Stepping Stones – An Augmented Reality Rehabilitation Game

Stuart Armstrong
QinetiQ Inc.
Orlando, Florida
Stuart.armstrong@qinetiq.com

ABSTRACT

Gait disabilities are highly prevalent in veteran populations and include a wide range of symptoms, often caused by trauma or disease. Recent experimental techniques suggests that rapid advancement of Augmented Reality (AR) and hybrid virtual reality (VR) technologies have the potential for simulation of sensorimotor training in gait rehabilitation. This paper describes the development of a game based AR system to support the rehabilitation of lower limb amputees.

The AR system was built was designed to be a standalone wearable system that can be used outside of a clinical setting. Initial trials were held at the Providence Veteran Administration Medical Centers Gait and Motion Analysis Laboratory and the AR system was identified as a novel tool that can be used for gait rehabilitation in the clinic and the home.

ABOUT THE AUTHOR

Stuart Armstrong is the Chief Technology Officer for QinetiQ's Simulation and Training Group. Stuart started his career at the Defense Evaluation and Research Agency (then part of the UK Ministry of Defence) in 1999, developing defense simulations and joined QinetiQ when it was privatized in 2001. Since then, Stuart has been responsible for the practical exploitation and application of many simulation technologies in support of a wide and diverse military user base. In his role as CTO, Stuart provides advice and support to senior decision makers on the impact of emerging technologies on the organization training and education policy. Through his work, Stuart has introduced the concept of Serious Games to the UK military training landscape and has developed numerous novel training applications from the technology. In particular, the fielding of two Urgent Operational capabilities based on games technologies has helped save UK military lives in current operations.

Stepping Stones – An augmented reality rehabilitation game

Stuart Armstrong
QinetiQ Inc.
Orlando, Florida
Stuart.armstrong@qinetiq.com

INTRODUCTION

Gait disabilities are highly prevalent in Veteran populations and include a wide spectrum of symptoms, often caused by trauma or disease. Lower limb injuries can be highly debilitating and often require patients to engage in a long term process of rehabilitation to return to an active lifestyle. For instance, knee ligament reconstruction is a common procedure that has a rehabilitation duration of over six months to regain the patient's full mobility. Parkinson's disease (PD) typically impairs posture and balance, requiring patients to engage in specialized exercise programs to simply maintain ambulation. Lower limb amputees need in depth training to get used to the new prosthesis and improve proprioceptive functioning. Furthermore, continuing postural and balance training for amputees is required to prevent osteoarthritis, a common side effect when using a prosthesis because patients tend to shift their weight onto their healthy leg. For all these impairments, there are a wide variety of rehabilitation techniques used for gait retraining.

Recent experimental techniques suggests that rapid advancement of augmented reality (AR) and hybrid virtual reality (VR) technologies have the potential for stimulation of sensorimotor training in gait rehabilitation. The engaging augmented environment could provide the massive and intense sensorimotor stimulation that is needed for brain recognition. Current VR training rehabilitation techniques require expensive setup of building and equipment and do not offer the potential of in-home rehabilitation to motivate and enable a faster recovery for patients.

BACKGROUND

Traditional rehabilitation programs can involve tedious and repetitive tasks resulting in participants quickly losing interest especially when improvements are not made immediately (Ryan et al, 2009) (Cruz-Cunha, 2012). Early and intensive practice of active functional tasks in an enriched environment has been shown to result in more positive rehabilitation outcomes (Wade et al, 1985) (Burke et al, 2010). In addition, many studies have found a relationship between patient motivation and better therapeutic outcomes (Burke et al, 2010) (Maclean, Pound, 2000).

Research has shown that serious games, VR and AR technologies can be used to provide an enriched environment and transform tedious rehabilitation exercises into engaging activities increasing motivation and participation and ultimately more positive therapeutic outcomes.

There are a number of examples of investigations into the use of VR and AR games for rehabilitation. However, most of those found carried out evaluations with healthy participants rather than studies undertaken to critically examine their effectiveness in a clinical setting. This may reflect the relative infancy of research in the field of using AR games in rehabilitation. Few clinical studies have been carried out to investigate the use of AR for rehabilitation. However, those that have been conducted show promising results giving good cause for further research to be undertaken.

