Motek
a DIH brand

VIRTUAL AND AUGMENTED REALITY BASED BALANCE AND GAIT TRAINING

Authors: Selma Papegaaij, Floris Morang, Frans Steenbrink

WHITE PAPER

February 2017

VIRTUAL AND AUGMENTED REALITY BASED BALANCE AND GAIT TRAINING

Authors:
Selma Papegaaij, PhD, PT; Clinical Applications & Research Manager
Floris Morang; Product Manager
Frans Steenbrink, PhD, PT; Head of Clinical Applications & Research

The use of virtual and augmented reality for rehabilitation has become increasingly popular and has received much attention in scientific publications (over 1,000 papers). This white paper aims to summarize the scientific background and efficacy of using virtual and augmented reality for balance and gait training.

For many patients with movement disorders, balance and gait training is an important aspect of their rehabilitation process and physical therapy treatment. Indications for such training include, among others, stroke, Parkinson's disease, multiple sclerosis, cerebral palsy, vestibular disorders, neuromuscular diseases, low back pain, and various orthopedic complaints, such as total hip or knee replacement. Current clinical practice for balance training include exercises, such as standing on one leg, wobble board exercises and standing with eyes closed. Gait is often trained with a treadmill or using an obstacle course. Cognitive elements can be added by asking the patient to simultaneously perform a cognitive task, such as counting down by sevens. Although conventional physical therapy has proven to be effective in improving balance and gait,[1,2] there are certain limitations that may compromise treatment effects. Motor learning research has revealed some important concepts to optimize rehabilitation: an external focus of attention, implicit learning, variable practice, training intensity, task specificity, and feedback on performance.[3]

Complying with these motor learning principles using conventional methods is quite challenging. For example, there are only a limited number of exercises, making it difficult to tailor training intensity and provide sufficient variation. Moreover, performance measures are not available and thus the patient usually receives little or no feedback. Also, increasing task specificity by simulating everyday tasks, such as walking on a crowded street, can be difficult and time consuming.

Virtual and augmented reality could provide the tools needed to overcome these challenges in conventional therapy. The difference between virtual and augmented reality is that virtual reality offers a virtual world that is separate from the real world, while augmented reality offers virtual elements as an overlay to the real world (for example virtual stepping stones projected on the floor). In the first part of this paper we will explain the different motor learning principles, and how virtual and augmented reality based exercise could help to incorporate these principles into clinical practice. In the second part we will summarize the scientific evidence regarding the efficacy of virtual reality based balance and gait training for clinical rehabilitation.

MOTOR LEARNING PRINCIPLES

FOCUS OF ATTENTION

During rehabilitation, physical therapists will need to explain the different exercises to the patient. The specific instructions that are given will influence the focus of attention, which can affect the movement execution and therapy outcome. Physical therapists often refer to body parts or movements in their instructions ("keep your knees behind your toes"). In motor learning literature this is described as an instruction promoting an internal focus of attention. Such internal focus induces more conscious movements, interfering with automatic motor control.[4] Recent research indicates that instructions promoting an external focus, i.e. directing attention to the effect of the movement on the environment ("squat down to the box"), result in better motor learning.[5] Studies in sports[6–8] and balance training[9] have consistently shown better motor performance after a learning period with external versus internal focused instructions. The evidence favoring instructions promoting an external focus of attention is thus quite convincing, and it should be recommended to practitioners to avoid instructions which focus the attention on body parts or movements. However, in practice, finding the right instructions to induce an external focus of attention is difficult. One advantage of augmented reality is, therefore, the ability to provide external cues in order to facilitate gait adjustments, such as stepping stones projected on the walking surface or auditory beeps.[10,11] Augmented reality using such external cues directs the attention of the patient to the virtual world instead of to his body, which therefore promotes an external focus of attention and likely improves the therapy outcome.

IMPLICIT LEARNING

Traditionally, new motor skills are taught by giving explicit instructions, resulting in conscious control of movement. However, movement control is usually based on implicit knowledge. We know how to make the movement, but are not consciously aware of how we control our muscles and cannot express it in words. Recent literature suggests that explicit learning may limit or interfere with such automatic processes, leading to worse performance, especially when subjects have to perform under pressure.[12–16] Rehabilitation may therefore benefit from using implicit learning, i.e. learning without awareness of what is being learned. For example, in stroke patients, performance on a dynamic balance task was worse after a period of explicit learning versus implicit learning.[17] In the previous paragraph we described one way to promote implicit learning, namely by giving instructions or tasks inducing an external focus of attention. Alternative ways are to use a concurrent cognitive task[13] or to provide variation in the tasks so that it is impossible to learn by explicit rules. Virtual and augmented reality based exercise games often promote implicit learning through one or more of these principles.

