Virtual Reality Balance Games Provide Little Muscular Challenge to Prevent Muscle Weakness in healthy older adults

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Abstract

Objective: Muscle weakness is an important risk factor for falls in older adults. Intensity and duration of muscle activity are important determinants of exercise effectiveness in combating muscle weakness. The aim of this paper was to assess the intensity and duration of muscle activity in Virtual Reality (VR) balance games.

Materials and Methods: Thirty young and thirty healthy older adults played seven different VR balance games. Muscle activity of the Vastus Lateralis, Vastus Medialis, Soleus and Gluteus Medius was obtained using surface EMG. The processed EMG signals were divided in 200ms blocks, after which each block was categorized by its average normalized EMG activity i.e. >80%, 60-80%, 40-60% or <40% of maximum voluntary contraction (MVC). We calculated the total number of blocks in each category to score intensity, as well as the maximal number of consecutive blocks (MCB) >40% MVC, to identify prolonged muscle activity.

Results: Muscle activity during game-play was mostly below 40% MVC and prolonged activation was lacking. Only the games that included more dynamic movements showed activation blocks of higher intensity and resulted in more MCB.

Conclusion: Our method allowed us to analyze the overall muscle activity and the distribution of activity over a trial. Although the activation levels during these VR games were low in general, we identified game elements that could potentially provide a strength training stimulus. Future research should aim to implement these elements, such that the intensity, prolonged activity and rest are optimized to sufficiently challenge lower limb muscles in VR training.

Introduction

Age-related decreases in muscle strength contribute to the increased incidence of falls at higher age^{1,2}. Muscle strength of the lower limbs has been shown to be a predictor of functional balance³, postural stability⁴ and fall incidence in older adults^{1,5,6}. Fortunately, sufficiently challenging exercises combined with optimized nutrition provides similar muscle protein synthesis in older compared to young adults⁷. Indeed, older adults can improve muscle strength and power after resistance training^{7,8}.

Virtual reality training (VRT), an alternative training method that combines playing games using commercial consoles (e.g. Wii console, Kinect) and exercising, is applied to improve balance in older adults^{9,10}. The term virtual reality (VR) covers a wide range of applications as described in the virtuality – reality continuum¹¹. In this study, VR is defined as computer games using commercial consoles as Wii and the Kinect console and that are controlled with body movements. VRT might lead to increased motivation because of the gaming element^{12,13}, which could help against low adherence in home-based training programs^{14,15}. Furthermore, VRT creates a training environment in which either direct (e.g. coach on the screen gives feedback on the posture of the player) or indirect feedback (e.g. scoring points of the game) can be provided. Feedback can help to increase physical activity during the game¹⁶. However, systematic reviews yielded conflicting results on the fact whether VRT can improve (components of) balance in elderly^{9,17,18}. This might be explained by the wide variety in VRT-tools and the different nature of the games. For VR to have an optimal effect on biomechanical constraints of balance⁴, it should challenge balance, by going to the individual limits of stability^{4,19,20}, and also include muscle strength training^{21,22}. However, all these goals have to be pursued keeping in mind the person's safety. Effects of training programs on muscle strength, as a determinant of balance, have received limited attention²³ and the muscular demands of different VRT programs have not been studied.

Training load is affected by overall muscle effort, which depends on the relative intensity of muscle activity and the amount of rest between periods with substantial muscle activity²⁴. Recommendations regarding conventional strength training in older adults suggest using moderate to heavy intensities, i.e., >60% of the maximum weight that can be moved for one repetition²⁵. Strength training using higher velocity concentric exercises improves muscle power and is more effective than traditional strength training in improving functional performance, as reflected in sit to stand, jump height and reaction time²⁶. Furthermore, the rate of torque development appears to help discriminate fallers from non fallers²⁷, suggesting that muscle strength should also be trained at high velocities.

Weight bearing exercises, possibly with added extra weights, are more suited for VRT than externally loaded exercises using weight machines. However, muscle activity during weight bearing exercises might be low. To maximize muscle fiber recruitment, it is recommended to add steps or to increase the number of repetitions until muscle exhaustion^{8,28}. The introduction of rests within a training set has been shown to attenuate increases in growth-hormone release and strength gains following a training regimen²⁹. Therefore, it is important to also consider the duration of the bouts of muscle activity within a training session. High intensity exercises at high speed will induce muscle hypertrophy, however a high number of repetitions at lower intensities will induce muscle fatigue and as such also induce muscle hypertrophy⁸. Low intensities are potentially more suitable for elderly compared to high intensities since these exercises are more accessible, safer and pleasant to perform³⁰.

