Displays 34 (2013) 125–131

Contents lists available at SciVerse ScienceDirect

Displays

journal homepage: www.elsevier.com/locate/displa

Motion games improve balance control in stroke survivors: A preliminary study based on the principle of constraint-induced movement therapy

Qicheng Ding [a,1], Ian H. Stevenson [b,1], Ninghua Wang [c], Wei Li [c], Yao Sun [a], Qining Wang [a], Konrad Kording [d], Kunlin Wei [a,*]

[a] Department of Psychology, Key Laboratory of Machine Perception (Ministry of Education), Beijing Engineering Research Center of Intelligent Rehabilitation Engineering, Peking University, Beijing, China

[b] Redwood Center for Theoretical Neuroscience, University of California, Berkeley, CA, USA

[c] Department of Rehabilitation Medicine, First Hospital, Peking University, Beijing, China

[d] Department of Physical Medicine and Rehabilitation, Rehabilitation Institute of Chicago, Northwestern University, Chicago, IL, USA

ARTICLE INFO

Article history:
Available online 27 August 2012

Keywords:
Virtual reality
Stroke rehabilitation
Balance control
Constraint-induced movement therapy
Motion games
Nintendo Wii

ABSTRACT

Stroke patients with hemiparesis often exhibit an asymmetrical weight distribution, with the paretic leg providing less support and less weight-shift activity than the sound leg does. For upper-limb hemiparesis constraint-induced movement therapy (CIMT), where the sound limb is constrained and the patient is forced to use the paretic limb, has proven to be one of the most effective rehabilitation methods. However, this method has not been successfully modified for balance rehabilitation, since hard constraints on the lower limb are difficult to impose and can increase the risk of patient injuries. Here we introduce a novel approach that encourages stroke survivors to use the paretic leg for weight-shifting tasks during balance control training in a virtual reality setting. We recorded motion signals from each leg in real time and streamed modified versions of these signals to the Nintendo Wii Fit gaming system. By independently manipulating the influence of each leg during game play, we successfully forced the stroke survivors to increase the use of the paretic leg. Our preliminary clinical trial, including three patients with hemiparesis in the chronic phase, found that one-week of training improved patients' ability to maneuver their center of pressure (COP) during a tracking task. More encouragingly, patient's weight distributions became more symmetrical. These initial results suggest that manipulating control gains during VR rehabilitation may allow the principles of CIMT to be applied during balance training in stroke survivors.

1. Introduction

Stroke is associated with a sudden loss of neurological function due to intracranial vascular problems. The occurrence of stroke is high in developed countries as well as in developing countries: the number of stroke occurrences in the United States has increased steadily from 3 million in 1997, to 4.7 million in 2004 and to about 5.8 million in 2009 [1]. Stroke is the leading cause of disability in China and the reported cases of stroke in China are larger than any other countries [2,3]. The socio-economical cost of stroke associated with stroke treatment and rehabilitation is high across the global. For United States alone the direct and indirect medical cost of stroke is estimated to be $34.3 billion for the year of 2008, as estimated by The American Heart Association [1]. By comparison, the estimated cost of all cancers is $219 billion. Stroke results in more disability than death. Among the millions of new stroke survivors each year, more than one half of them experience long lasting disability. This makes long-term management of stroke an important therapeutic, rehabilitation and social issue.

Many stroke survivors have postural and balance problems, such as increased body sway and asymmetric weight distribution, that reduce their mobility and affect their daily life. Conventional in-hospital therapies and recently developed robot-assisted therapies for improving balance in stroke survivors are costly and often difficult to implement. Rehabilitation robots can cost up to hundreds of thousands of dollars, and may only provide limited therapeutic benefits [4]. Moreover, the need for patients to travel to the hospital limits practice time and compliance. Rehabilitation researchers have also resorted to simple computer games for balance training, such as commercially available [5,6] or custom systems [7–9]. The former systems are limited by their high cost and the need for trained therapists to constantly supervise the rehabilitation program. The latter, customized systems are inexpensive but the training tasks they can provide are fairly simplistic, typically prompting patients to shift a cursor that represents their

* Corresponding author. Address: Department of Psychology, Peking University, Beijing 100871, China. Tel./fax: +86 10 62753617.

E-mail address: wei.kunlin@pku.edu.cn (K. Wei).

[1] These authors contribute equally to this paper.

0141-9382/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.displa.2012.08.004

center of pressure (COP) on a computer screen. They are certainly not as engaging as state of the art games on console systems such as Microsoft Xbox, Nintendo Wii or Sony PlayStation see a recent review [10]. Long compliance to a training regime would likely be much higher, if therapeutic systems could leverage the games available on console-based systems. There is a small body of studies trying to introduce virtual reality (VR), particularly motion gaming using the Sony PlayStation EyeToy and Nintendo Wii Fit, into balance training [11–14]. As compared to dedicated VR systems, these gaming systems are inexpensive, portable and easy to set up at home. Therapies that utilize current quality motion games and that are able to improve balance control have the potential to benefit a growing stroke population.