VARIATION

The importance of variation in exercises is another new insight from motor learning research. Instead of training the exact same movement over and over, small movement variations will result in more robust motor learning.[18] Also, variation in the sequence of exercises (random versus blocked) will improve motor learning, especially retention and transfer.[19] Although studies consistently favor variable practice, most studies have focused on laboratory tasks[19,20] or applications in sports.[18,21–23] When applying these principles to balance training, reduced postural sway during standing after fifteen minutes of varied balance exercises was reported (weight shifting and reduced base of support exercises), whereas no differences were found after repetitive training of standing as still as possible.[24] It therefore seems that variable practice can also improve rehabilitation. By using virtual or augmented reality, variation can easily be created by the numerous exercise parameters, such as target placement, context, and speed requirements. Virtual or augmented reality based rehabilitation thus enables variable practice with little or no effort for the practitioner, thereby increasing efficiency and reducing costs.

TRAINING INTENSITY

It is well established that the intensity of the training (number of repetitions, training frequency, task difficulty) is an important determinant of therapy outcome.[25–27] High intensity training is recommended in order to maximize treatment effects. Virtual reality can aid in achieving high training intensities by increasing patient motivation and adherence, improving training efficiency, and providing an adequate challenge.

Clinical rehabilitation or physical therapy often requires repetitive training of relatively simple movements. Such monotone exercises quickly become boring, thereby making it difficult for the patient to stay focused and motivated. One of the key benefits of virtual rehabilitation is being able to use gaming techniques, which makes the therapy more fun and enjoyable.[28–30] Because of this, the patient is more engaged in the therapy session and therapy adherence is higher.[31–34] Also, the number of repetitions reached and the active training time are both greater with virtual and augmented reality based training than with conventional therapy.[35–37]

For example, twice as many steps were taken during an augmented reality based treadmill training when compared to conventional gait training.[35] Increased motivation is surely one factor to explain this, but it’s not the only one; practical aspects such as the fact that there is no need to physically set out different walking tracks also factor in to the increased output.

Lastly, virtual and augmented reality enable the maximization of training intensity by challenging the patient to the limits of his or her abilities. The difficulty of the game can easily and gradually be adjusted by changing settings, such as speed and target distance.

TASK SPECIFICITY

Another important recommendation for rehabilitation is to include task-specific training.[26,38] To improve the transfer of progress in motor function to activities outside of therapy, the therapy should include practice of everyday challenges. Virtual and augmented reality can be used to simulate such challenges in a safe environment.

For example, virtual and augmented reality could help train gait under difficult circumstances. This is essential because everyday walking is more than setting one foot in front of the other; it also requires the ability to adjust your walking pattern to different situations. You may need to lift your leg up higher to avoid tripping over a loose tile, or slow down to avoid bumping into someone. Gait adaptability, defined as the ability to adjust gait to environmental circumstances, is therefore a crucial element of walking at home or in the community. Augmented reality can be a helpful tool to train gait adaptability by projecting stepping targets or obstacles on the walking surface.[10,39] In addition, virtual reality can be used to create optical flow when walking on a treadmill in order to enhance the feeling of natural walking.[40,41]

Further examples of everyday challenges are activities comprising both physical and cognitive tasks, such as crossing a street while watching traffic or walking while remembering your groceries list. When doing two tasks simultaneously it is often the case that performance of one or both tasks decreases. This so-called dual-task interference becomes more pronounced with age[42] and with neurological disorders, such as stroke[43] or Parkinson's disease.[44] Dual-task interference has been shown to be a predictor of falls.[45] Since dual-task training is more effective in reducing dual-task interference than single-task training,[46–49] fall prevention programs should always include dual-tasking.[1] With virtual reality it is relatively simple to add cognitive elements to the training, and therefore, to train dual-tasking. One way to do this is to include a cognitive task that is not related to the motor task, such as counting backwards or a memory task. Another way is to incorporate the cognitive task in the virtual reality game, for example, games that require planning or strategy development. Lastly, cognitive elements can be added by actually simulating real-life dual-task challenges like walking through a virtual supermarket while putting items in a basket,[50] crossing a street while avoiding obstacles[51] or, for militaries, walking on unstable terrain while identifying and shooting military targets.[52]

FEEDBACK

In order to improve our motor performance, we require at least some information on our current performance. This feedback often comes from intrinsic sources, such as vision or proprioception. Intrinsic feedback can also be augmented by providing information that would normally be inaccessible for the patient, such as exact joint angles or moments (biofeedback). Using virtual reality, biofeedback can be shown to the patient or even incorporated into an exercise game.