The aim of this study was therefore to assess intensity and duration of lower limb muscle activation elicited by different commercially available VRT applications in young and older adults. The results were interpreted in the context of reported recommendations for conventional strength training^{8,25,31}.

Methods

Participants

Table 1. Subject characteristics.

Thirty young and thirty healthy older adults (aged >65) were recruited using flyers around the sports facilities of the KU Leuven (Table 1). All participants had to be free of any pathology of the musculoskeletal and neurological or vestibular system, cardiovascular disease or diabetes that would prevent them from safely performing exercises. Participants signed written informed consent prior to participation, in accordance with the Declaration of Helsinki. The study was approved by the local ethics committee (Commissie Medische Ethiek K.U. Leuven). All participants completed the Mini Mental State Examination (MMSE) to ensure they were in a cognitive good state. Participants had to score at least 25 out of 30 to be eligible for the study. Mean score for the test was 29.3 and no participants were excluded (Table 1).

Material

Seven games involving different movements were tested (Table 2 and appendix for full description of the games). Games were selected on their potential ability to challenge balance or muscle activity or were used in VR balance training studies previously^{10,18,32}. Games were selected to represent a varied but

realistic sample of games that can be used as VR training at home or in retirement homes and small rehabilitation facilities. There are different forms of virtual environments that can be used for VRT. In this study, we will focus on projection-based environments³³. The games were controlled by the Xbox Kinect camera (Microsoft, US), which tracks the players' movements via depth sensing cameras, or by the Wii Balance Board (Nintendo, Japan), which registers movements of the Center of Pressure (COP). Recommendations regarding conventional strength training in older adults suggest using >60% of the maximum weight that can be moved for one repetition (1RM)²⁵. However, this 1RM concept cannot be used for unloaded exercises. Therefore, the intensity in unloaded exercises is hard to quantify and we used surface electromyography (EMG) to measure muscle activation. EMG signals that are normalized to values achieved during maximum voluntary contractions (MVC) have shown to be approximately linearly correlated with force^{34,35}. Neuromuscular activation was obtained using silver-silver chloride, pre-gelled bipolar electrodes (Ambu Blue Sensor, DK) connected to an eight-channel wireless EMG system (Aurion, Zero-wire, IT), which was recorded in Nexus (Vicon, Oxford Metrics, UK) at 1000Hz.

Table 2. Overview of the included games.

Protocol

Before participants engaged in the VRT experiments, EMG electrodes were placed on four lower limb muscles which have been shown to be important in balance and preventing falls in older adults^{1,36,37}; Vastus lateralis (VL), Vastus medialis (VM), Soleus (Sol) and Gluteus medius (GluM). For practical reasons, we chose to measure muscle activity unilaterally. Electrodes were consistently placed on the left leg, according to the SENIAM guidelines³⁸. Maximal voluntary contraction (MVC) was obtained according to SENIAM guidelines³⁸. Participants played seven different games in a randomized order, during which EMG signals were recorded. The shorter games (Adventure, Wiiski, Kinski, Wiiyogaw, Wiiyogahm), were played three times, whereas the longer games (Boxing and Kinyoga) with repeating sequences were played once. After each game, the participants were asked to sit down and take a rest for approximately five minutes.

Processing

All processing was performed in Matlab (MathWorks, USA). EMG signals were high-pass filtered at 20Hz, using a 3rd order high-pass Butterworth filter before being rectified and smoothed using a moving average technique with a window of 100ms³⁹. The processed signals from the experimental trials were normalized to maximum values obtained during the MVCs.

Outcome measures

Traditional outcome measures quantifying intensity obtained from EMG-data include the area under the curve, mean, median or maximum values⁴⁰. However, these methods lose potentially valuable temporal and amplitude information. Therefore, muscle activity was averaged over 200-ms blocks and categorized each block in one of four activation zones, <40%, 40-60%, 60-80% and >80% MVC (fig. 1). The number of blocks in each zone was counted and total time spent in each zone was normalized to the duration of the game, to express the Time in Zone (TIZ). This normalization was done because a shorter game will more likely result in less blocks than longer games, but could in practice be played several times to accommodate for this difference. Larger metabolic stress is expected from a high number of consecutive blocks of muscle activation and plays a crucial role in strength gains following exercise at lower intensities²⁹. Therefore, we calculated the maximal number of consecutive 200-ms blocks (MCB) separated by no more than three seconds of <40% MVC EMG activity.