Without rehabilitation, stroke patients tend to stop using the affected, paretic limb after being discouraged by the difficulty. Consequently, the cortical area representing the affected limb is dramatically reduced [15,16]. By constraining the unaffected limb and forcing the patient to use the affected limb, researchers can help patients recover the use of their affected limb. This type of therapy has been named as constraint-induced movement therapy (CIMT) and it usually requires the patient to wear a mitt or a sling on the paretic hand or arm to constrain its use. Through repetitive practice with non-constrained, paretic upper limb, patients can improve their motor control ability even for patients disabled for many years after stroke [17]. As a result, the affected cortical area returns to the normal size [18–20]. This therapy has been recognized by American Heart Association as "the forefront of a revolution", and has led to impressive results for upper limb rehabilitation. Developing effective lower limbs constraints, however, has been challenging. Several studies have examined lower limb CIMT by locking the knee joint of the unaffected leg [21]. However, constraining the lower limbs hinders the patient's mobility and makes maintaining postural stability even more difficult. Moreover, coordination across legs is essential to postural control, in contrast to the upper limbs which are generally much more independent. The challenge of lower limb CIMT is to encourage the use of the affected leg in balance control without hindering the unaffected leg.

In the present study, we combined the principle of CIMT with balance-related motion games for balance rehabilitation in chronic stroke survivors. Our novel system measures the center-of-pressure (COP) of both legs separately and modifies the signals such that the patient needs to make more physical effort in the paretic leg to produce the motion signals (a virtual COP excursion). This augmented COP signal is then routed to a commercially available Nintendo Wii Fit gaming system allowing the subject to control the avatar in first-person balance games. We present case study results from 3 stroke survivors who underwent balance training with this system. We found that compared to conventional stroke rehabilitation, one-week training with the modified Wii Fit system resulted in substantial improvement in the ability to dynamically control COP as well as improvement in stance symmetry. The simplicity and affordability of this VR system make this a potentially useful rehabilitation tool for balance training in stroke patients both in clinical settings and at home.

2. Methods

2.1. Modified VR system

We adopted hardware components from the Nintendo Wii Fit game system (Fig. 1A). Patients stood on two separate balance boards, one for each foot. Each balance board has load cells on each of the four corners that measure the vertical force. Using these four measurements, the center-of-gravity can be estimated. Individual

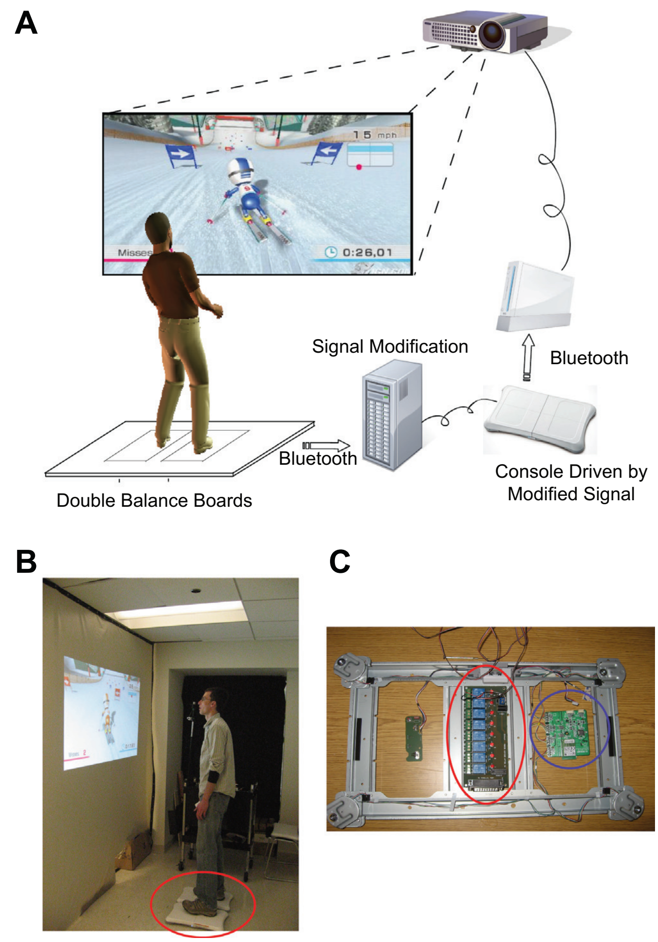

Fig. 1. (A) Schematic illustration of the system setup. The participant stands on an enlarged platform, each foot on an individual Wii Fit balance board. The COP signals and load cell readings from each board are transmitted to a PC via Bluetooth adapter. Signals are then fused and modified to allow the legs to contribute differentially to the game. These virtual control signals are then sent to a modified Wii Fit board, which is connected to a Wii console on which the actual games are played. Visual feedback is provided on a back-projection screen. (B) A healthy control standing on double balance boards to play the Wii Fit game ski slalom with the modified Wii Fit system. (C) An inside view of modified Wii balance board. An A/D card (in the white oval) converts the virtual COP signals received from the computer to analog signals. It then feeds this signal into the control chip onboard (in the black circle). This control chip communicates with the Wii console for gaming.

balance boards have been used previously to assess standing balance [22]. Here two balance boards were placed side by side with a center-to-center distance of 31 cm. Rather than communicating with a Wii console, these two balance boards communicated with a notebook computer via a Bluetooth adapter (Trendnet TBW-104UB). The computer would then use the signals from both boards and combine them in real time into a single "virtual" Wii Fit signal. This was achieved by weighting the COP readings from both boards according to:

$$COP_{virtual} = \alpha \times COP_{unaffected} + \beta \times COP_{affected}$$

where $COP_{unaffected}$ and $COP_{affected}$ are the COP coordinates from the unaffected leg and the affected leg, respectively. α and β are their corresponding weighting gains. $COP_{virtual}$, the virtual center-of-gravity, is a weighted average of two COPs from both legs and it controls the movement of the avatar in game playing. The magnitudes of α and β directly affect the control gains of each leg. For instance, with a smaller β, the affected leg will need to move more to exert the same influence on the combined, virtual COP.