Providing biofeedback can be useful for both balance and gait training. Balance training with feedback usually consists of weight shifting exercises supported by feedback on the patient's center-of-pressure (CoP) position. In a systematic review, the effectiveness of feedback-based balance training in old adults was evaluated and it was concluded that such training can result in reduced postural sway, improved weight-shifting ability, reduced attentional demands in quiet standing and increased scores on the Berg Balance Scale.[53]

There is also some evidence suggesting that adding biofeedback to balance training can be beneficial for stroke patients.[54,55]

A large body of literature shows the effectiveness of biofeedback for gait retraining in different patient populations. For example, training with feedback can reduce the knee adduction moment or increase the toe-out angle for the prevention of knee osteoarthritis.[56–58] Also, it can enhance forward propulsion during push-off in healthy old adults, making their gait pattern more similar to that of young adults.[59] Feedback can help people with Parkinson's disease or incomplete spinal cord injury to take longer steps,[60,61] and improve gait performance following transfemoral amputation.[62] Knee hyperextension patterns in young women can be corrected using feedback in order to prevent knee problems due to excessive loading of knee structures.[63,64] Training with feedback has also been shown to reduce impact loading while running thus helping to prevent running-related injuries,[65–67] and it has been shown to help modulate various gait parameters in both typically developing children and children with cerebral palsy.[68,69] Future experiments are planned to test the ability to use the feedback protocol for diagnostic purposes in cerebral palsy.[69] Together, these examples show that biofeedback is an effective and versatile tool that enables patients to adapt specific aspects of their gait.

In conclusion, the ability to provide biofeedback is one of the great assets of virtual reality training. By incorporating augmented feedback in a game, one can ensure patient motivation and engagement.

EFFICACY

Numerous studies have examined the efficacy of virtual reality balance and gait games. Most of the balance training studies have used commercially available exercise games using the center of pressure as measured by a balance board. When compared to no intervention, virtual reality balance games were shown to be effective in improving balance in the elderly.[70–73] When compared to conventional balance training, some studies report greater improvements in the virtual reality group,[74–76] whereas others report similar improvements.[77–79] Comparable findings were reported in patients with stroke, Parkinson's disease and multiple sclerosis. Similarly for these same populations, the *addition* of virtual reality training to conventional physical therapy or no therapy was consistently found to improve balance.[80–82] When training duration was matched between the experimental and control group, some studies found greater improvement in the virtual reality training group,[83–86] yet other studies found no differences between the groups.[87–89] Virtual reality games have thus proven to be at least as effective, and maybe even more effective, in improving balance than conventional treatment. It should be noted that most games examined in these studies were not designed for rehabilitation, therefore greater improvements may be possible when games are specifically developed for patients.[90]

Studies investigating the effect of virtual reality during gait training are consistently positive. A large six-week randomized control trial (RCT) with 282 subjects defined as fallers compared virtual reality based treadmill training with regular treadmill training.[91] Only in the virtual reality group was the fall rate significantly reduced, with half as many falls in the following six months as compared with values from before training. Additionally, physical performance on several gait and balance tasks improved more in the virtual reality group. Similar RCTs with 25 multiple sclerosis patients[92] and 20 stroke patients[93] also showed the added value of virtual reality. Greater improvements were reported in walking speed,[93] hip range of motion and hip generated power during walking,[92] and clinical balance tests.[92] Lastly, the transfer of ankle movement training to overground walking was greater using a virtual environment coupled with a robot than with the robot alone.[94]

CONCLUSION

Overall, we can conclude that virtual and augmented reality are powerful tools for balance and gait training in clinical rehabilitation. The therapy outcome is optimized because virtual and augmented reality training follow the motor learning principles: an external focus of attention, implicit learning, variable practice, high training intensity, task specificity, and feedback. With the introduction of gaming elements, patients will experience the training as more enjoyable, resulting in greater motivation, engagement, and training adherence. By combining cognitive and physical aspects, rehabilitation exercises can more closely resemble real-life challenges, but in a safe environment. Moreover, real-time feedback on the screen can facilitate balance training and the retraining of specific gait parameters. Numerous studies have proven the added value of virtual and augmented reality for balance and gait training. Virtual and augmented reality, therefore, may well be the future of rehabilitation.

