
Mills, R and Levac, D and Sveistrup, H (2018)The Effects of a 5-Day Virtual-Reality Based Exercise Program on Kinematics and Postural Muscle Activity in Youth with Cerebral Palsy. Physical and Occupational Therapy in Pediatrics, 39 (4). pp. 388-403. ISSN 0194-2638

Version: Accepted Version

Publisher: Taylor & Francis

DOI: https://doi.org/10.1080/01942638.2018.1505801

The effects of a 5-day virtual-reality based exercise programme on kinematics and postural muscle activity in youth with cerebral palsy

ABSTRACT

Aims: To determine the effects of a 5-day virtual reality (VR)-based intervention on anticipatory and reactive mechanisms of postural control in children and adolescents with cerebral palsy (CP). ***Methods***: Eleven youth with CP (GMFCS levels I and II), ages 7 to 17, were allocated to intervention (N=5) and control (N=6) groups. Both groups attended balance assessment sessions 1 week apart. Participants in the intervention group received 1 hour one-on-one physiotherapist-supervised VR balance games for 5 consecutive days between assessments. For balance assessments, participants stood erect with eyes open on a movable platform that translated progressively through four speeds in the anterior/posterior direction. Participants performed two trials each of experimenter-triggered and self-triggered perturbations. Postural muscle activity and kinematics were recorded. The Anchoring Index and body segment cross-correlations were calculated as an indication of body stabilization, and the number of steps taken to regain balance/avoid falling were counted. Mann Whitney-U tests for between group differences in change scores were undertaken with an accepted significance level of 0.01. ***Results:*** No consistent differences in change scores were identified between groups. ***Conclusions:*** There was no effect of a 5-day VR-based intervention on postural control mechanisms used in response to oscillating platform perturbations. Subsequent studies will further tailor VR interventions to patients' functional balance needs.

KEYWORDS: postural control, anchoring index, balance mechanisms, cerebral palsy, IREX, virtual reality

Running footer: Virtual reality exercise and postural control

Cerebral palsy (CP) is a non-progressive lesion in the central nervous system (CNS) resulting in motor disability and developmental delays. It is the most common physical disability in children, (Badawi & Keogh, 2013) affecting 2.11 persons per 1000 live births (Oskoui et al., 2013). Children with CP have motor deficits which contribute to impaired functional mobility and are associated with disruptions in postural control (Assaiante et al., 2005; Schmit et al., 2016). Loss of functionality in individuals with CP can limit participation in physical activity (Bult et al., 2013; Engel-Yeger et al., 2009), which can then lead to further de-conditioning resulting in subsequent reduction in daily functional performance (Hombergen et al., 2012).

Children and adolescents with CP are at an increased risk of falls (Bult et al., 2013). Because balance is an important aspect of daily living, functional performance of children and adolescents with CP is dependent on the role of postural control (Girolami, Shiratori, & Aruin, 2011). We have recently characterized anticipatory and reactive mechanisms of postural control in youth with CP on a continuously oscillating platform (Mills et al., under review). When exposed to repeated oscillations on a moving platform at lower speeds, children and adolescents with CP generally behaved similarly to typically developing age-matched controls. However, at higher frequencies, participants with CP took more steps and maintained increased levels of tonic muscle activity in response to the platform movements. Furthermore, children (aged 7-12) and adolescents (aged 13-17) with CP exhibited a preference (Mills et al, under review) for a head strapped to trunk strategy (Amblard et al., 2001), a measure of upper body stabilization during movement. Comparatively, typically developing youth tended to prefer the head stabilized in space strategy as a means of stabilizing the head, which helps to contribute a stable visual reference input to balance. We proposed that these changes at the higher frequencies were mostly due to the participants' with CP (1) inability to control the body's multiple degrees of freedom during the task, and (2) incapacity to generate appropriate muscular responses.

Interventions that require full body movements to interact with a virtual environment have been found to improve static and dynamic standing balance (Brien & Sveistrup, 2011; Dewar et al., 2015). For example, replacing regular physiotherapy sessions with training using the Nintendo Wii for 3 weeks (four 25-minute sessions per week) resulted in improved balance scores as well as clinical motor function/performance testing in children with CP (Jelsma et al., 2012) and those with poor motor performance as identified by physical education teachers (Mombarg et al., 2013). Meanwhile, feasibility studies in specially developed virtual reality (VR) games for children with CP have demonstrated clinical improvements in functional balance and gait measures (Bonnechere et al., 2017; Jaume-I-Capó et al., 2014).