Figure 1, Example of blocks detection: The smoothed EMG amplitude of the VL muscle during a section of the Adventure game is plotted in grey. The colored 200-ms blocks represent different activation zones, based on the average of the smoothed signal over these 200-ms blocks.

Statistics

The games that provoke very low muscle activation were omitted from further statistical analysis. Threshold was defined as less than 5% of total game duration activations higher than 40% of MVC and in addition a low number of MCB's. Generalized Estimating Equations (GEE), were used to perform null hypothesis testing for the factors game and age group on the variables TIZ and MCB for all muscles, with trial number as a covariate. The correlation structure was set to autoregressive. Post-hoc pairwise comparisons were done using Least Significant Difference (LSD). No previous effect sizes were available to estimate power and sample size. Since our main focus was to test the proof of concept and feasibility of the novel exergames, only a limited sample size of 16 subjects were recruited. All statistical analysis were performed in IBM SPSS Statistics Version 21.0.

Results

Wiiyogaw, Wiiyogahm and Wiiski, all using a COP-based controller, provoked only minor muscle activation parameters and were omitted from further statistical analysis.

In general, all games elicited during less than 20% of total game duration a muscle activation higher than 40% of the MVC. The longest periods of consecutive high muscle activity were very short (< 5%) in almost all games. The number of MCB that muscles were active at or above 40% of the MVC was also low.

Time in Zone

To assess duration of lower limb muscle activation, TIZ for every activity zone was calculated. TIZ was compared between age groups and games (Fig 2, Table 3), and in case of an interaction effect further analyses were performed (Fig 3).

For older adults, a very low time (<5%) with activations higher than 40%, was seen for the **GluM** in all games. However, for the >40% categories Adventure showed longer periods of activation compared to the other games.

For the **VM** and **VL**, longer TIZ was seen for the adventure game compared to the other games for all activation zones except the lowest activation zone. For the latter, the Kinski game showed the longest time.

For the **SOL**, longer activation in the >60% activation zones was seen for both Adventure and Boxing game compared to the other games.

Table 3. TIZ: Summary of the GEE model effects.

Figure 2. TIZ descriptive statistics. In rows, games, muscles and age groups (y=young, e=elderly) are indicated. Along the x-axis the TIZ as a percentage of the total game duration is plotted. The TIZ for the four different categories are stacked, to provide an overview of the total time that each muscle is active during each game.

Figure 3. TIZ post hoc comparisons

Panels show mean values and standard deviations of TIZ, horizontally grouped by muscle and vertically grouped by activity zone. Significant differences ($P < .05$) between games are marked 'x' spanning groups, and in case game x group interactions were found and between game comparisons were made within the elderly group '*'. Significant group differences within games are indicated '#'.

adv= Adventure, kiny= Kinyoga, box= Boxing, kski= Kinect ski

Between-game differences

Group differences

For the **VL**, during Adventure, young participants showed longer TIZ in the >80% category than older adults. In contrast, during the Boxing game older adults spent more time in the >80% category. In the 40-60% category, older adults had longer TIZ than young participants across all games. Furthermore, young

participants had longer TIZ in the <40% category during both Boxing and Kinyoga. The **VM** did not show a significant game*age effect. However, a significant main effect of age indicates that older adults show slightly more activity than young in the 40-60% across all games.

For the **SOL**, a significant game*age effect was seen for all activation zones. Young participants showed longer TIZ in the >60% categories than older adults during Adventure. In the 40-60% category, older adults had longer TIZ than young subjects during, Kinski, Boxing and Kinyoga. In the lowest category, older adults had longer TIZ than young during Adventure whereas young participants spent more time in this category during Kinyoga.

For the **GluM**, in the 40-60% category, older adults showed longer TIZ than young participants during Kinski, Boxing and Kinyoga. In the lowest activity category, young subjects had longer TIZ during the Boxing and Kinyoga game.

Maximal Consecutive Blocks

Larger metabolic stress is expected from a high number of consecutive blocks of muscle activation and plays a crucial role in strength gains following exercise at lower intensities²⁹. For this, we calculated the MCB for each muscle in the Adventure, Kinyoga and Boxing game (Table 4).