REFERENCES

1. Granacher U, Muehlbauer T, Zahner L, Gollhofer A, Kressig RW. Comparison of traditional and recent aproaches in the promotion of balance and strength in older adults. *Sport Med*. 2011;41(5):377-400.
2. Polese JC, Ada L, Dean CM, Nascimento LR, Teixeira-Salmela LF. Treadmill training is effective for ambulatory adults with stroke: a systematic review. *J Physiother*. 2013;59(2):73-80. doi:10.1016/S1836-9553(13)70159-0.
3. Beek PJ, Roerdink M. Evolving insights into motor learning and their implications for neurorehabilitation. In: *Textbook of Neural Repair and Rehabilitation, Volume 2: Medical Neurorehabilitation*. Cambridge University Press; 2014:95-104.
4. Wulf G, McNevin N, Shea CH. The automaticity of complex motor skill learning as a function of attentional focus. *Q J Exp Psychol A*. 2001;54(4):1143-1154. doi:10.1080/713756012.
5. Wulf G, Shea C, Lewthwaite R. Motor skill learning and performance: a review of influential factors. *Med Educ*. 2010;44(1):75-84. doi:10.1111/j.1365-2923.2009.03421.x.
6. Zachry T, Wulf G, Mercer J, Bezodis N. Increased movement accuracy and reduced EMG activity as the result of adopting an external focus of attention. *Brain Res Bull*. 2005;67(4):304-309. doi:10.1016/j.brainresbull.2005.06.035.
7. Wulf G, Mcconnel N, Gärtner M, Schwarz A. Enhancing the Learning of Sport Skills Through External-Focus Feedback. *J Mot Behav*. 2002;34(2):171-182. doi:10.1080/00222890209601939.
8. Marchant DC, Clough PJ, Crawshaw M. The effects of attentional focusing strategies on novice dart throwing performance and Their task experiences. *Int J Sport Exerc Psychol*. 2007;5(3):291-303. doi:10.1080/161219 7X.2007.9671837.
9. Park SH, Yi CW, Shin JY, Ryu YU. Effects of external focus of attention on balance: a short review. *J Phys Ther Sci*. 2015;27(12):3929-3931. doi:10.1589/jpts.27.3929.
10. Hollands KL, Pelton TA, Wimperis A, et al. Feasibility and Preliminary Efficacy of Visual Cue Training to Improve Adaptability of Walking after Stroke: Multi-Centre, Single-Blind Randomised Control Pilot Trial. Quinn TJ, ed. *PLoS One*. 2015;10(10):e0139261. doi:10.1371/journal.pone.0139261.
11. Suteerawattananon M, Morris GS, Etnyre BR, Jankovic J, Protas EJ. Effects of visual and auditory cues on gait in individuals with Parkinson's disease. *J Neurol Sci*. 2004;219(1-2):63-69. doi:10.1016/j.jns.2003.12.007.
12. Orrell AJ, Masters RSW, Eves FF. Reinvestment and movement disruption following stroke. *Neurorehabil Neural Repair*. 2009;23(2):177-183. doi:10.1177/1545968308317752.
13. Masters R. Knowledge, knerves and know-how: The role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *Br J Psychol*. 1992. http://onlinelibrary.wiley.com/doi/10.1111/j.2044-8295.1992.tb02446.x/full. Accessed February 3, 2017.
14. Wong W-L, Masters RSW, Maxwell JP, Abernethy B. The role of reinvestment in walking and falling in community-dwelling older adults. *J Am Geriatr Soc*. 2009;57(5):920-922. doi:10.1111/j.1532-5415.2009.02228.x.
15. Masters RSW, Pall HS, MacMahon KMA, Eves FF. Duration of Parkinson disease is associated with an increased propensity for "reinvestment". *Neurorehabil Neural Repair*. 2007;21(2):123-126. doi:10.1177/1545968306290728.
16. Liao C-M, Masters RSW. Analogy learning: A means to implicit motor learning. *J Sports Sci*. 2001;19(5):307-319. doi:10.1080/02640410152006081.
17. Orrell AJ, Eves FF, Masters RSW. Motor learning of a dynamic balancing task after stroke: implicit implications for stroke rehabilitation. *Phys Ther*. 2006;86(3):369-380. http://www.ncbi.nlm.nih.gov/pubmed/16506873. Accessed February 3, 2017.
18. Frank TD, Michelbrink M, Beckmann H, Schöllhorn WI. A quantitative dynamical systems approach to differential learning: self-organization principle and order parameter equations. *Biol Cybern*. 2008;98(1):19-31. doi:10.1007/s00422-007-0193-x.
19. Shea J, Morgan R. Contextual interference effects on the acquisition, retention, and transfer of a motor skill. *J Exp Psychol*. 1979. http://psycnet.apa.org/journals/xlm/5/2/179/. Accessed December 15, 2016.
20. Wright DL, Magnuson CE, Black CB. Programming and reprogramming sequence timing following high and low contextual interference practice. *Res Q Exerc Sport*. 2005;76(3):258-266. doi:10.1080/02701367.2005.10599297.
21. Schollhorn W, Beckmann H. Does noise provide a basis for the unification of motor learning theories? *J Sport …*. 2006. https://www.researchgate.net/profile/Wolfgang_Schoellhorn/publication/27466409_Does_noise_provide_a_basis_for_the_unification_of_motor_learning_theories/links/0deec53873db69db4e000000.pdf. Accessed December 15, 2016.
22. Beckman H, Schöllhorn WI. Differencial learning in shot put. *Schöllhorn, WI, Bohn, C, Jäger, JM, Schaper, H, Alichmann, M Eur Work Mov Sci*. 2003.
23. Hall KG, Domingues DA, Cavazos R. Contextual interference effects with skilled baseball players. *Percept Mot Skills*. 1994;78(3 Pt 1):835-841. doi:10.2466/pms.1994.78.3.835.
24. James EG. Short-term differential training decreases postural sway. *Gait Posture*. 2014;39(1):172-176. doi:10.1016/j.gaitpost.2013.06.020.
25. Holleran CL, Rodriguez KS, Echauz A, Leech KA, Hornby TG. Potential Contributions of Training Intensity on Locomotor Performance in Individuals With Chronic Stroke. *J Neurol Phys Ther*. 2015;39(2):95-102. doi:10.1097/NPT.0000000000000077.
26. Langhorne P, Bernhardt J, Kwakkel G. Stroke rehabilitation. *Lancet*. 2011;377(9778):1693-1702. doi:10.1016/S0140-6736(11)60325-5.
27. Lesinski M, Hortobagyi T, Muehlbauer T, Gollhofer A, Granacher U. Effects of Balance Training on Balance Performance in Healthy Older Adults: A Systematic Review and Meta-analysis. *Sport Med*. 2015;45(12):1721-1738. doi:10.1007/s40279-015-0375-y.
28. Chen M-H, Huang L-L, Lee C-F, et al. A controlled pilot trial of two commercial video games for rehabilitation of arm function after stroke. *Clin Rehabil*. 2015;29(7):674-682. doi:10.1177/0269215514554115.