Al-Issa (Al-Issa et al 2012), conducted a systematic review of the literature that investigated effectiveness of AR application in rehabilitation within a physical context, concluding that, 'the existing evidence is limited but that encouraging results indicated that further research should be undertaken and more patient-based studies conducted'. Three of the studies cited are detailed in the following paragraphs.

Baram (Baram et al 2002), investigated the use of a 'virtual tiled floor' to improve gait impairment of PD patients. The virtual tiled floor is presented to the patient on a see through Head Mounted Display (HMD). Fourteen PD patients tested the system in two modes during the study in addition to completing a control reference test with the display turned off. The two test modes were open-loop, where the virtual tiled floor was displayed in perpetual motion towards the observer at the maximum comfortable speed for the patient, and closed loop, where the virtual display was actively adjusted to the user's motion. It was found that, on average, the closed-loop system improved performance by ~26% (speed) or 31% (stride length) with respect to the reference test. It also noted that the standard deviations of the results were high; implying that results should be evaluated mainly on an individual basis with certain PD patients helped significantly (50%-100%). Improvement with other patients helped to a lesser degree. The average result for the open-loop system was found to be half as good as that of the closed-loop system.

Jaffe (Jaffe et al, 2004) evaluated two training interventions for improving gait parameters in individuals with post stroke hemiplegia using a training methodology requiring them to step over objects. Twenty subjects were asked to step over either virtual objects while walking on a motorized treadmill or real foam objects on a 10m walkway. The study found that virtual obstacle training generated greater improvements in gait velocity compared with real training (20.5% vs. 12.2% improvement) during the fast walk test ($p<0.01$). Gait velocity improvements for both training methods in the self-selected walk test were found to be similar (33.3% vs. 34.7% improvement). Jaffe also stated that 'overall, subjects showed clinically meaningful changes in gait velocity, stride length, walking endurance, and obstacle clearance capacity as a result of either training method' with changes persisting for 2 weeks post training.

Kaminsky (Kaminsky et al, 2007), investigated the impact of Visual Cueing Spectacles (VCS) on the functional mobility of people with akinesia due to PD in their home and community environments. The VCS used in this study consisted of a pair of spectacles which displayed a series of horizontal lines that appeared when the user looked at the ground giving the appearance of lines on the surface in front of them. The study found that the use of the VCS improved functional mobility of all six study participants in some way. All six participants were observed to have qualitative improvement in their gait when they used the VCS, including .larger step length (3 participants), decreased rigidity during mobility (four participants), increased arm swing (two participants) and increased ground clearance with decreased shuffling (4 participants).

Games have been shown to increase patient motivation and participation in rehabilitation exercise with some key game design attributes identified as key to their success. AR as a platform for delivering rehabilitation exercises is still in its infancy but has already been recognized as providing a positive tool for enhancing rehabilitation programs and potentially having the advantage over VR systems (Burke et al, 2010) (Al-Issa et al, 2012).

SYSTEM DESIGN

Working with the clinical partner at the Providence Veterans Administration Gait some top level system requirements were developed. The intent is to produce a system that can provide a level of Gait training and rehabilitation outside the clinical environment. The system itself needs to be completely self-contained so that patients can theoretically play at home or other non-clinical settings.

Display

D1	The system shall capture real time video of the environment and relay to the user.
D2	The system shall project a virtual path into the user's field of view.
D3	The system shall project virtual targets on the floor.
D4	The system shall project virtual obstacles on the floor.
D5	The system shall display a real-time score in the user's field of view based upon detection of lower limb positions in relation to virtual targets.
D6	The system shall provide real time feedback on balance in the user's field of view, based on shoulder angle of user.

Tracking

T1	The system shall track and record body position and skeletal tracking at 0.1 second intervals.
T2	The system shall be capable of being configured to adapt to patients height, stride length and intervention duration.
T3	The system shall log to text file user information, start conditions of intervention and tracking data for post analysis.