Table 4. GEE model (game, age and their interaction) effects for MCB for VL, VM, SOL and GluM. .

Most of the games showed little sustained muscle activity indicated by a very low number of MCB (>40%MVC) (fig 4). It should be noted that the median values of the games that elicited the longest active periods, indicate that the muscle was active for a consecutive bout of only 8 seconds. For all muscles a game*age interaction was found for the MCB.

Figure 4. Maximal consecutive blocks

Median values are indicated with a horizontal line, the box ranges from the 1st to the 3rd quartile. Whiskers indicate the range of the data. The games included in the statistical analysis are indicated by the bold border. Significant game effects (x) and outliers (+) are indicated as well as group differences within games ('#').
adv= Adventure, wski= Wiiski, kski= Kinski, bo = Boxing, wyw= Wiiyogaw, wyhm= Wiiyogahm, kiny= Kinyoga

Game differences

VL and **VM** showed higher MCB, reflecting more consecutive muscle activity, during Kinyoga than during Adventure and Boxing in older adults. **SOL** and **GluM** did not show significant differences between games.

Group differences

For the **VL**, **SOL** and **GluM**, older adults showed more MCB than young subjects during Kinyoga (and Boxing for the GluM). In the SOL, young participants showed more MCB than older participants during Adventure. For the **VM**, there were no group differences.

Discussion

The aim of this study was to identify potential effective VR games for muscle strength training. Muscle strength training is seen as one of the balance components that need training in elderly. The percentage of total game-time that a muscle was active in pre-defined activity categories was studied, as well as the MCB that muscles remained active, were studied. Both factors are seen as indicators of overall muscular effort during different VRT-games.

In general, all included games elicited very low muscle activity. Most of the games elicited substantial muscle activity (> 40% of MVC) only during a small fraction of the total game-time. The longest periods of consecutive muscle activity at more than 40% MVC were very short. Especially GluM activation was most of the time in the <40% MVC category. Regarding the MCB that muscles were active at or above 40% was also low. This raises questions on the effectiveness of these games in improving muscle strength.

Only few studies investigated muscle activation during exergames, and used a different approach to assess this activation. The study of Soltani et al., where EMG of the upper limb was recorded during a swimming exergame⁴¹, reported muscle activations in the arms between 4.9 and 95.2% of the MVC. Further, Da Silva et al reported low activation (relative to the maximum voluntary contraction) of the quadriceps during Wii games, which is in line with the low activations we found for the Wii games⁴². None of these studies used such an extensive approach as the present one (i.e. by using the novel activation measures; time in zone and maximal consecutive blocks) to determine muscle activation.

Game differences

For all muscles, the Adventure game elicited the highest percentage of game time at muscle activity above 80%. This highly dynamic game, with frequent squatting and jumping movements, also had the highest percentages of activation in the 60-80% category. The Kinski game, with frequent weight shifts but only occasional jumps, resulted in the lowest TIZ in the higher activity zones. Consequently, muscle activation was more prominent in the <40% MVC category during Kinski for VL, VM and Sol. For the GluM, Kinyoga and Kinski did not differ in this category. The longer TIZ in the <40% category during the Kinski game, reflects that the combined TIZ of the higher categories is longer during Adventure, Kinyoga and Boxing. The Kinyoga and Boxing games incorporated dynamic exercises (e.g. squats, lunges and one leg stance), but these were performed at lower speeds than in the Adventure game.

The games that scored lowest on muscle activation parameters (Wiiyogaw, Wiiyogahm and Wiiski) were omitted from statistical analysis. It is interesting to note that the Kinski game seemed favorable over the Wiiski game when looking at the muscle activation despite the similar objective. This difference may be attributable to the different controller, kinematic controller (Kinski) and force plate (WiiSki). A kinematic controller, which tracks kinematics, may impose more dynamic and varied movements, such as jumps, squats and taking steps. This is in agreement with findings of our previous study, that games with different type of controllers, lead to different center of mass displacements ⁴³.