29. Meldrum D, Herdman S, Vance R, et al. Effectiveness of conventional versus virtual reality-based balance exercises in vestibular rehabilitation for unilateral peripheral vestibular loss: results of a randomized controlled trial. *Arch Phys Med Rehabil*. 2015;96(7):1319-1328.e1. doi:10.1016/j.apmr.2015.02.032.
30. Ibrahim MS, Mattar AG, Elhafez SM. Efficacy of virtual reality-based balance training versus the Biodex balance system training on the body balance of adults. *J Phys Ther Sci*. 2016;28(1):20-26. doi:10.1589/jpts.28.20.
31. Kramer A, Dettmers C, Gruber M. Exergaming With Additional Postural Demands Improves Balance and Gait in Patients With Multiple Sclerosis as Much as Conventional Balance Training and Leads to High Adherence to Home-Based Balance Training. *Arch Phys Med Rehabil*. 2014. doi:10.1016/j.apmr.2014.04.020.
32. Lee M, Suh D, Son J, Kim J, Eun S-D, Yoon B. Patient perspectives on virtual reality-based rehabilitation after knee surgery: Importance of level of difficulty. 2016;53(2):239-252. doi:10.1682/JRRD.2014.07.0164.
33. Annesi JJ, Mazas J. Effects of virtual reality-enhanced exercise equipment on adherence and exercise-induced feeling states. *Percept Mot Skills*. 1997;85(3):835-844. doi:10.2466/pms.1997.85.3.835.
34. Wüest S, Borghese NA, Pirovano M, Mainetti R, van de Langenberg R, de Bruin ED. Usability and Effects of an Exergame-Based Balance Training Program. *Games Health J*. 2014;3(2):106-114. doi:10.1089/g4h.2013.0093.
35. van Ooijen MW, Roerdink M, Timmermans C, et al. P268: Feasibility of C-mill gait-adaptability training in older adults after fall-related hip fracture: user's perspective and training content. In: *European Geriatric Medicine*. Vol 5. Elsevier; 2014:S169. doi:10.1016/s1878-7649(14)70439-5.
36. Rand D, Givon N, Weingarden H, Nota A, Zeilig G. Eliciting Upper Extremity Purposeful Movements Using Video Games. *Neurorehabil Neural Repair*. 2014;28(8):733-739. doi:10.1177/1545968314521008.
37. Brunner I, Skouen JS, Hofstad H, et al. Is upper limb virtual reality training more intensive than conventional training for patients in the subacute phase after stroke? An analysis of treatment intensity and content. *BMC Neurol*. 2016;16(1):219. doi:10.1186/s12883-016-0740-y.
38. Kwakkel G, Kollen B, Lindeman E. Understanding the pattern of functional recovery after stroke: facts and theories. *Restor Neurol Neurosci*. 2004;22(3-5):281-299. http://www.ncbi.nlm.nih.gov/pubmed/15502272. Accessed January 26, 2017.
39. Heeren A, van Ooijen M, Geurts ACH, et al. Step by step: a proof of concept study of C-Mill gait adaptability training in the chronic phase after stroke. *J Rehabil Med*. 2013;45(7):616-622. doi:10.2340/16501977-1180.
40. Sloot LH, van der Krogt MM, Harlaar J. Effects of adding a virtual reality environment to different modes of treadmill walking. *Gait Posture*. 2014;39(3):939-945. doi:10.1016/j.gaitpost.2013.12.005.
41. Sloot LH, Harlaar J, van der Krogt MM. Self-paced versus fixed speed walking and the effect of virtual reality in children with cerebral palsy. *Gait Posture*. 2015;42(4):498-504. doi:10.1016/j.gaitpost.2015.08.003.
42. Ruffieux J, Keller M, Lauber B, Taube W. Changes in Standing and Walking Performance Under Dual-Task Conditions Across the Lifespan. *Sports Med*. 2015;45(12):1739-1758. doi:10.1007/s40279-015-0369-9.
43. Yang Y-R, Chen Y-C, Lee C-S, Cheng S-J, Wang R-Y. Dual-task-related gait changes in individuals with stroke. *Gait Posture*. 2007;25(2):185-190. doi:10.1016/j.gaitpost.2006.03.007.
44. Wild LB, de Lima DB, Balardin JB, et al. Characterization of cognitive and motor performance during dual-tasking in healthy older adults and patients with Parkinson's disease. *J Neurol*. 2013;260(2):580-589. doi:10.1007/s00415-012-6683-3.
45. Beauchet O, Annweiler C, Dubost V, et al. Stops walking when talking: a predictor of falls in older adults? *Eur J Neurol*. 2009;16(7):786-795. doi:10.1111/j.1468-1331.2009.02612.x.
46. Wollesen B, Voelcker-Rehage C. Training effects on motor–cognitive dual-task performance in older adults. *Eur Rev Aging Phys Act*. 2013;11(1):5-24. doi:10.1007/s11556-013-0122-z.
47. Konak HE, Kibar S, Ergin ES. The effect of single-task and dual-task balance exercise programs on balance performance in adults with osteoporosis: a randomized controlled preliminary trial. *Osteoporos Int*. May 2016. doi:10.1007/s00198-016-3644-1.
48. Cho KH, Kim MK, Lee H-J, Lee WH. Virtual Reality Training with Cognitive Load Improves Walking Function in Chronic Stroke Patients. *Tohoku J Exp Med*. 2015;236(4):273-280. doi:10.1620/tjem.236.273.
49. Eggenberger P, Theill N, Holenstein S, Schumacher V, de Bruin ED. Multicomponent physical exercise with simultaneous cognitive training to enhance dual-task walking of older adults: A secondary analysis of a 6-month randomized controlled trial with I-year follow-up. *Clin Interv Aging*. 2015;10:1711-1732. doi:10.2147/CIA.S91997.
50. Kizony R, Levin MF, Hughey L, Perez C, Fung J. Cognitive load and dual-task performance during locomotion poststroke: a feasibility study using a functional virtual environment. *Phys Ther*. 2010;90(2):252-260. doi:10.2522/ptj.20090061.
51. Fung J, Richards CL, Malouin F, McFadyen BJ, Lamontagne A. A treadmill and motion coupled virtual reality system for gait training post-stroke. *Cyberpsychol Behav*. 2006;9(2):157-162. doi:10.1089/cpb.2006.9.157.
52. Rábago CA, Wilken JM. Application of a mild traumatic brain injury rehabilitation program in a virtual realty environment: a case study. *J Neurol Phys Ther*. 2011;35(4):185-193. doi:10.1097/NPT.0b013e318235d7e6.
53. Zijlstra A, Mancini M, Chiari L, Zijlstra W. Biofeedback for training balance and mobility tasks in older populations: a systematic review. *J Neuroeng Rehabil*. 2010;7:58. doi:10.1186/1743-0003-7-58.
54. Maciaszek J, Borawska S, Wojcikiewicz J. Influence of posturographic platform biofeedback training on the dynamic balance of adult stroke patients. *J Stroke Cerebrovasc Dis*. 2014;23(6):1269-1274. doi:10.1016/j.jstrokecerebrovasdis.2013.10.029.
55. Cheng PT, Wu SH, Liaw MY, Wong AM, Tang FT. Symmetrical body-weight distribution training in stroke patients and its effect on fall prevention. *Arch Phys Med Rehabil*. 2001;82(12):1650-1654. doi:10.1053/apmr.2001.26256.
56. Hunt MA, Takacs J, Hart K, Massong E, Fuchko K, Biegler J. Comparison of mirror, raw video, and real-time visual biofeedback for training toe-out gait in individuals with knee osteoarthritis. *Arch Phys Med Rehabil*. 2014;95(10):1912-1917. doi:10.1016/j.apmr.2014.05.016.
57. Richards R, van den Noort JC, Dekker J, Harlaar J. Gait Retraining with real-time Biofeedback to reduce Knee adduction moment: systematic review of effects and methods used. *Arch Phys Med Rehabil*. July 2016. doi:10.1016/j.apmr.2016.07.006.
58. van den Noort JC, Steenbrink F, Roeles S, Harlaar J. Real-time visual feedback for gait retraining: toward application in knee osteoarthritis. *Med Biol Eng Comput*. 2015;53(3):275-286. doi:10.1007/s11517-014-1233-z.