The four force sensor values associated with $COP_{virtual}$ were converted into voltage signals (−5 to 5 V) by an A/D card (Arduino Duemilanove) and fed into a third balance board that was modified to accept analog inputs from external sources instead of the readings of its own load cells (Fig. 1B). A similar modification on the Wii gaming system has been proposed [23]. Our configuration allowed participants to play commercial Wii Fit games with each leg contributing a variable amount of control.

In Wii Fit games, gaming performance is usually determined by the COP movement, which corresponds to $COP_{virtual}$ in our system. Here we can measure the force and COP applied by each individual leg. Importantly, with our hardware design we can change the influence of the signal from each foot separately and adaptively by varying α and β. To encourage patients to use the paretic leg, we assign relatively less weighting to its signals to force the participant to load more on the paretic leg. Specifically, when β is smaller than α, the avatar will lean to one side unless the participant applies more load on the paretic leg. This will thus encourage the patients to make more effort to manipulate weight shifts using the paretic leg in game playing. Too large of a discrepancy between α and β should be avoided, however, as it tends to make game play too challenging. In our experiment, most of the game trials had α set as 1.2 and β at 1, resulting in a gain ratio of 1.2.

The data acquisition programs running on the PC were written in Matlab and the A/D conversion performed by the Arduino card were controlled by an on-board processing program. The actual COP displacement of each leg and the vertical forces from individual load cells of the Wii balance boards were sampled at a frequency of 100 Hz.

2.2. Experiment protocol

Three individuals with chronic hemiparesis subsequent to stroke participated in our study. The study protocol was approved by the Ethnics Committee of Peking University First Hospital, and written, informed consent was obtained from each participant before the study. The participants were 55-, 71- and 78-years old with 25, 78 and 8 months since stroke, respectively. Patient 1 had high blood pressure for 6 years and type-II diabetes for 15 years; patient 2 had high blood cholesterol for 10 years; patient 3 (control) had high blood pressure for 21 years and rheumatic heart disease for 12 years. However, they did not have any motor disorder that prevents them from participation in VR training. They could perform single leg standing and walk independently. Their 10-m walking test was finished within 14, 9 and 8 s, respectively. All participants could comprehend our experimental tasks. The first two participants (test group) took part in our balance training and had left and right hemiparesis, respectively. The third participant had right hemiparesis and served as a control, only receiving conventional rehabilitation (see below).

The study consisted of 3 weeks of training. In the first and the third week, the two test participants received a 3-h conventional rehabilitation program on each working day. The program included aerobic exercise, muscle strength training, as well as upper-limb and lower-limb functional training. In the second week, the test participants received 30–40 min of Wii training in addition to conventional training on each working day. The total training time remained the same at 3 h by reducing the duration of conventional training. During the Wii training, a therapist and two graduate students accompanied the participants and supervised game play at all times. The control participant received one-week of conventional rehabilitation only.

To facilitate comparisons between trials and between days, we selected the game "ski slalom" as the primary training game. This game requires participants to shift their COP laterally to navigate an avatar through a series of gates, simulating a real ski slalom. It is appropriate for our therapeutic purposes, since it prompts patients to overcome lateral asymmetry. Medio-lateral COP excursions control direction, while anterior–posterior excursion of COP controls the speed of downhill skiing. We found that the two test participants tended to lean forward, resulting in uncontrollable, high speed in the ski game. To correct this bias, we modified $COP_{virtual}$ during A/D conversion by assigning higher weights to the virtual load cells in the back. This produced a slightly backward shift in actual COP used in game playing, similar what would occur with leaning the body backward. With this small modification, participants could play the ski slalom game fluently despite their abnormal posture.

During the first and the second days of VR-training, we randomly selected 9 trials and assigned an α:β ratio of (0.8, 1, 1.05, 1.08, 1.4, 1.5, 1.6, 1.8, 2.0) to examine the systematic effect of control gain on the actual activity of legs. These trials, together with the standard trials (1.2 gain ratio), were analyzed to examine the relationship between gain ratio and the resulting COP movements.

2.3. Performance assessment

To independently evaluate participants' ability to steer their COP, we designed a task that required the participants to track a moving visual stimulus with a COP-controlled cursor. A red target cursor moved left and right on a projection screen, driven by a sinusoidal waveform with a frequency of 0.5 Hz. Participants were required to track the target with a small blue cursor that was driven by their lateral COP excursion. The amplitude of the desired oscillation was 24 cm, and the tests consisted of 1-min long trials. The integral of the distance between the target and the actual COP (called tracking error) was calculated for each trial. The first 5 s of each trial were excluded from the analysis to eliminate the influence of initial transients that occurred as the participants acquired the target.

To assess the symmetry of participant's weight distributions, we also measured the weight bearing on each foot. Participants stood still on the same two Wii balance boards that were used for their VR training. They were required to fixate at the center of the projection screen and remained relaxed for a minute. The vertical loading of each leg was averaged during the period of the trial and the relative ratio between two legs (left versus right, called load ratio) served as a symmetry measure.

For the test group, the COP tracking test and the quiet standing test were conducted on Monday and Friday in the first week to establish a baseline performance level before the VR training week (see Fig. 2C). They were then tested on every working day in the second week (VR training week) and third week (retention week, with conventional therapy only). For the control participant, the tests were conducted every working day of his only training week. These two tests were conducted twice, one before and one immediately after the rehabilitation session on each day and their average were reported. We also gave participants 5 familiarization trials when they first learned the COP tracking test. The inclusion of a control participant for a single week was to test how his COP tracking performance improved without Wii training. The daily averages were reported.