The MCB measure was introduced to study the effectiveness of the game in inducing a prolonged muscle training stimulus at more than 40%MVC, to induce the desired metabolic stress ²⁹. The variations in duration, from around one minute for the adventure and the skiing games up to more than seven minutes for Kinyoga, might obscure the effectiveness of the longer games, when only evaluating the TIZ measure. Indeed, we found that for the VL and VM muscles, the Kinyoga game, which incorporated structured sets of squats at a low pace, induced a higher number of MCB than Adventure, which performed better for the TIZ measure. However, the number of MCB and therefore the duration of sustained muscle activity was still low. In the future, research can be conducted with focus on the development of games with fast and/or specific movements (e.g. squatting, single leg stance), adding extra weights (weight belts) or adding steps to increase muscle activation.

Group differences

Differences in muscle activation level and duration between young and older subjects were found. For the VL young subjects showed longer TIZ in the >80% category during the Adventure game, whereas older subjects showed longer TIZ in the Boxing game. For Sol, young subjects had longer TIZ during the Adventure in both the >80% and 60-80% categories, and during Kinski in the >80% category. These

differences might be attributable to the incentive that is used to elicit more movements. In both the Adventure and Kinski game, the player is encouraged to squat and jump to speed up the game. However, older adults are typically less inclined than young to speed up these games. Furthermore, the jumps might be outside of the comfort zone of the older players, resulting in lower TIZ for the >80% category. The Boxing and Kinyoga game on the other hand, have coaches that perform the movements that the player has to follow and the player is rewarded more points when performing the movements in time. This type of game dictates the speed at which the movements are performed, and might therefore be more challenging for older adults. The caveat in a game design with fixed difficulty would be an inappropriate difficulty level, which could result in negative feedback and decrease motivation and effectiveness ^{44,45}.

Limitations

The multitude of comparisons, with significant, but small, differences between age groups and games, could obscure the main finding, i.e. that all included games elicited very low muscle activity, especially the games omitted from the statistical analysis. However, since the exact criteria at which muscle activation during weight bearing exercises can be effective are not well established, we choose to study multiple outcome measures. Nonetheless, the main finding is that in all studied VRT, the muscle activity appears low.

For traditional strength training, recommendations are to use at least 60% of 1RM ²⁵, but for functional weight-bearing exercise these thresholds are less well established. Furthermore, there is no exact linear relationship between EMG and force. However, it is shown that higher EMG correlates with higher forces. Additionally, if EMG is normalized to values achieved during MVC they are approximately linearly correlated with force ^{34,35}. Therefore, we categorized the EMG activity in different activity zones based on the level of muscle activity. Especially the faster movements induced activity in the highest (>80% MVC) zone, which is in line with findings of Soltani et al. They find higher muscle activations in games that were played at higher compared to lower velocities ⁴¹. When lower loads are used it is recommended to increase the number of repetitions up to muscle exhaustion ⁸. However, the small amount of prolonged muscle activity, as indicated by the low MCB, shows that it is unlikely that the games studied challenge the player enough to reach muscle exhaustion. Yet there is no literature on the duration of muscle activity and the accompanying recovery time required to induce an optimal metabolic response. Three seconds without any muscle activation blocks, was chosen as the cut-off point for initiating a new series. Small changes of this threshold, ranging from one to ten seconds, did not lead to

different conclusions for this study. Low muscle activity can also be due to low effort of the subject while playing the games. Game performance scores were not assessed, however based on our observations it seemed that participants tried their best when playing the games.

Data were collected and analyzed in the present study with only focus on muscle activations, as one of the factors that need to be trained for balance. It is evident that other factors are also important to improve balance in elderly (e.g. center of mass movement, muscle force, sensory and movement strategies ...) and that the balance component that needs most training can vary between patients ^{4,19}. This differentiation was beyond the scope of this manuscript.

Conclusions

Overall, the muscle activity when performing the VRT-games studied seems low for effective muscle strength training. This means that muscular benefits for the tested games are unclear. However, the games could have other beneficial effects such as on cardiovascular health or wellbeing. Muscle activity was only high during jumping, indicating that certain elements of these games could be part of an effective muscle training, when suited for the participants.

In future studies, games with higher muscle activity (e.g. more dynamics movements, kicks, ...) should be developed and tested, keeping the safety of participants, i.e. elderly, in mind ^{46–49}. To improve VR-games for muscle strength training, muscle activity should be higher (e.g. > 40% of the MVC) and better structured over time (e.g. longer bouts), to induce higher metabolic stress and make better use of the total game time. Especially increasing the length of the sets, while keeping the muscle activity at a low percentage of the MVC seems a more viable way for VR training. Furthermore, the incentives to trigger more challenging exercises should be adequate for the target population, and preferably be adaptable to the physical fitness of the individual player.