Research supports the use of full-body movement VR-based exercise such as that promoted by GestureTek Health's (Toronto, Canada) commercially available rehabilitation-specific Interactive Rehabilitation Exercise System (IREX) as an intervention to improve functional balance and mobility outcomes in children with CP (Levac et al., 2017; Glegg et al., 2014; Weiss et al., 2009). For example, we have previously demonstrated that an intensive 1-week IREX intervention improves short-term balance and functional mobility in adolescents with CP aged 13-19 years (Brien & Sveistrup, 2011). While functional improvements were noted for clinical measures including the Community Balance and Mobility Scale, the Six-Minute Walk Test and the Timed Up and Down Stairs, the effects of VR and serious gaming interventions on anticipatory and reactionary mechanisms of postural control have not been reported.

The aim of this study was to investigate the effects of a 5 day, 60 minutes/day VR-based intervention on mechanisms of postural control in children and adolescents with CP. We hypothesized that immediately following the one-on-one supervised IREX intervention, anticipatory and reactive postural control would improve compared to participants with CP who received no intervention. We hypothesized that changes would be evidenced through a reduction in (1) total number of steps taken and (2) postural muscle tonic activity, while demonstrating an increase in (1) preference towards a head stabilization in space strategy, and (2) correlations between movements of body segments. The preliminary data reported is part of a larger study on the effects of a 6-week, therapist-monitored home VR gaming program for children and adolescents with CP (Levac et al., 2017).

METHODS

Participants

Participants were 11 children and adolescents aged 7-17 years (6 males and 5 females) with a confirmed diagnosis of cerebral palsy classified as levels I or II on the Gross Motor Function Classification System (Palisano et al., 2008). Exclusion criteria were visual, cognitive or auditory impairment that would interfere with understanding of and/or ability to carry out instructions and/or play the video games, and orthopaedic surgery or Botox injections in the past 12 months. Children were recruited via study information letters mailed from the Ottawa Children's Treatment Centre (OCTC) and disseminated in schools by physical and occupational therapists via the Community Care Access Centre. Ethical approval was granted through the University of Ottawa research ethics board in accordance with the Tri-Council policy statement (CIHR et al., 2014). All participants and/or parents provided written informed consent. We did not undertake power analyses for this pilot study as our goal was to generate effect size and variability estimates to power a subsequent trial. Participant demographics are presented in table 1.

[Table 1 about here]

Intervention design

Participants were non-randomly assigned to either the Interactive Rehabilitation Exercise System (IREX) group ("Intervention", N=5) or the control group ("Control", N=6) based on their self-declared ability to attend the 1-week of VR sessions at OCTC. The 5 day IREX intervention program consisted of 60 minutes of VR-based balance training for 5 consecutive days. The program (Brien & Sveistrup, 2011; Levac et al., 2017) was delivered in the VR therapy room of the OCTC using the commercially available system consisting of a 32" widescreen display, a computer, video camera, and a green screen for computer-generated images.

The participants interacted with virtual objects in each game to achieve tasks with adjusted difficulty levels, which challenged dynamic standing balance, coordination, and timing. Games were ranked as 'Easy', 'Medium', or 'Hard' based on physical and cognitive demands when played on the lowest game parameters (Levac et al., 2017). Each exercise program was tailored to the individual's needs, with suggested games, challenge parameters, and progression across the 5 days. A full description of the intervention, approach used to determine when to increase task/game difficulty, games used, and feedback provided is provided in Levac et al (2017).

Procedures: Assessment schedule, protocol, and outcome measures

All participants attended two test sessions, each consisting of balance testing and administration of clinical measures. For the intervention group, participants completed a testing session the weekend prior to and the weekend following a 5-day intensive therapy block. Participants in the control group completed two testing sessions scheduled one week apart.