Hardware

H1	The system shall consist of a Head Mounted Display complete with stereo camera, inertial skeletal tracker, portable PC, and self-contained power.
H2	The system shall be man-wearable.

Initial Game Design

Previous exercise interventions have shown that stepping exercises are an effective treatment method to improve postural stability and balance [11]. The game is designed to encourage mobility around a fixed area while recording and rewarding 'correct' gait characteristics.

The aim of the AR system is to compare and contrast a VR environment (already in use) with an equivalent AR environment. AR is essentially taking two worlds, one a video-representation of the physical world and the other a 3D virtual world and overlaying the latter on the former so as to create a convincing illusion of virtual objects being co-located with the user in the real world.

Full skeletal tracking allows mapping of the motion data captured by the 3DSuit to a virtual avatar, which would follow the user's physical movements 1:1 in the virtual world. As long as the coordinate systems of the both the real and virtual worlds were perceptually aligned, overlaying the virtual world onto the stereo-video image of the real world should create a convincing augmented reality experience.

In this case, targets on the ground of the virtual world should also appear to be lying on the ground of the real world and there would be minimal disconnect when interacting with them (moving around them, stepping on them, etc.). Virtual targets and barriers were created that the virtual avatar could collide with (step on) and score/lose points thus facilitating the gameplay.

The obstacles displayed with the AR system are 1 foot diameter stepping stones and 1'x0.5'x2' foot rectangular obstacles presented at varying distances apart. The distances are scaled base on participant height in order to compensate for varying stride lengths. The subject's goal is to step on the stones and step over the obstacles.

In the VR Environment the obstacles travel at 1.3m per second towards the subject who is walking forward at 1.3m per second. Within the AR environment the obstacles remain static and the patient travels around the room. The patient will score points depending on whether they make contact with the stones –and how close to the center of the stone they step. In addition, making contact with the rectangular objects will show a loss of points. A typical game session will last 30 seconds – the distance travelled in both the VR and AR systems would be approximately 39m (assuming a walking speed of 1.3m/s).

Hardware Design

This project required full skeletal motion tracking and an immersive Head Mounted Display (HMD) for displaying the augmented physical world as accurately as possible. It was important that the completed system be portable and not dependent upon a traditional fixed space motion capture solution. In order to accomplish this, three different hardware technologies were joined together in the Unity game engine using the C# scripting language. An Inertial Labs 3DSuit was used for untethered mobile motion capture, a first generation Oculus Rift served as the HMD and an Ovrvision stereo-camera system called mounted on the HMD and provided realistic video-through capabilities.

The Inertial Measurement Unit (IMU) suit consists of 14 inertial trackers connected via an interface box to a USB 2.0 port and the 5V power output on the USB Hub. From the data generated by the motion suit we could calculate and analyze the following gait characteristics:

- Range of motion of knee (during swing phase).
- Range of motion of ankle.
- Range of motion of hip.
- Side to side motion (trunk instability).
- Anterior posture (when walking) – a behavior that should be discouraged.

Two generations of suits were built, the first generation was a prototype suite with the computation done via a laptop and the second generation suit moved the computation onto a wearable device.

For the first generation suit, the inertial sensors were carefully separated from the board and attached to a full body suit using Velcro as illustrated in Figure 1 and 2.