In conclusion, VRT-games have potential for muscle strength training in elderly, however, in future, games should be developed with the purpose to sufficiently activate and thereby train their muscles, since the existing games elicit too low muscle activity

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References

1. Moreland JD, Richardson JA, Goldsmith CH, Clase CM. Muscle Weakness and Falls in Older Adults: A Systematic Review and Meta-Analysis. *J Am Geriatr Soc.* 2004;52(7):1121-1129. doi:10.1111/j.1532-5415.2004.52310.x
2. Rubenstein LZ. Falls in older people: epidemiology, risk factors and strategies for prevention. *Age Ageing.* 2006;35(suppl 2):ii37-ii41. doi:10.1093/ageing/afl084
3. Daubney ME, Culham EG. Lower-extremity muscle force and balance performance in adults aged 65 years and older. *Phys Ther.* 1999;79(12):1177-1185.
4. Horak FB. Postural orientation and equilibrium : what do we need to know about neural control of balance to prevent falls ? *Age Ageing.* 2006;7-11. doi:10.1093/ageing/afl077
5. Cattagni T, Scaglioni G, Laroche D, Van Hoecke J, Gremeaux V, Martin A. Ankle muscle strength discriminates fallers from non-fallers. *Front Aging Neurosci.* 2014;6:336. doi:10.3389/fnagi.2014.00336
6. Shad BJ, Thompson JL, Breen L. Does the muscle protein synthetic response to exercise and amino acid-based nutrition diminish with advancing age ? A systematic review. 2019. doi:10.1152/ajpendo.00213.2016
7. Hess JA, Woollacott M. Effect of High-Intensity Strength-Training on Functional Measures of Balance Ability in Balance-Impaired Older Adults. *J Manipulative Physiol Ther.* 2005;28(8):582-590. doi:http://dx.doi.org/10.1016/j.jmpt.2005.08.013
8. Van Roie E, Delecluse C, Coudyzer W, Boonen S, Bautmans I. Strength training at high versus low external resistance in older adults: effects on muscle volume, muscle strength, and force-velocity characteristics. *Exp Gerontol.* 2013;48(11):1351-1361. doi:10.1016/j.exger.2013.08.010
9. van Diest M, Lamothe CJC, Stegenga J, Verkerke GJ, Postema K. Exergaming for balance training of elderly: state of the art and future developments. *J Neuroeng Rehabil.* 2013;10:101. doi:10.1186/1743-0003-10-101
10. Donath L, Rössler R, Faude O. Effects of Virtual Reality Training (Exergaming) Compared to Alternative Exercise Training and Passive Control on Standing Balance and Functional Mobility in

- 373 Healthy Community-Dwelling Seniors: A Meta-Analytical Review. *Sport Med.* 2016:1-17.
374 doi:10.1007/s40279-016-0485-1
- 375 11. Milgram P. Augmented reality: A class of displays on the reality-virtuality continuum.
376 *Telemanipulator telepresence Technol.* 1994;2351:282-292.
- 377 12. Fitzgerald D, Trakarnratanakul N, Smyth B, Caulfield B. Effects of a wobble board-based
378 therapeutic exergaming system for balance training on dynamic postural stability and intrinsic
379 motivation levels. *J Orthop Sports Phys Ther.* 2010;40(1):11-19. doi:10.2519/jospt.2010.3121
- 380 13. de Vries AW, van Dieën JH, van den Abeele V, Verschueren SMP. Understanding Motivations and
381 Player Experiences of Older Adults in Virtual Reality Training. *Games Health J.* 2018.
382 doi:10.1089/g4h.2018.0008
- 383 14. Forkan R, Pumper B, Smyth N, Wirkkala H, Ciol MA, Shumway-Cook A. Exercise adherence
384 following physical therapy intervention in older adults with impaired balance. *Phys Ther.*
385 2006;86(3):401-410. doi:10.1046/j.1532-5415.2002.50601.x
- 386 15. Simek EM, McPhate L, Haines TP. Adherence to and efficacy of home exercise programs to
387 prevent falls: A systematic review and meta-analysis of the impact of exercise program
388 characteristics. *Prev Med (Baltim).* 2012;55(4):262-275.
389 doi:http://dx.doi.org/10.1016/j.ypmed.2012.07.007
- 390 16. Lyons EJ. Cultivating Engagement and Enjoyment in Exergames Using Feedback , Challenge , and
391 Rewards. 2015;4(1):12-18. doi:10.1089/g4h.2014.0072
- 392 17. Faude O, Donath L, Ro R. Effects of Virtual Reality Training (Exergaming) Compared to
393 Alternative Exercise Training and Passive Control on Standing Balance and Functional Mobility in
394 Healthy Community-Dwelling Seniors : A Meta-Analytical Review. 2016:1293-1309.
395 doi:10.1007/s40279-016-0485-1
- 396 18. Goble DJ, Cone BL, Fling BW. Using the Wii Fit as a tool for balance assessment and
397 neurorehabilitation: the first half decade of "Wii-search." *J Neuroeng Rehabil.* 2014;11(1):12-.
398 doi:10.1186/1743-0003-11-12
- 399 19. Sherrington C, Tiedemann A, Fairhall N, Close J, Lord S. Exercise to prevent falls in older adults : an
400 updated meta-analysis and best practice recommendations. *NSW public Heal Bull.* 2011;22:78-83.