The COP excursion and the weight bearing were also measured during actual game play. In the ski slalom game, the gates, i.e., the intermediate movement goals, are constant across game trials. The COP movements that participants produced would thus follow a similar path with certain trial-to-trial variance. We quantified each leg's involvement in game playing by calculating the range, standard deviation, and total distance of COP excursions within a trial. Similarly, the ratio of weight bearing between the two legs was calculated to assess their symmetry of body weight distribution during active play.

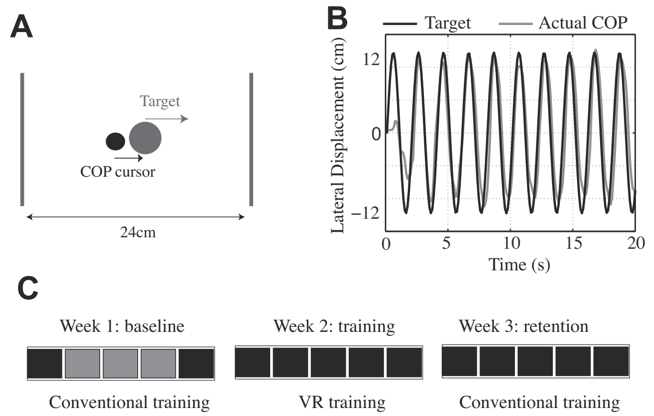

Fig. 2. The visual tracking task designed to evaluate participant's ability to maneuver their COP laterally. (A) Screen display of the task. The target marker moves sinusoidally and continuously between two vertical lines. The black cursor, representing the lateral displacement of the participant's COP, is controlled by the participant to track the target, denoted by the gray disk. (B) A typical COP trajectory measured from participant 1. The gray curve denotes the target movements and the black curve is the actual COP movement. (C) The timeline of experiment for the test group. Each square represents a day of therapy and the filled black square represents a day with tests. Week 1 is to establish a performance baseline; week 2 is for assessing day-by-day learning effect; week 3 is to measure the retention of learning from week 2.

3. Results

Two patients in the test group successfully finished the VR training session without any discomfort or nausea. Depending on participants' performance, the number of game playing trials that each participant could finish within a day varied. On average participants finished 22.2 ± 3.7 trials per day with the number of trials performed on each day varying slightly. We evaluated their performance measures over trials and across days.

Without control gain manipulations the COP movements measured from two feet clearly indicated that the paretic leg has less activity and less weight bearing during normal game (Fig. 3 top). Participant 1 had left hemiparesis and his right leg on average had less weight bearing. This asymmetry was reflected in the COP movement during game playing such that the right leg exhibited much less COP excursion than the left leg. However, when we increased the gain for the affected leg from 1 to 1.2, the weight supported by the right leg increased while the weight supported by the left leg decreased. The COP trajectory appeared to increase its variance slightly.

By quantifying the COP excursions, we confirmed that our manipulation of control gains on individual legs were effective in biasing the relative contribution of the paretic leg in the task (Fig. 4). Using participant 2 as an example, when the gain increased for the left (unaffected) leg, the participant put more body weight on the right (paretic) side such that the overall weight bearing on the right board was higher. Furthermore, the range, distance and standard deviation of the COP movements were reduced for the paretic leg when the gain increased. This might be due to the difficulty subjects encountered in maneuvering the affected leg when it was more loaded. Each of these gain-dependences were approximately linear (linear regression, $p < 0.05$, 0.0005 and 0.01 for load, COP distance, standard deviation of COP, respectively) except for the COP range ($p = 0.11$). These simple linear relationships thus enabled us to quantitatively manipulate the relative activity of each of the participant's legs.

We evaluated the participants' ability to maneuver their COP during three weeks of training (Fig. 5). In the first week of conventional therapy, their performance appeared to remain the same when tested on Monday and Friday. However, during the second week there was a clear tendency of reduction in tracking error over days. This improvement happened mostly at the beginning two days. During the third week, the participants were tested again to examine the retention of learning. Both participants exhibited a rebound in performance (spontaneous recovery) but learning retention was still visible at the end of the third week. For the control participant his tracking error only showed slight improvement over the week of conventional therapy. The average improvements in tracking error (normalized by participants' initial performance) were 27.8%, 46.2% and 8.2% for the two test participants and the control participant, respectively.