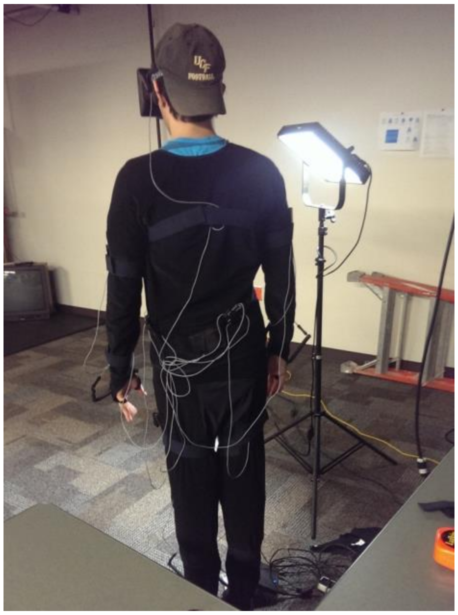

Figure 1 Generation 1 suit in use

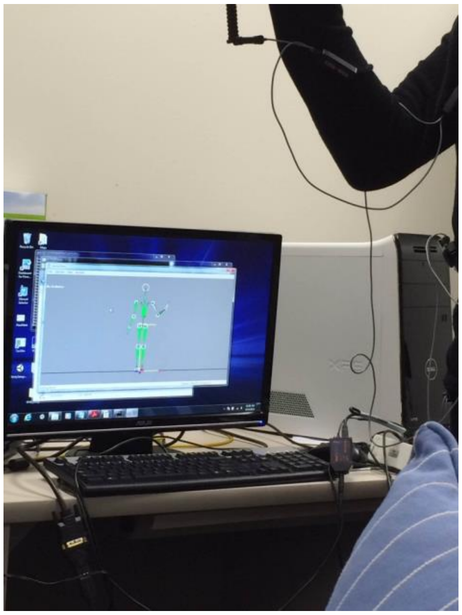

Figure 2 Generation 1 suit driving skeleton

This set-up enabled skeletal limb movements to be implemented and tested, as well as, footfall and gait patterns to be measured within the virtual environment. The suit proved to be a useful first step; however the inertial sensors were prone to movements on the body due to the suit being loose fitting to enable movement of the user. These sensor movements decreased accuracy in measuring the physical location of the limbs as well as occasionally providing skeletal movements that did not match the movement of the user.

The second generation suit was comprised of a tight body vest and ‘chaps’ (small straps), which each hold an inertial sensor as illustrated in Figure 3 and 4. These chaps can be placed by the user on each limb and securely fixed the inertial sensor in place without restricting movements of the user.

Figure 3 Generation 2 suit front view

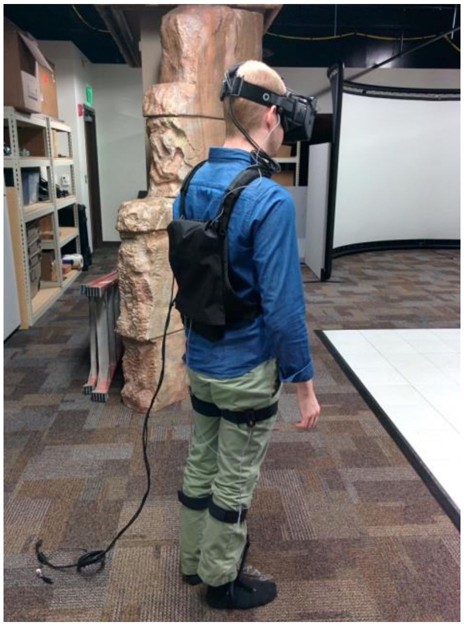

Figure 4 Generation 2 suit rear view

The body 'jacket' housed all the hardware required to operate the game, including power supply, portable PC, and USB hub.

IMPLEMENTATION

The AR system was developed using the Unity game (4.5) engine and involved integrating the Oculus, Ovrvision and Inertial Suit development kits together in the Unity development environment. In addition to the integration and modification of the hardware, target and barrier game objects were created. The target object is a 2 dimension circular objects, approximately 1 foot in diameter that is able to be placed on the floor of the virtual environment. When the avatar object collides with the target object the score is incremented by 10 points and the target is removed from the virtual environment.

