and Berg Balance Scale [45]. One of the challenges, particularly for implementing in-home PCI-ART platform can be the cost of the entire system. Two of the expensive components of the present PCI-ART platform are the Task Computer and the BioPac MP150 for measuring the Heart Rate information. To address the issue of cost while preparing for home-based studies, our present research is in porting our algorithm (namely the Adaptive Speed Engine (ASE)) to cost-effective lattepanda board [67] while interfacing the board with commercially-available watch offering heart rate and blood pressure information [68]. Subsequently, we plan to interface the pre-programmed lattepanda board to (a) any
LCD or LED monitor (can be a Television available at homes) for offering the VR-based graphical user interface and (b) motorized treadmill (available at homes). The rest of the items, namely the Speed Tracker and Speed Modulator being cost-effective portable units can be easily interfaced with the home-based treadmill setup.

Notwithstanding the limitations, the findings of our study with the PCI-ART gait exercise platform were promising and the feedback from the subjects with stroke using our platform was encouraging. Thus, we hope that the PCI-ART gait exercise platform can pave the way towards implementing a home-based individualized exercise platform that can monitor one’s cardiac and gait performance capabilities. In turn, it can offer an adaptive and progressive gait exercise environment to the individuals with stroke while providing exercise challenges within the safety thresholds suitings one’s exercise capabilities. Such a platform can hold promise to bring in a paradigm shift in the post-stroke healthcare in low-resource settings like India.

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**REFERENCES**

[1] J. D. Pandian and P. Sudhan, “Stroke epidemiology and stroke care services in India,” J. Stroke, vol. 15, no. 3, pp. 128–134, 2013, doi: 10.5853/jos.2013.15.3.128.

[2] A. S. Ryan, C. L. Dobrovolny, K. H. Silver, G. V. Smith, and R. F. Macko, “Cardiovascular fitness after stroke: Role of muscle mass and gait deficit severity,” J. Stroke Cerebrovasc. Diseases, vol. 9, no. 4, pp. 185–191, Jul. 2000, doi: 10.1053/jscd.2000.7237.

[3] G. E. Gresham, T. E. Fitzpatrick, P. A. Wolf, P. M. McNamara, W. B. Kannel, and T. R. Dawber, “Residual disability in survivors of stroke—The Framingham study,” New England J. Med., vol. 293, no. 19, pp. 954–956, Nov. 1975, doi: 10.1056/NEJM197511062931903.

[4] P. Lindsay, K. L. Furie, S. M. Davis, G. A. Donnan, and B. Norrving, “World Stroke Organization global stroke services guidelines and action plan,” Int. J. Stroke, vol. 9, no. A100, pp. 4–13, Oct. 2014, doi: 10.1111/jis.12371.

[5] S. Li, G. E. Francisco, and P. Zhou, “Post-stroke hemiplegic gait: New perspective and insights,” Frontiers Physiol., vol. 9, p. 1021, Aug. 2018, doi: 10.3389/fphys.2018.01021.

[6] R. F. Macko, G. V. Smith, C. L. Dobrovolny, J. D. Sorkin, A. P. Goldberg, and K. H. Silver, “Treadmill training improves fitness reserve in chronic stroke patients,” Arch. Phys. Med. Rehabil., vol. 82, no. 7, pp. 879–884, Jul. 2001, doi: 10.1016/S1050-3819(01)23853-8.

[7] A. Sharma, E. Ladd, and M. K. Unnikrishnan, “Healthcare inequity and physician scarcity: Empowering non-physician healthcare,” Econ. Political Weekly, vol. 48, no. 13, pp. 112–117, 2013.

[8] J. D. Pandian, V. Sitkanth, S. J. Read, and A. G. Thrift, “Poverty and stroke in India: A time to act,” Stroke, vol. 38, no. 11, pp. 3063–3069, Nov. 2007, doi: 10.1161/STROKEAHA.107.496869.

[9] A. Mahmood, I. M. Solomon, C. English, U. Bhaskaran, G. Menon, and N. Manikanand, “Measurement of adherence to home-based exercises among community-dwelling stroke survivors in India,” Physiotherapy Res. Int., vol. 25, no. 2, p. e1827, Jan. 2019, doi: 10.1002/pri.1827.