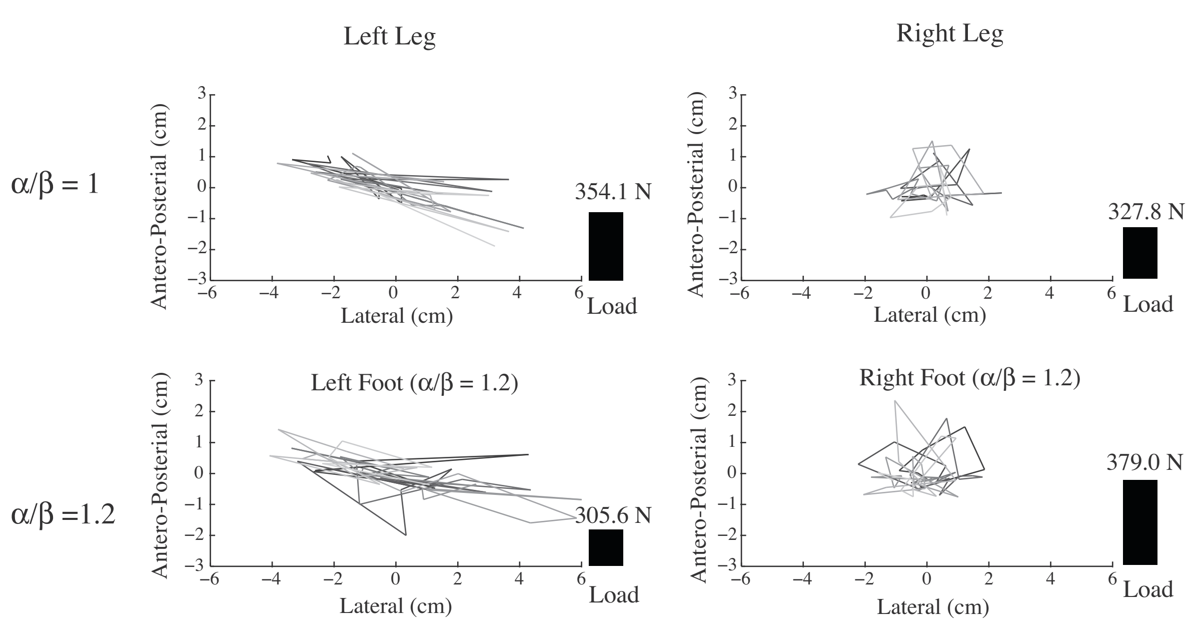

Fig. 3. The COP trajectory and the average loading of two legs during a single trial of game playing. Two trials from participant 1 are shown with gain ratio set at 1 and 1.2, respectively. The trajectory is down-sampled to 20 Hz for clarity with gray level denoting increasing time within the trial. Participant 1 has left hemiparesis; thus, his right side is the affected side.

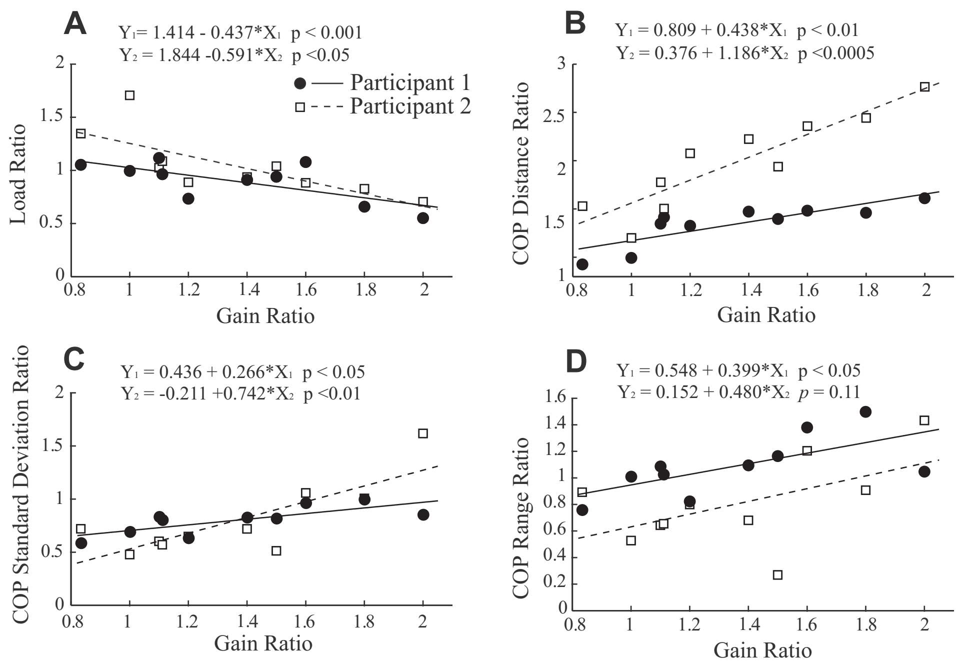

Fig. 4. The ratio of COP measures and load (A) between the left versus the right leg as a function of the ratio of control gains ($\alpha\beta$). The COP measures include the total distance (B), standard deviation (C), and range (D) of lateral COP displacement. The data is from participant 2 whose right leg is paretic. The general trend is similar for participant 2 (not shown). The linear regression equations and their corresponding p-values are also shown for each measure. These results indicate that with increasing gain on the unaffected leg, the relative amplitudes of loading and COP excursion in the paretic leg increases and decreases, respectively.

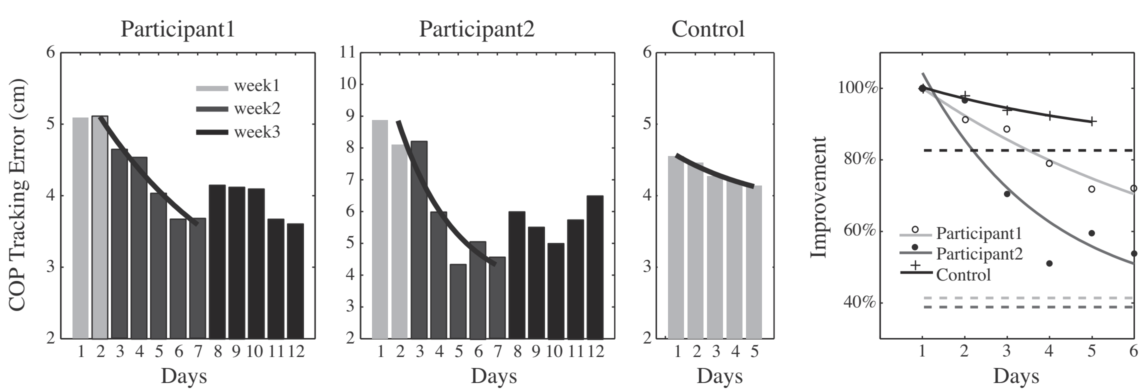

Fig. 5. The average COP tracking error within a day plotted as a function of day. Data from different participants are shown in separate plots. The last panel shows learning curves within one week for each participant; the dotted lines denote the exponential-learning targets.