Balance testing and outcome measures

The balance testing paradigm used was the same as that used previously in our lab (Mills & Sveistrup, 2018; Bugnariu & Sveistrup, 2006). Briefly, participants stood upright on an oscillating platform (anterior/posterior) with their eyes open, and barefoot with feet shoulder-width apart. They were instructed to maintain their balance and to avoid taking steps unless necessary. Two trials in each of two test conditions were observed: experimenter-triggered (ETP) and self-triggered (STP) increases in oscillation frequency. A minimum number of cycles at each frequency (10, 20, 40, and 50 cycles at 0.1 Hz, 0.25 Hz, 0.5 Hz, and 0.61 Hz, respectively) were completed before initiating the next frequency.

Full body kinematics (100 Hz) were recorded using motion analysis software (Vicon, Oxford, UK). Bilateral surface EMG (Delsys Inc., Natick, USA) was recorded at 1000 Hz for tibialis anterior, gastrocnemius, quadriceps, and hamstring muscles, with a reference electrode placed on the iliac crest. The first three (0.1 Hz) to five (0.25 Hz, 0.5 Hz, 0.61 Hz) consecutive cycles without stepping for each frequency were considered 'transition-state' (TS). In the last half of each frequency following the transition state, a period of 3 to 5 consecutive cycles without stepping (0.1 Hz) and 8 to 10 consecutive cycles (0.25 Hz, 0.5 Hz, 0.61 Hz) without stepping were considered 'steady-state (SS) periods' during which the movement of the platform was considered to be predictable (Bugnariu & Sveistrup, 2006).

The number of steps taken at each frequency during the oscillating platform paradigm was counted. The Anchoring Index (AI) was used to determine the stabilization of the head with respect to external space and/or the trunk (Amblard et al., 1997, 2001; Mesure et al., 1999) and was calculated as follows:

$$AI = [\sigma^2_r - \sigma^2_a] / [\sigma^2_a + \sigma^2_r]$$

where σ_a is the dispersion of the head with respect to the absolute vertical (external space), and σ_r is the angular dispersion of the head relative to the trunk. A negative AI indicates a preference for a Head Strapped to Trunk Strategy (HSTS), whereas a positive AI indicates a preferred Head Stabilization in Space Strategy (HSSS).

Cross-correlations (CC) of anteroposterior linear displacements of the ankle-head, hip-head, and ankle-hip marker pairs were calculated. Each CC temporal relationship (lag/lead) was calculated for ±50% time shift of one cycle. The maximum correlation and percent cycle at which it occurred were recorded.

Raw EMG signals were full-wave rectified. Postural muscle bursting activity was expressed as the percent of cycles in which bursts occurred. Tonic activity levels were expressed as a percentage of the measured tonic activity at ETP SS 0.1 Hz.

Clinical testing and outcome measures

Following the balance testing protocol, participants were offered a period of 10-15 minutes rest before continuing with the clinical testing. Clinical testing consisted of the 6-minute walk test (6MWT) (Maher et al., 2008) to assess the functional capacity for walking a prolonged distance. This was followed by the Gross Motor Function Measure Challenge Module (GMFM-CM)

(Glazebrook & Wright, 2014) to assess gross motor skills of balance and postural control, coordination, agility, speed, and strength. Scores were converted to percentages. The 6MWT and GMFM-CM clinical outcome measures were recorded by accredited physiotherapists.

Data Analysis

Participant demographics and stepping data were summarized using descriptive statistics. Statistical analyses of clinical, kinematic, and postural muscle outcome measures were performed using SPSS v 23.0.0.2 (IBM Corp.). In the balance testing protocol, cycles during which steps were taken were excluded from statistical analyses. Data were determined to be non-normally distributed through inspection of skewness and kurtosis, histograms, and Shapiro-Wilk tests of normality. First, baseline comparisons were made for between group differences, followed by inferential testing using the non-parametric Mann-Whitney U test for between group differences of the change scores (difference between assessments, i.e. assessment 2-1). Cases where baseline measures were found to be significantly different between groups were excluded from the change-score analyses to ensure any differences detected were as a result of the intervention. Results considered significant for $p < 0.0125$ (Bonferroni adjusted).

RESULTS

Baseline comparisons

A significant difference between groups was identified at baseline for the Ankle-Head marker trajectory pair correlation at 0.1 Hz ($U = 1$, $p = 0.009$) in the ETP TS condition. This measure was excluded from subsequent change-score analyses. No significant differences between groups at baseline were detected in the STP conditions, nor in the clinical outcome measures.