- 401 20. Horak FB, Wrisley DM, Frank J. The Balance evaluation systems test (BESTest) to differentiate
402 balance deficits. *Phys Ther.* 2009;89(5):484-498.
- 403 21. Messier SP, Royer TD, Craven TE. Long-Term Exercise and its Effect on Balance in Older ,
404 Osteoarthritic Adults : Results from the Fitness, Arthritis and Seniors trial (FAST). *JAGS.* 2000:131-
405 138.
- 406 22. Kannus P, Sievänen H, Palvanen M, Järvinen T, Parkkari J. Prevention of falls and consequent
407 injuries in elderly people. 2005;366. doi:10.1016/S0140-6736(05)67604-0
- 408 23. Kim J, Son J, Ko N, Yoon B. Unsupervised Virtual Reality-Based Exercise Program Improves Hip
409 Muscle Strength and Balance Control in Older Adults: A Pilot Study. *Arch Phys Med Rehabil.*
410 2013;94(5):937-943. doi:10.1016/j.apmr.2012.12.010
- 411 24. Fry a C. The role of resistance exercise intensity on muscle fiber adaptation. *Sport Med.*
412 2004;34(10):663-669. doi:10.2165/00007256-200434100-00004
- 413 25. Mazzeo RS, Tanaka H. Exercise Prescription for the Elderly. *Sport Med.* 2001;31(11 LB-
414 Mazzeo2001):809-818. doi:10.2165/00007256-200131110-00003
- 415 26. Correa C, LaRoche D, Cadore E, et al. 3 Different Types of Strength Training in Older Women. *Int J*
416 *Sports Med.* 2012;33(12):962-969. doi:10.1055/s-0032-1312648
- 417 27. Pijnappels M, van der Burg JCE, Reeves ND, van Dieën JH. Identification of elderly fallers by
418 muscle strength measures. *Eur J Appl Physiol.* 2008;102(5):585-592.
419 doi:http://dx.doi.org/10.1007/s00421-007-0613-6
- 420 28. Baggen RJ, Roie E Van, Dieën JH Van, Verschueren SM, Delecluse C. Weight bearing exercise can
421 elicit similar peak muscle activation as medium – high intensity resistance exercise in elderly
422 women. *Eur J Appl Physiol.* 2018;118(3):531-541. doi:10.1007/s00421-017-3793-8
- 423 29. Goto K, Ishii N, Kizuka T, Takamatsu K. The impact of metabolic stress on hormonal responses and
424 muscular adaptations. *Med Sci Sports Exerc.* 2005;37(6):955-963.
425 doi:10.1249/01.mss.0000170470.98084.39
- 426 30. Kan GAVAN, André E, Boirie Y, Onder G. CARLA TASK FORCE ON SARCOPENIA : PROPOSITIONS
427 FOR CLINICAL TRIALS *. 2009;13(8).