To assess learning extent and learning rates we fitted an exponential learning function to each participant's data (Fig. 5), according to $y = e^{-t/\tau} + b$, where y is the tracking error, t is the number of the day, τ signifies the learning rate, and b is the learning target. For the test participants, the average performance from the first week was used as the initial performance. Hence, together with data from the VR-training week, the learning curves were derived from performances in 6 days. For the control participant, only data from 5 days could be used. Data from each participant were normalized by dividing their first-day performance. We found that the learning rates varied substantially across participants with $\tau = 7.1$, 3.0 and 5.0 days for two test and the control participants, respectively. On the other hand, the two test participants had much lower learning targets (41.4% and 38.9%, respectively) than the control participant (82.7%). The improvement in COP tracking appears to be substantially larger with VR-training than without.

To evaluate stance symmetry, we examined the relative weight bearing between the legs over the course of training (Fig. 6). On the first day of training, participants 1 and 2 had load ratios smaller and larger than 1, respectively. This was expected as they had left and right hemiparesis and the unaffected leg had higher weight bearing in both cases. Over the course of VR-training the load ratio trended towards 1, indicating that more weight was being put on the paretic leg. This improvement in weight distribution was still visible during the third week (after the VR training). In contrast, the control participant did not show a similar improvement during the week of conventional rehabilitation. We performed linear regression on the load ratio against the number of days (Fig. 6) to assess the trend of change. Both test participants have significant linear trends ($p < 0.05$) towards 1, while the control participant did not show the same trend ($p = 0.11$). These results suggest that, in addition to improving dynamic tracking accuracy, VR-training can improve stance symmetry.

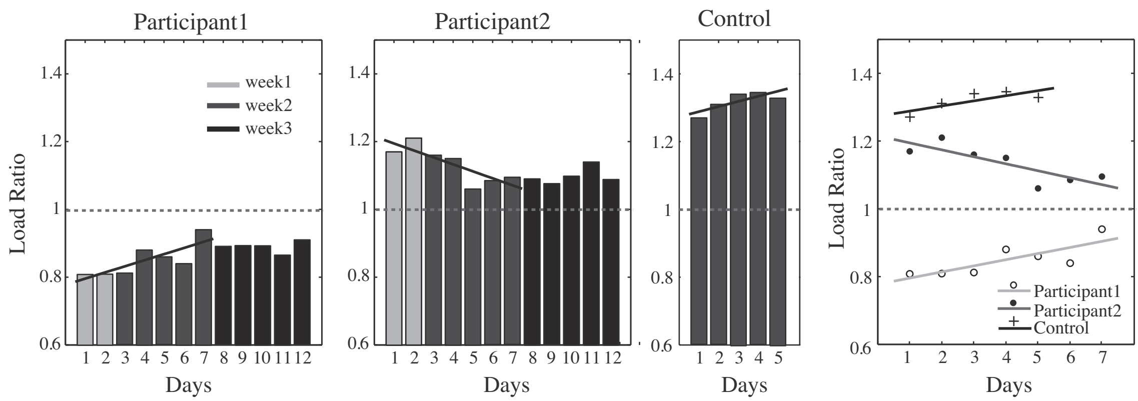

Fig. 6. The ratio of loading between the left versus the right leg during quiet standing. Each bar denotes an average load ratio of two 1-min long trials collected on a single day. Data from different participants are shown in separate plots. The dash horizontal line denotes a load ratio of 1, which is typically observed in the healthy. The right-most panel shows the linear regression of the load ratio over the course of one week. Note that the test participants trend towards a symmetric stance.

4. Discussion

The present study applied the principles of CIMT to lower-limb balance rehabilitation by using a modified off-the-shelf motion gaming system. Our preliminary results from three chronic stroke patients with hemiparesis demonstrated that a virtual reality system with augmented control gains can increase weight bearing on the paretic leg. Compared to a conventional stroke rehabilitation program, one week of training with this modified CIMT rehabilitation improved participants' performance in COP tracking and stance symmetry. Although our study is a small-sample clinic study, our results suggest that the principles of CIMT therapy may be applied to balance training in stroke survivors with a low-cost, customizable VR system.

One of the goals of constraint induced movement therapy is to encourage stroke survivors to make use of their paretic limb. Without correction, functional limitations on one side of the body can cause stroke survivors to use their unaffected side more frequently, leading to further physical deteriorations on the paretic side. Although most off-the-shelf gaming systems lack the capacity to control the influence of different limbs [11–13], our VR system can modulate the control gains of individual legs during game play. Our manipulation increases weight bearing on the paretic leg and reduces COP excursion, since participants had difficulty maneuvering the leg under higher load. By manipulating the COP signals in different ways we may be able to encourage greater excursions as well. Here we have simply shown that our modified system can apply CIMT principles to encourage participants to make use of their paretic limb.