59. Franz JR, Maletis M, Kram R. Real-time feedback enhances forward propulsion during walking in old adults. *Clin Biomech (Bristol, Avon)*. 2014;29(1):68-74. doi:10.1016/j.clinbiomech.2013.10.018.
60. Jellish J, Abbas JJ, Ingalls TM, et al. A System for Real-Time Feedback to Improve Gait and Posture in Parkinson's Disease. *IEEE J Biomed Heal informatics*. 2015;19(6):1809-1819. doi:10.1109/JBHI.2015.2472560.
61. Yen S-C, Landry JM, Wu M. Augmented multisensory feedback enhances locomotor adaptation in humans with incomplete spinal cord injury. *Hum Mov Sci*. 2014;35:80-93. doi:10.1016/j.humov.2014.03.006.
62. Darter BJ, Wilken JM. Gait training with virtual reality-based real-time feedback: improving gait performance following transfemoral amputation. *Phys Ther*. 2011;91(9):1385-1394. doi:10.2522/ptj.20100360.
63. Teran-Yengle P, Birkhofer R, Weber MA, Patton K, Thatcher E, Yack HJ. Efficacy of gait training with real-time biofeedback in correcting knee hyperextension patterns in young women. *J Orthop Sports Phys Ther*. 2011;41(12):948-952. doi:10.2519/jospt.2011.3660.
64. Teran-Yengle P, Cole KJ, Yack HJ. Short and long-term effects of gait retraining using real-time biofeedback to reduce knee hyperextension pattern in young women. *Gait Posture*. 2016;50:185-189. doi:10.1016/j.gaitpost.2016.08.019.
65. Napier C, Cochrane CK, Taunton JE, Hunt MA. Gait modifications to change lower extremity gait biomechanics in runners: a systematic review. *Br J Sports Med*. 2015;49(21):1382-1388. doi:10.1136/bjsports-2014-094393.
66. Crowell HP, Davis IS. Gait retraining to reduce lower extremity loading in runners. *Clin Biomech (Bristol, Avon)*. 2011;26(1):78-83. doi:10.1016/j.clinbiomech.2010.09.003.
67. Noehren B, Scholz J, Davis I. The effect of real-time gait retraining on hip kinematics, pain and function in subjects with patellofemoral pain syndrome. *Br J Sports Med*. 2011;45(9):691-696. doi:10.1136/bjsm.2009.069112.
68. Booth A, Steenbrink F, Buizer A, Harlaar J, van der Krogt M. Is avatar based real-time visual feedback a feasible method to alter gait parameters of interest? *Gait Posture*. 2016;49:98. doi:10.1016/j.gaitpost.2016.07.154.
69. van Gelder L, Booth ATC, van de Port I, Buizer AI, Harlaar J, van der Krogt MM. Real-time feedback to improve gait in children with cerebral palsy. *Gait Posture*. 2016;52:76-82. doi:10.1016/j.gaitpost.2016.11.021.
70. Cho GH, Hwangbo G, Shin HS. The Effects of Virtual Reality-based Balance Training on Balance of the Elderly. *J Phys Ther Sci*. 2014;26(4):615-617. doi:10.1589/jpts.26.615.
71. Jorgensen MG, Laessoe U, Hendriksen C, Nielsen OBF, Aagaard P. Efficacy of Nintendo Wii training on mechanical leg muscle function and postural balance in community-dwelling older adults: a randomized controlled trial. *J Gerontol A Biol Sci Med Sci*. 2013;68(7):845-852. doi:10.1093/gerona/gls222.
72. Rendon AA, Lohman EB, Thorpe D, Johnson EG, Medina E, Bradley B. The effect of virtual reality gaming on dynamic balance in older adults. *Age Ageing*. 2012;41(4):549-552. doi:10.1093/ageing/afs053.
73. Schwenk M, Grewal GS, Honarvar B, et al. Interactive balance training integrating sensor-based visual feedback of movement performance: a pilot study in older adults. *J Neuroeng Rehabil*. 2014;11:164. doi:10.1186/1743-0003-11-164.
74. Szturm T, Betker AL, Moussavi Z, Desai A, Goodman V. Effects of an interactive computer game exercise regimen on balance impairment in frail community-dwelling older adults: a randomized controlled trial. *Phys Ther*. 2011;91(10):1449-1462. doi:10.2522/ptj.20090205.