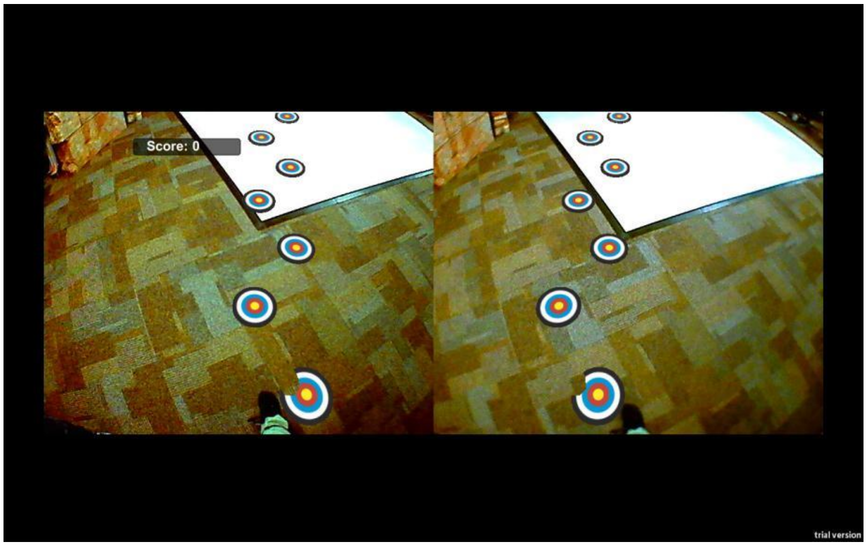

Figure 5 Target objects in the AR environment

The barrier object implementation was a 3D object that can be placed in the virtual world, which when collided with by any part of the avatar deducted points from the overall score.

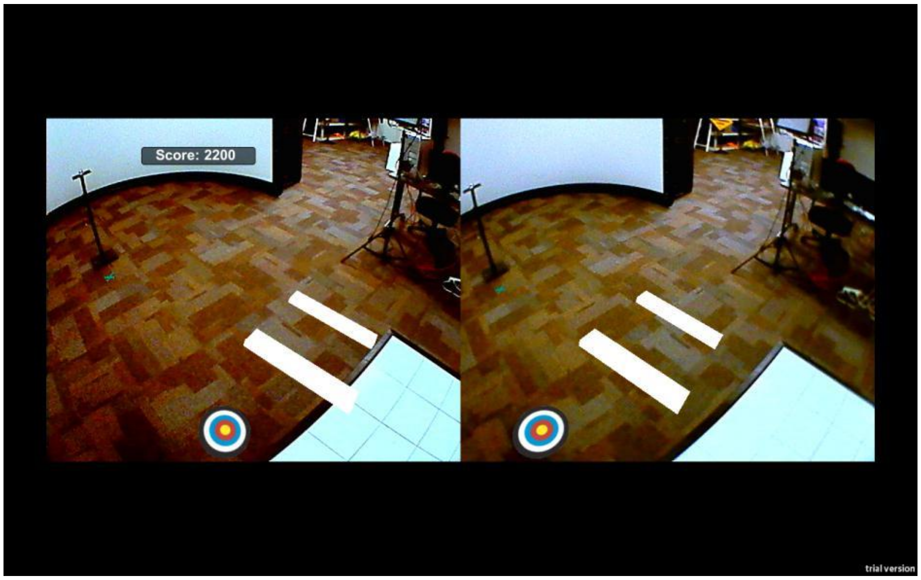

Figure 6 Barrier objects in the AR environment

The biggest challenge by far was the alignment of the virtual and real worlds. Although the Ovrvision documentation specified it matched the FOV of the Oculus, manual measurements suggested the horizontal field of view did not quite match the Oculus Horizontal Field Of View. In addition, the focal length and image distortion of the Ovrvision lenses meant that it was incredibly difficult to align the real and virtual worlds leading to targets that appear to move on the floor.

After several attempts at alignment other solutions were investigated including using physical AR markers for aligning the virtual objects as well as programmatically offsetting their position in three-dimensional space to create the illusion. However, after several experiments the conclusion was made that neither of those solutions would give us the desired results so we returned to the camera-based alignment.

After further experimentation and research we were able to achieve an acceptable level of alignment. The final system was able to take the user's height (provided by the user at the beginning of the experiment) scale the height of the virtual avatar to match and layout the virtual targets at distances appropriate for the user's estimated step length. The user could then walk the course and was able to reliably step on virtual targets and score points while remaining adequately convinced of the augmented reality illusion.