Balance Testing

Stepping Responses

Statistical analysis was not performed for the stepping response data as many participants were unable or unwilling to complete trials in the first assessment, but could complete trials at the second assessment. Thus, change scores could not be calculated. Results for the stepping responses of all participants at 0.5 Hz and 0.61 Hz in externally- and self-triggered conditions are presented in Table 2. Generally, the lower frequencies (0.1 Hz and 0.25 Hz) did not elicit stepping responses in either condition. A greater number of steps was observed at the higher frequencies (0.5 Hz and 0.61 Hz) in both conditions. More steps were taken in the externally-triggered condition compared to the self-triggered condition, and a reduction in steps taken between assessments was observed in both the IREX and control groups.

[Table 2 about here]

Anchoring Index

Although no significant differences were found between groups for the change in Anchoring Index at any frequency in any condition, both groups initially tended towards no preference in stabilization strategy. Following the one-week period, the participants in both groups exhibited less reliance on the head strapped to trunk strategy and adopted either no preference for either strategy, or switched to a head stabilized in space strategy entirely – this was especially noticeable in the transition state periods in both externally- and self-triggered conditions (see figure 1). Results for the anchoring index Mann-Whitney U tests including effect sizes can be found in Table 3.1 . Briefly, effect sizes were mostly small, ranging from 0.09 to 0.62.

[Figure 1 about here]

[Table 3.1 about here]

Kinematics

Few significant differences were found between groups in the cross-correlation analyses. In the externally-triggered condition during steady state periods, the Ankle-Head cross-correlation at 0.25 Hz tended to decrease more (U = 0, p = 0.024) in the IREX group (M = -0.624; SD = 0.47) than in the control group (M = -0.02; SD = 0.03). The Ankle-Hip cross-correlation at 0.1 Hz increased more (approached significance: U = 1, p = 0.019) in the IREX group (M = 0.45; SD = 0.35) than in the control group (M = -0.18; SD = 0.49) following the 1-week intensive program. No significant differences between groups were detected in any marker-pair trajectory cross-correlation in the other frequencies/conditions. Briefly, effect sizes were mostly small to medium, ranging from 0 to 0.8. Full results of the cross-correlation analyses including effect sizes can be found in Tables 3.2 (transition states) and 3.3 (steady states).

[Tables 3.2 and 3.3 about here]

Postural muscle activity

The tonic activity of the hamstrings in the externally-triggered condition during steady state (0.25 Hz) increased more (approached significance: U = 1, p = 0.019) in the IREX group (M = 9.72; SD = 12.34) than in the control group (M = -6.46; SD = 11.47) following 1-week intensive therapy. No other significant differences between groups were detected in either tonic activity levels or bursting activity for all muscles in all other frequencies/conditions. Full results of the postural muscle activity MWU tests including effect sizes are presented in Tables 3.4 (transition states) and 3.5 (steady states). Effect sizes for postural muscle activity ranged from 0 to 2.7.

[Tables 3.4 and 3.5 about here]

Clinical Outcome Measures

There were no significant differences in change scores between groups found in the 6MWT and the GMFM-CM (see figure 2).

[Figure 2 about here]

DISCUSSION

We examined the effect of a 1-week VR-based intensive exercise program on anticipatory and reactive mechanisms of postural control in children and adolescents with CP. Contrary to our hypotheses, children and adolescents with cerebral palsy who participated in the program did not exhibit significant changes to postural control mechanisms following the VR exercise program.

The lack of differences in change scores in the kinematic and muscle activity analyses could be explained by redundancy in responses. During acquisition of new motor tasks (or re-learning of old ones), it has been hypothesized that development occurs in phases (Woollacott & Sveistrup, 1992) whereby initially the control of degrees of freedom throughout the body (eg. hips, knees, and ankles) is poor and a clear behavioural strategy in response to a postural perturbation is not exhibited. In the second phase of learning, the degrees of freedom are constrained or ‘frozen’ to a minimum, allowing for a strong, rigid system, before being ‘released’ and re-integrated with practice in phase 3 for fluid movement (Vereijken et al., 1992; Bernstein, 1967). Thus, study participants may have been constrained to a phase 2 stage of motor (re)learning with insufficient time and practice to consolidate response reorganization. Future studies would ideally investigate the effect of an intensive VR-based intervention over several weeks, with multiple baselines.