75. Park E-C, Kim S-G, Lee C-W. The effects of virtual reality game exercise on balance and gait of the elderly. *J Phys Ther Sci*. 2015;27(4):1157-1159. doi:10.1589/jpts.27.1157.
76. Fu AS, Gao KL, Tung AK, Tsang WW, Kwan MM. Effectiveness of Exergaming Training in Reducing Risk and Incidence of Falls in Frail Older Adults With a History of Falls. *Arch Phys Med Rehabil*. 2015;96(12):2096-2102. doi:10.1016/j.apmr.2015.08.427.
77. Singh DKA, Rajaratnam BS, Palaniswamy V, Raman VP, Bong PS, Pearson H. Effects of balance-focused interactive games compared to therapeutic balance classes for older women. *Climacteric*. 2013;16(1):141-146. doi:10.3109/13697137.2012.664832.
78. Singh DKA, Rajaratnam BS, Palaniswamy V, Pearson H, Raman VP, Bong PS. Participating in a virtual reality balance exercise program can reduce risk and fear of falls. *Maturitas*. 2012;73(3):239-243. doi:10.1016/j.maturitas.2012.07.011.
79. Pluchino A, Lee SY, Asfour S, Roos BA, Signorile JF. Pilot study comparing changes in postural control after training using a video game balance board program and 2 standard activity-based balance intervention programs. *Arch Phys Med Rehabil*. 2012;93(7):1138-1146. doi:10.1016/j.apmr.2012.01.023.
80. Kim JH, Jang SH, Kim CS, Jung JH, You JH. Use of virtual reality to enhance balance and ambulation in chronic stroke: a double-blind, randomized controlled study. *Am J Phys Med Rehabil*. 2009;88(9):693-701. doi:10.1097/PHM.0b013e3181b33350.
81. Cho KH, Lee KJ, Song CH. Virtual-reality balance training with a video-game system improves dynamic balance in chronic stroke patients. *Tohoku J Exp Med*. 2012;228(1):69-74. http://www.ncbi.nlm.nih.gov/pubmed/22976384. Accessed October 25, 2016.
82. Eftekharsadat B, Babaei-Ghazani A, Mohammadzadeh M, Talebi M, Eslamian F, Azari E. Effect of virtual reality-based balance training in multiple sclerosis. *Neurol Res*. 2015;37(6):539-544. doi:10.1179/1743132815Y.0000000013.
83. Lloréns R, Noé E, Colomer C, Alcañiz M. Effectiveness, usability, and cost-benefit of a virtual reality-based telerehabilitation program for balance recovery after stroke: a randomized controlled trial. *Arch Phys Med Rehabil*. 2015;96(3):418-425.e2. doi:10.1016/j.apmr.2014.10.019.
84. McEwen D, Taillon-Hobson A, Bilodeau M, Sveistrup H, Finestone H. Virtual reality exercise improves mobility after stroke: an inpatient randomized controlled trial. *Stroke*. 2014;45(6):1853-1855. doi:10.1161/STROKEAHA.114.005362.
85. Rajaratnam BS, Gui Kaien J, Lee Jialin K, et al. Does the Inclusion of Virtual Reality Games within Conventional Rehabilitation Enhance Balance Retraining after a Recent Episode of Stroke? *Rehabil Res Pract*. 2013;2013:649561. doi:10.1155/2013/649561.
86. Liao Y-Y, Yang Y-R, Cheng S-J, Wu Y-R, Fuh J-L, Wang R-Y. Virtual Reality-Based Training to Improve Obstacle-Crossing Performance and Dynamic Balance in Patients With Parkinson's Disease. *Neurorehabil Neural Repair*. 2015;29(7):658-667. doi:10.1177/1545968314562111.
87. da Fonseca PE, Ribeiro da Silva NM, Pinto EB. Therapeutic Effect of Virtual Reality on Post-Stroke Patients: Randomized Clinical Trial. *J Stroke Cerebrovasc Dis*. September 2016. doi:10.1016/j.jstrokecerebrovasdis.2016.08.035.
88. Singh DKA, Mohd Nordin NA, Abd Aziz NA, Lim BK, Soh LC. Effects of substituting a portion of standard physiotherapy time with virtual reality games among community-dwelling stroke survivors. *BMC Neurol*. 2013;13:199. doi:10.1186/1471-2377-13-199.