OBSERVATIONS

The final version of the AR system was demonstrated at the Providence Veterans Administration (Providence VA) between the 9th and 10th September 2014. The AR system was evaluated subjectively by the Gait and Motion Analysis laboratory clinical staff and feedback provided on the body tracking system and AR system.

The following observations were made about the sub system components.

Suit and IMU

Two different means to attach the IMUs to the body were presented: the lycra suit and the chaps. The lycra suit, while effective in positioning the IMU sensors and keeping them in place, may not be the best fit for patients. Most individuals will not be comfortable wearing a full body suit due to it being time consuming to change into it and then adding clothing on top.

The chaps seem to be a great alternative to the lycra suit. They can be donned over clothing relatively easily. However, they should be designed to don sitting down especially for patient populations with limited balance and strength to don standing up. Buckles should be replaced with Velcro straps to further facilitate the donning process. An alternative material for the chaps should be considered - something resilient but washable such as neoprene or some type of fabric/foam combination. The IMUs should be fixed on the inside of the chaps next to the skin for a more snug fit. The chaps must also be adjustable to account for patient leg length.

Augmented Reality System

The AR System has been designed to enable the user to see the real world while, at the same time, be presented with virtual obstacles such as stepping stone targets or hurdles. The patient must don the IMU sensors on their legs while wearing a head mounted display with an attached camera. The user is able to see their own feet as well as a virtual foot mapped on top of each foot. To use the AR system, the patient must place his or her foot in the center of the target or lift their foot over the hurdle as they are walking through the room. A score is given for each obstacle. The more accurate and the closer each foot gets to the center of the target, the higher the score. If a target is missed or a foot hits the hurdle instead of clearing it, points are subtracted from the overall score.

The AR System is great way to motivate patients during gait rehabilitation. They can keep track of the score and have instant feedback on how well they are doing. The game itself is challenging and fun while at the same time has the potential to improve balance and mobility. The “gaming” part of it was definitely important. Patients would enjoy this activity and work to improve their score.

Several features need to be improved for a more effective and safe system:

- There is a delay in moving the head and how the targets and the scene shift. This can cause disorientation, which could result in falling or motion sickness.
- Calibration methods need to be simplified.
- The resolution on the screen was very grainy and needs to improve so patients can navigate through the world with more confidence.
- The bull’s eye was a good way to provide accurate targeting of the foot; however, the representation of the virtual hurdles needs to be improved. A three dimensional block would allow the user to see how far they needed to lift their foot to clear the hurdle.
- The view in the head mounted display needs to have a greater peripheral area, primarily downward, in order to see more of the feet relative to the targets.
- A big concern would be the use of the AR system in the home environment primarily due to the potential disorientation, which may require some spotting to prevent unsteadiness and the lack of open space constraints.

Patients that have balance and proprioceptive issues tend to rely heavily upon vision for balance and mobility, particularly knowing where their body is in relation to their environment. This includes patient populations such as amputees, older individuals, diabetics, stroke, etc. AR really challenges this by distorting their visual field with reduced peripheral vision, latency and an unusual presentation of what is real and what is virtual. These issues would have to be resolved in order to make this technology useful to these patient populations otherwise they will not feel comfortable in the environment and reject it as a therapeutic intervention.

CONCLUSIONS

This was the first time these technologies have been brought together into a single system to provide a means of medical rehabilitation. Although in some areas the implementation was immature, the overall system showed good promise in addressing the needs of the clinical community.

The AR System is a novel tool that can be used for gait rehabilitation in the clinic and at home. Many different patient populations can benefit from such a tool. Future research studies could evaluate whether or not this decreases the time needed for rehabilitation and if patients achieve greater functional gains. Therapists could also use report generation functions to decrease the time needed to write medical notes and therefore increase time with patients. The AR system could be used to challenge more functional patients and increase their outcomes beyond what conventional therapy would do. The motivational aspect of this system makes it a great tool for a younger population as well.