Because many of the games played during the VR-based intervention require lateral movements, it is possible that improved postural control in the lateral direction may not have carried-over to the postural balance mechanisms in the anteroposterior direction of the platform oscillations. For example, in a systematic review of balance training interventions, Kümmel et al. (2016) discussed how training can improve balance and performance on a trained task but not necessarily in a non-trained, related task. Indeed, Giboin et al. (2015) showed that balance training only had an effect on the trained tasks, even if the non-trained tasks were performed on a similar platform but in a different direction of perturbation. Moreover, it was found that groups outperformed others only on the tasks in which they were trained. Thus, the authors suggested identifying and training exactly those tasks requiring improvement.

Recent studies have demonstrated benefits of VR training on dynamic balance control, but have mostly focussed on clinical assessments, such as the Berg Balance Scale or Paediatric Balance Scale (PBS). For example, Cho et al (2016) found that virtual reality treadmill training improved scores on the PBS, while Pavao et al. (2014) observed similar changes on the PBS following VR-based therapy. However, our aim was to understand if anticipatory and reactive postural control mechanisms are necessary for functional balance and mobility. The results from our study suggest that this dosage of VR-based exercise alone did not result in significant changes in anticipatory and reactive mechanisms of postural control in youth with CP. While this may be a result of employing multiple mechanisms for achieving the same task, improvements in postural control for this population may rely on improving the ability to generate appropriate muscle responses. The VR games in this study did not target specific muscles for strength training and muscle activation timing.

There are also possible limitations as to why no changes were observed in either group. Most notably, the sample size was small and not powered to detect change as evidenced by the mostly small to medium effect sizes. The number of participants recruited was limited to those who volunteered for the study, which greatly influenced the effect sizes of our statistical analyses. Due to the small sample size and large variability in our data, it is possible that benefits gained by some participants were within the magnitude of the grouped variability. However, while we have previously demonstrated improvements on clinical measures in four adolescents with CP following a 5-day intensive VR program (Brien & Sveistrup, 2011), it is possible the intervention was not sufficiently challenging or intense, as there may not have been enough repetition to obtain improvement. The relatively shorter duration of the daily program – 60 minutes per day in our intervention compared to the 90 minutes per day in Brien & Sveistrup's study – might not have provided the required intensity of stimulation for improvement. Furthermore, it is possible the participants who received the IREX intervention simply used this exercise to replace another physical activity they would have otherwise done throughout the week.

CONCLUSIONS

Five days of VR-based intervention did not alter the anticipatory or reactive postural control mechanisms used in response to oscillating platform perturbations in children with cerebral palsy. In subsequent studies, increasing the sample size and increasing the intensity, specificity, and duration of the activity may inform physiotherapists of the potential benefits to an intensive VR-based exercise program. Furthermore, more work is required to understand the transferability of the lateral training of the VR-based exercises to the anteroposterior aspects of postural control mechanisms. The use of head-mounted displays to provide 3D VR environments may also encourage movements in both medio-lateral and antero-posterior planes.

Declaration of interest

The authors declare that they have no conflict of interest.

REFERENCES

Amblard, B., Assaiante, C., Fabre, J.-C., Martin, N., Massion, J., Mouchnino, L., & Vernazza, S. (1997). Voluntary head stabilization in space during trunk movements in weightlessness. *Experimental Brain Research*, *114*, 214–225.

Amblard, B., Assaiante, C., Vaugoyeau, M., Baroni, G., Ferrigno, G., & Pedotti, A. (2001). Voluntary head stabilisation in space during oscillatory trunk movements in the frontal plane performed before, during and after a prolonged period of weightlessness. *Experimental Brain Research*, *137*(2), 170–179. https://doi.org/10.1007/s002210000621

Assaiante, C., Mallau, S., Viel, S., Jover, M., & Schmitz, C. (2005). Development of postural control in healthy children: A functional approach. *Neural Plasticity*, *12*(2–3), 109–118. https://doi.org/10.1155/NP.2005.109

Badawi, N., & Keogh, J. M. (2013). Causal pathways in cerebral palsy. *Journal of Paediatrics and Child Health*, *49*(1), 5–8. https://doi.org/10.1111/jpc.12068

Bernstein, N. (1967). *The coordination and regulation of movements*. New York: Pergamon Press.