With our VR training, participants exhibited substantial reductions in tracking error during a COP tracking task and increases in stance symmetry. These results suggest that both dynamic and static stability may be improved by a modified balance game therapy. Although it is difficult to draw strong conclusions from the limited patient sample in our study, our initial results are encouraging.

In the tracking task a portion of the observed improvement is likely to be contaminated by practice effects. However, we attempted to minimize the effects of practice by providing five familiarization trials before formal tests on the two testing days in the first week. Since most improvement happened during the second week with VR training and the control participant did not exhibit the same dramatic improvement, most of the improvement cannot be attributed to practice. Moreover, on the third week when subjects had only conventional rehabilitation, both test participants exhibited spontaneous recovery (e.g., [24]). That is, performance did not improve despite having patients having more practice. This recovery may suggest that improvement in dynamic stability was directly related to VR training during the second week. On the other hand, stance symmetry, as assessed by the quiet standing task, appears to be free of practice effects and the lack of spontaneous recovery may suggest that it is possible to retain improvements in symmetry induced by VR training.

Although our findings suggest that VR-based rehabilitation may be an effective approach to lower-limb hemiparesis, our performance metrics may only be capturing very specific learning effects. The Wii Fit games require players to coordinate the trunk and leg muscles to swiftly and accurately shift body weight. The Wii training is, thus, very similar to the COP tracking assessment task. Similarly, the augmented control gain forces participants to load their paretic leg during VR training and encourages a more symmetrical stance. Since a direct transfer of learning may be inflating participants' performance during our evaluation, additional measures are necessary to examine more general improvement in participant's balance. A full-scale clinical trial using balance-related clinic scales such as Berg Balance Scale, Timed-up and Go test and Dynamic Gait Index [12] is necessary to draw any concrete conclusions about the effectiveness of this technology in rehabilitation.

In a full-scale clinical trial it would also be valuable to assess motivation, compliance, and retention. Previous studies on VR rehabilitation have suggested that learning can be sustained up to three or six months [5] and that functional recovery can be transferred to daily activity [25]. Anecdotally, our test participants were generally very satisfied and motivated after playing the Wii-based games, calling the daily session "happy rehabilitation". Although it may be engaging, it is not clear whether game play will have benefits that generalize to daily life.

Our novel approach to combine VR rehabilitation with CIMT overcomes several major drawbacks of previous approaches. A major concern for dedicated VR systems in rehabilitation (such as IREX system) is their high cost [26]. Recent studies in utilizing off-the-shelf motion gaming systems such as Nintendo Wii, Sony PlayStation EyeToy, and stock games in the rehabilitation settings clearly circumvent the cost problem [11–14,25,27,28]. However, these VR systems lack the customization necessary to be useful for patient populations [12]. Due to diverse disabilities, patients often have difficulties engaging in motion gaming environments that are designed for the healthy. Game playing or performance feedback is usually frustrating for the patients, since they can rarely achieve normal performance and rehabilitation practitioners cannot easily change the rating system hard-coded in the stock game. Relative to most dedicated VR systems, our system is inexpensive: modification of the Wii Fit system and inclusion of two additional Wii balance boards costs about $200. In contrast to off-the-shelf gaming systems, our system has the capacity to modify participants' motion signals in real time according to their individual needs. For instance, here we found that the two participants had a tendency to lean forward during game playing, resulting in uncontrollable speeds in the ski slalom game. To correct this we simply assigned large weights to signals from load cells on the back of the balance board such that the virtual player leaned backwards and allowed more fluent game play. Similarly, we could dynamically and adaptively change the control gain of each leg to continually encourage the use of the paretic leg over the course of rehabilitation. The VR system presented here allows a high degree of customization and can balance effort and ease of use during balance rehabilitation.

Our system also has the potential to be a true remote rehabilitation system, such that post-stroke therapy programs can be performed and monitored at home [29,30]. Our system stores all of the motion signals from VR training on a PC. This rich data set contains a complete record of training outcomes and can be analyzed by health practitioners who can then make necessary adjustments or suggestions according to each individual's baseline performance and progress during the rehabilitation program.

5. Conclusion

Here we have presented initial efforts towards a low-cost, customizable, lower-limb VR rehabilitation system. Our study applies CIMT principles to lower-limb balance rehabilitation in stroke survivors via a novel modification of an off-the-shelf motion game system. By augmenting the control gain between motion signals to the movement of virtual avatars in VR, we successfully encouraged chronic stroke survivors to use the paretic leg with more effort. Our preliminary clinic trial demonstrated that this VR-based CIMT training improved dynamic stability and weight symmetry in two chronic stroke survivors, relative to the control patient who only received conventional rehabilitation. Although these initial results are encouraging, our technique requires a full-scale case-control clinic trial to test its effectiveness across patients with varying deficits. Whether and how the benefits observed in the study can be retained and transferred to daily life call for further investigation.

Acknowledgments

This work has been funded by the National Natural Science Foundation of China (Nos. 61005082, 31000456, & 61020106005), the Fundamental Research Funds for the Central Universities.