89. Yang W-C, Wang H-K, Wu R-M, Lo C-S, Lin K-H. Home-based virtual reality balance training and conventional balance training in Parkinson's disease: A randomized controlled trial. *J Formos Med Assoc*. 2016;115(9):734-743. doi:10.1016/j.jfma.2015.07.012.
90. Borghese NA, Pirovano M, Lanzi PL, Wüest S, de Bruin ED. Computational Intelligence and Game Design for Effective At-Home Stroke Rehabilitation. *Games Health J*. 2013;2(2):81-88. doi:10.1089/g4h.2012.0073.
91. Mirelman A, Rochester L, Maidan I, et al. Addition of a non-immersive virtual reality component to treadmill training to reduce fall risk in older adults (V-TIME): a randomised controlled trial. *Lancet (London, England)*. 2016;388(10050):1170-1182. doi:10.1016/S0140-6736(16)31325-3.
92. Peruzzi A, Zarbo IR, Cereatti A, Della Croce U, Mirelman A. An innovative training program based on virtual reality and treadmill: effects on gait of persons with multiple sclerosis. *Disabil Rehabil*. November 2016:1-7. doi:10.1080/09638288.2016.1224935.
93. Yang Y-R, Tsai M-P, Chuang T-Y, Sung W-H, Wang R-Y. Virtual reality-based training improves community ambulation in individuals with stroke: a randomized controlled trial. *Gait Posture*. 2008;28(2):201-206. doi:10.1016/j.gaitpost.2007.11.007.
94. Mirelman A, Bonato P, Deutsch JE. Effects of training with a robot-virtual reality system compared with a robot alone on the gait of individuals after stroke. *Stroke*. 2009;40(1):169-174. doi:10.1161/STROKEAHA.108.516328.

MOTEK
Hogehilweg 18–C
1101 CD Amsterdam
The Netherlands
https://www.motekforcelink.com/

MOTEK IS A PROUD PARTNER OF

DIH
Hocoma
a DIH brand
FYSIOROADMAP
a DIH brand