The design of the system means it could be used as a home therapeutic tool thus increasing the amount of time patients would have for rehabilitation. Combining the systems in one unit may be advantageous. Patients would be able to train their gait patterns using an Outcome Measurement System, then challenge their gait using the AR System and subsequently re-evaluate how well they are walking. Monitoring the gait patterns while walking in augmented reality may also provide the means to assess gait during real life challenges that are presented within the AR environment.

RECOMMENDATIONS

Based on the comments from the clinical staff during the demonstration the following recommendations are suggested as improvements to the AR system.

Software

- Improved set-up and scoring procedures based off Gait characteristics of patient – In particular a streamlined configuration process that enables game parameters (e.g. target locations) to be automatically generated from simple input characteristics.
- Improved recording and after action review capability – Based off clinically relevant joint angles and an inbuilt skeletal tracking function within the Unity game environment.
- Improvement in real time feedback including special parameters such as stride-length.
- Improved texturing of the virtual barriers to enable better visibility within the environment.

Hardware

- Replace the buckles on some of the inertial sensors with Velcro alternatives.
- Addition of a heart rate monitor and foot-pressure sensors to the hardware mix.
- Upgrade HMD device from Oculus DK1 to Oculus DK2 (improved resolution) and address field of view issues.
- Investigate alternative USB camera’s to replace the Ovrvision (possibly Logitech C130 with upgraded lenses).

ACKNOWLEDGEMENTS

The author would like to acknowledge Providence Veterans Administration Gait and Motion Analysis laboratory for their support and the University of Central Florida i2E laboratory for game development.

REFERENCES

Ryan, M., Smith, S., Chung, B., Cossell, S., Jackman, N., & Kong, J. … Ong, V. (2009). Rehabilitation games – Designing computer games for balance rehabilitation in the elderly. Australia: ACM.

Cruz-Cunha, M. M. (2012) Handbook of Research on Serious Games as Educational, Business and Research Tools: IGI Global.

Wade, D. T., Wood, V. A., & Hewer, R. L., (1985), Recovery after stroke - the first three months, Journal of Neurology, Neurosurgery, and Psychiatry, 48, pp. 7-13.

Burke, J. W., McNeill, M. D. J., Charles, D. K., & Morrow, P. J., Crosbie, J. H., & McDonough, S. M. (2010). Designing engaging, playable games for rehabilitation. Proc. 8th Intl Conf. Disability, Virtual Reality & Associated Technologies Vina del Mar Valparasio, Chilie, 31 Aug. – 2 Sept. 2010, pp. 195-201.

Maclean, N., & Pound, P. (2000). A critical review of the concept of patient motivation in the literature on physical rehabilitation, Social Science & Medicine, 50: 495-506.

Burke, J. W., McNeill, M. D. J., Charles, D. K., & Morrow, P. J., Crosbie, J. H., & McDonough, S. M. (2010) Augmented Reality Games for Upper-Limb Stroke Rehabilitation, 2010 Second International Conference on Games and Virtual Worlds for Serious Applications, pp75-78.

Al-Issa, H., Regenbrecht, H., & Hale, L. (2012) Augmented reality applications in rehabilitation to improve physical outcomes, Physical Therapy Reviews, Vol 17 No 1.

Baram, Y., Aharon-Peretz, J., Simionovic, Y., & Ron, L. (2002) Walking on virtual tiles. Neural Processing Letters; 16(3): 227–33.

Jaffe, D.L., Brown, D.A., Pierson-Carey, C.D., Buckley, E.L., & Lew, H.L. (2004) Stepping over obstacles to improve walking in individuals with poststroke hemiplegia. Journal of Rehabilitation Research and Development; 41(3A): 283–92.

Kaminsky, T.A., Dudgeon, B.J., Billingsley, F.F., Mitchell, P.H., & Weghorst, S.J. (2007) Virtual cues and functional mobility of people with Parkinson's disease: a single-subject pilot study. Journal of Rehabilitation Research and Development; 44(3): 437–48.

Leimkuehler, P, "Outcome Measures in Lower Limb Prosthetics", Online Learning Center, American Academy of Orthotists & Prosthetics.