- 428 31. Glenn JM, Gray M, Binns A. The effects of loaded and unloaded high-velocity resistance training
429 on functional fitness among community-dwelling older adults. *Age Ageing*. 2015;44(6):926-931.
430 doi:10.1093/ageing/afv081
- 431 32. Diest M Van, Lamothe CJC, Stegenga J, Verkerke GJ, Postema K. Exergaming for balance training of
432 elderly : state of the art and future developments. 2013.
- 433 33. Keshner EA. Virtual reality and physical rehabilitation : a new toy or a new research and
434 rehabilitation tool ? 2004;2:1-2. doi:10.1186/1743-0003-1-8
- 435 34. Alkner A, Tesch PERA, Berg HE. Quadriceps EMG / force relationship in knee extension and leg
436 press. 2000;(January 1999):459-463.
- 437 35. Onishi H, Yagi R, Akasaka K, Momose K, Ihashi K, Handa Y. Relationship between EMG signals and
438 force in human vastus lateralis muscle using multiple bipolar wire electrodes. 2000;10:59-67.
- 439 36. Pijnappels M, Reeves ND, Maganaris CN, van Dieën JH. Tripping without falling; lower limb
440 strength, a limitation for balance recovery and a target for training in the elderly. *J Electromyogr*
441 *Kinesiol*. 2008;18(2):188-196. doi:http://dx.doi.org/10.1016/j.jelekin.2007.06.004
- 442 37. Pandy MG, Lin Y-C, Kim HJ. Muscle coordination of mediolateral balance in normal walking. *J*
443 *Biomech*. 2010;43(11):2055-2064. doi:10.1016/j.jbiomech.2010.04.010
- 444 38. Hermens H, Freriks B, Merletti R, et al. SENIAM. European recommendations for surface
445 electromyography; 1999. *Roessingh Res Dev Enschede*.
- 446 39. De Luca CJ, Gilmore LD, Kuznetsov M, Roy SH. Filtering the surface EMG signal : Movement
447 artifact and baseline noise contamination. *J Biomchanics*. 2010;43(8):1573-1579.
448 doi:10.1016/j.jbiomech.2010.01.027
- 449 40. Konrad P. The abc of emg. *A Pract Introd to Kinesiol Electromyogr*. 2005;1:30-35.
- 450 41. Soltani P, Figueiredo P, Fernandes RJ, Vilas-boas JP. Muscle activation behavior in a swimming
451 exergame : Differences by experience and gaming velocity. *Physiol Behav*. 2017;181(August):23-
452 28. doi:10.1016/j.physbeh.2017.09.001
- 453 42. Fernandes Da Silva F, Aparecido de Souza R, Fernandes Dias E, Silveira L, Balbin Villaverde A.
454 Effects of feedback on activation of the quadriceps during weight-bearing tasks of the Wii. *J Phys*

455 *Ther Sci.* 2015;27:1701-1704.

- 456 43. Vries AW De, Faber G, Jonkers I, Dieen JH Van, Verschueren SMP. Virtual reality balance training
457 for elderly : Similar skiing games elicit different challenges in balance training. *Gait Posture.*
458 2018;59(December 2016):111-116. doi:10.1016/j.gaitpost.2017.10.006

- 459 44. Vijver I Van De, Ridderinkhof KR, Wit S De. Age-related changes in deterministic learning from
460 positive versus negative performance feedback. *Aging, Neuropsychol Cogn.* 2015;22(5):595-619.
461 doi:10.1080/13825585.2015.1020917

- 462 45. Reed AE, Carstensen LL. The Theory Behind the Age-Related Positivity Effect. *Front Psychol.*
463 2012;3:339. doi:10.3389/fpsyg.2012.00339

- 464 46. Prata MG, Scheicher ME. Effects of strength and balance training on the mobility , fear of falling
465 and grip strength of elderly female fallers. *J Bodyw Mov Ther.* 2015;19(4):646-650.
466 doi:10.1016/j.jbmt.2014.11.013

- 467 47. Bisson E, Contant B, Sveistrup H. Functional Balance and Dual-Task Reaction Times in Older Adults
468 Are Improved by Virtual Reality and Biofeedback Training. 2007;10(1):16-23.
469 doi:10.1089/cpb.2006.9997

- 470 48. Pedroli E, Id LG, Serino S, et al. System Combining Cognitive and Physical Therapy in a Virtual
471 Environment : Positive Bike. 2018. doi:10.3390/s18072343

- 472 49. Willaert J, De Vries A, Tavernier J, Van Dieen J, Jonkers I, Verschueren Sa. Does a novel exergame
473 challenge balance and activate muscles more than existing off-the-shelf exergames? *J*
474 *Neuroengineering Rehabil.*, submitted.

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