[10] J. Napolioni, E. Endzyley, I. Jasevičienė, and R. Savickas, “Stroke patients motivation influence on the effectiveness of occupational therapy,” Rehabil. Prakt. Prakt., vol. 2018, pp. 1–7, Jul. 2018, doi: 10.1155/2018/9367942.
W. M. Chung, S. Yeung, C. H. Pak, and R. Lee, “Validity of VICON motion tracking system,” in IEEE Proc. IEEE Proceedings. Int. Conf. Robot. Autom., vol.3, May 1990, pp. 1646–1652, doi: 10.1109/ROBOT.1990.126246.

A. Field, “Non-parametric models,” in Discovering statistics using IBM SPSS statistics, 4th ed. Los Angeles, CA, USA: Sage, 2014.

M. Arapzoup, M. A. Bani, S. W. Hutchins, and R. K. Jones, “The physiological cost index of walking with mechanical and powered gait orthosis in patients with spinal cord injury,” Spinal Cord, vol. 51, no. 5, pp. 356–359, May 2013, doi: 10.1088/1362-3079/7/2/353.

T. Thaweewannakij, P. Suwannarat, L. Mato, and S. Amatachaya, “Functional ability and health status of community-dwelling late age elderly people with and without a history of falls,” Hong Kong Physiotherapy J., vol. 34, no. 1-9, Jun. 2016, doi: 10.1016/j.hkpj.2015.08.001.

A. Schmid, P. W. Duncan, S. Studenski, S. M. Lai, L. Richards, S. Perera, and S. S. Wu, “Improvements in speed-based gait classifications are meaningful,” Stroke, vol. 38, no. 7, pp. 2096–2100, Jul. 2007, doi: 10.1161/STROKEAHA.107.122520.

E. H. Sinitski, E. D. Lemaire, N. Baddour, M. Besemann, N. L. Dudek, and J. S. Hebert, “Fixed and self-paced treadmill walking for able-bodied and transfemoral amputees in a multi-tenant virtual environment,” Gait Posture, vol. 41, no. 2, pp. 568–573, Feb. 2015, doi: 10.1016/j.gaitpost.2014.12.016.

L. H. Sloot, M. M. van der Krogt, and J. Harlaar, “Self-paced versus fixed speed treadmill walking,” Gait Posture, vol. 39, no. 1, pp. 478–484, Jan. 2014, doi: 10.1016/j.gaitpost.2013.08.022.

A. Lamontagne and J. Fung, “Faster is better: Implications for speed-intensive gait training after stroke,” Stroke, vol. 35, no. 11, pp. 2543–2548, Nov. 2004, doi: 10.1161/01.STR.0000144685.88760.d7.

M. Youssufuddin and N. Young, “Aging and ischemic stroke,” Aging, vol. 11, no. 9, pp. 2542–2544, May 2019, doi: 10.18632/aging.101931.

S. K. Liu and M. H. Nguyen, “Elderly stroke rehabilitation: Overcoming the complications and its associated challenges,” Current Gerontol. Geri- atrics Res., vol. 2018, pp. 1–9, Jun. 2018, doi: 10.1155/2018/9853837.

I. Muus, L. S. Williams, and K. C. Ringsberg, “Validation of the stroke specific quality of life scale (SS-QOL): Test of reliability and validity of the Danish version (SS-QOL-DK),” Clin. Rehabil., vol. 21, no. 7, pp. 620–627, 2007.

M. E. Tinetti, D. Richman, and L. Powell, “Falls efficacy as a measure of fear of falling,” J. Gerontol., vol. 45, no. 6, pp. P239–P243, Nov. 1990, doi: 10.1093/geronj/45.6.P239.

J. W. P. Kuzieck, E. X. Redman, G. D. Splinter, and K. E. Mathewson, “Increasing the mobility of EEG data collection using a laptop panda computer,” J. Neurocomput. Methods, vol. 308, pp. 34–47, Oct. 2018, doi: 10.1016/j.jneumeth.2017.07.013.

S. Gradl, M. Wirth, R. Richer, N. Rohleder, and B. M. Eskofier, “An overview of the feasibility of permanent, real-time, unobtrusive stress measurement with current wearables,” in Proc. 13th EAI Int. Conf. Pervasive Comput. Technol. Healthcare, May 2019, pp. 360–365, doi: 10.1145/3329189.3329233.
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