References

[1] Donald Lloyd-Jones, M.C. Robert Adams, Giovanni De Simone, T. Bruce Ferguson, Katherine Flegal, Earl Ford, Karen Furie, Alan Go, Kurt Greenlund, Nancy Haase, Susan Hailpern, Michael Ho, Virginia Howard, Brett Kissela, Steven Kittner, Heart disease and stroke statistics—2009 update: a report from the American heart association statistics committee and stroke statistics subcommittee, Circulation 119 (2009) 21–181.
[2] M. Liu et al., Stroke in China: epidemiology, prevention, and management strategies, The Lancet Neurology 6 (5) (2007) 456–464.
[3] D. Zhao et al., Epidemiological transition of stroke in China, Stroke 39 (6) (2008) 1668–1674.
[4] J. Mehrholz et al., Electromechanical and robot-assisted arm training for improving arm function and activities of daily living after stroke, Cochrane Database of Systematic Reviews (Online) (4) (2008).
[5] P.T. Cheng et al., Effects of visual feedback rhythmic weight-shift training on hemiplegic stroke patients, Clinical Rehabilitation 18 (7) (2004) 747–753.
[6] S.H. Jang et al., Cortical reorganization and associated functional motor recovery after virtual reality in patients with chronic stroke: an experimenter-blind preliminary study, Archives of Physical Medicine and Rehabilitation 86 (11) (2005) 2218–2223.
[7] R.A. Geiger et al., Balance and mobility following stroke: effects of physical therapy interventions with and without biofeedback/forceplate training, Physical Therapy 81 (4) (2001) 995.
[8] A. Shumway-Cook, D. Anson, S. Haller, Postural sway biofeedback: its effect on reestablishing stance stability in hemiplegic patients, Archives of Physical Medicine and Rehabilitation 69 (6) (1988) 395.
[9] C.M. Sackley, N.B. Lincoln, Single blind randomized controlled trial of visual feedback after stroke: effects on stance symmetry and function, Disability and Rehabilitation 19 (12) (1997) 536–546.
[10] G. Saposnik, M. Levin, Virtual reality in stroke rehabilitation, Stroke 42 (5) (2011) 1380–1386.
[11] J. Deutsch et al., Wii-Based Compared to Standard of Care Balance and Mobility Rehabilitation for Two Individuals Post-Stroke, IEEE, 2009.
[12] H. Sugarman et al., Use of the Wii Fit System for the Treatment of Balance Problems in the Elderly: A Feasibility Study, IEEE, 2009.
[13] G. Saposnik et al., Effectiveness of virtual reality using Wii gaming technology in stroke rehabilitation a pilot randomized clinical trial and proof of principle, Stroke 41 (7) (2010) 1477–1484.
[14] S. Flynn, P. Palma, A. Bender, Feasibility of using the sony playstation 2 gaming platform for an individual poststroke: a case report, Journal of Neurologic Physical Therapy 31 (4) (2007) 180.
[15] P. Cicinelli, R. Traversa, P. Rossini, Post-stroke reorganization of brain motor output to the hand: a 2–4 month follow-up with focal magnetic transcranial stimulation, Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control 105 (6) (1997) 438–450.
[16] R.J. Nudo, G.W. Milliken, Reorganization of movement representations in primary motor cortex following focal ischemic infarcts in adult squirrel monkeys, Journal of Neurophysiology 75 (5) (1996) 2144–2149.
[17] K.C. Lin et al., Effects of modified constraint-induced movement therapy on reach-to-grasp movements and functional performance after chronic stroke: a randomized controlled study, Clinical Rehabilitation 21 (12) (2007) 1075–1086.
[18] T. Elbert et al., Increased cortical representation of the fingers of the left hand in string players, Science 270 (5234) (1995) 305.
[19] C.E. Levy et al., Functional MRI evidence of cortical reorganization in upper-limb stroke hemiplegia treated with constraint-induced movement therapy, American Journal of Physical Medicine & Rehabilitation 80 (1) (2001) 4.
[20] J. Liepert et al., Treatment-induced cortical reorganization after stroke in humans, Stroke 31 (6) (2000) 1210–1216.
[21] K. Numata et al., Effect of modified constraint-induced movement therapy on lower extremity hemiplegia due to a higher-motor area lesion, Brain Injury 22 (11) (2008) 898–904.
[22] R.A. Clark et al., Validity and reliability of the Nintendo Wii balance board for assessment of standing balance, Gait & Posture 31 (3) (2010) 307–310.
[23] H. Oppenheim, R.S. Armiger, R.J. Vogelstein, WiiEMG: A Real-Time Environment for Control of the Wii With Surface Electromyography, IEEE, 2010.
[24] R.A. Rescorla, Spontaneous recovery, Learning & Memory 11 (5) (2004) 501–509.
[25] M.R. Mouawad et al., Wii-based movement therapy to promote improved upper extremity function post-stroke: a pilot study, Journal of Rehabilitation Medicine 43 (6) (2011) 527–533.
[26] P.L. Weiss et al., Video capture virtual reality as a flexible and effective rehabilitation tool, Journal of NeuroEngineering and Rehabilitation 1 (1) (2004) 12.
[27] L.Y. Joo et al., A feasibility study using interactive commercial off-the-shelf computer gaming in upper limb rehabilitation in patients after stroke, Journal of Rehabilitation Medicine 42 (5) (2010) 437–441.
[28] D. Rand, R. Kizony, P.T.L. Weiss, The sony playstation II EyeToy: low-cost virtual reality for use in rehabilitation, Journal of Neurologic Physical Therapy 32 (4) (2008) 155.
[29] L. Piron et al., Motor tele-rehabilitation in post-stroke patients, Informatics for Health and Social Care 29 (2) (2004) 119–125.
[30] T. Kalisch et al., Rapid assessment of age-related differences in standing balance, Journal of Aging Research 2011 (2011).