Bonnechere, B., Omelina, L., Jansen, B., & Van Sint Jan, S. (2017). Balance improvement after physical therapy training using specially developed serious games for cerebral palsy children : preliminary results. *Disability and Rehabilitation*, *39*(4), 403–406. https://doi.org/10.3109/09638288.2015.1073373

Brien, M., & Sveistrup, H. (2011). An intensive virtual reality program improves functional balance and mobility of adolescents with cerebral palsy. *Pediatric Physical Therapy*, *23*(3), 258–266. https://doi.org/10.1097/PEP.0b013e318228c327

Bugnariu, N., & Sveistrup, H. (2006). Age-related changes in postural responses to externally- and self-triggered continuous perturbations. *Archives of Gerontology and Geriatrics*, *42*(1), 73–89. https://doi.org/10.1097/PEP.0b013e318227ca0f

Bult, M. K., Verschuren, O., Lindeman, E., Jongmans, M. J., Westers, P., Claassen, A., & Ketelaar, M. (2013). Predicting leisure participation of school-aged children with cerebral palsy: Longitudinal evidence of child, family and environmental factors. *Child: Care, Health and Development*, *39*(3), 374–380. https://doi.org/10.1111/j.1365-2214.2012.01391.x

Cho, C., Hwang, W., Hwang, S., & Chung, Y. (2016). Treadmill Training with Virtual Reality Improves Gait, Balance, and Muscle Strength in Children with Cerebral Palsy. *The Tohoku Journal of Experimental Medicine*, *238*(3), 213–218. https://doi.org/10.1620/tjem.238.213

CIHR; NSERC; SSHRC. (2014). TCPS2: Ethical Conduct for Research Involving Humans. Government of Canada.

Dewar, R., Love, S., & Johnston, L. M. (2015). Exercise interventions improve postural control in children with cerebral palsy: A systematic review. *Developmental Medicine and Child Neurology*, *57*(6), 504–520. https://doi.org/10.1111/dmcn.12660

Engel-Yeger, B., Jarus, T., Anaby, D., & Law, M. (2009). Differences in patterns of participation between youths with cerebral palsy and typically developing peers. *American Journal of Occupational Therapy*, *63*(1), 96–104. https://doi.org/10.5014/ajot.63.1.96

Giboin, L. S., Gruber, M., & Kramer, A. (2015). Task-specificity of balance training. *Human Movement Science*, *44*(August), 22–31. https://doi.org/10.1016/j.humov.2015.08.012

Girolami, G. L., Shiratori, T., & Aruin, A. (2011). Anticipatory postural adjustments in children with hemiplegia and diplegia. *Journal of Electromyography and Kinesiology*, *21*(6), 988–997. https://doi.org/10.1016/j.jelekin.2011.08.013

Glazebrook, C. M., & Wright, F. V. (2014). Measuring advanced motor skills in children with cerebral palsy: further development of the challenge module. *Pediatric Physical Therapy*, *26*(2), 201–213. https://doi.org/10.1097/PEP.0000000000000035

Glegg, S. M. N., Tatla, S. K., & Holsti, L. (2014). The GestureTek virtual reality system in rehabilitation: a scoping review. *Disability and Rehabilitation. Assistive Technology*, *9*(2), 89–111. https://doi.org/10.3109/17483107.2013.799236

Hombergen, S. P., Huisstede, B. M., Streur, M. F., Stam, H. J., Slaman, J., Bussmann, J. B., & Van Den Berg-Emons, R. J. (2012). Impact of cerebral palsy on health-related physical fitness in adults: Systematic review. *Archives of Physical Medicine and Rehabilitation*, *93*(5), 871–881. https://doi.org/10.1016/j.apmr.2011.11.032

Jaume-I-Capó, A., Martinez-Bueso, P., Moya-Alcover, B., & Varona, J. (2014). Interactive rehabilitation system for improvement of balance therapies in people with cerebral palsy.

IEEE Transactions on Neural Systems and Rehabilitation Engineering, *22*(2), 419–427. https://doi.org/10.1109/TNSRE.2013.2279155

Jelsma, J., Pronk, M., Ferguson, G., & Jelsma-Smit, D. (2012). The effect of the Nintendo Wii Fit on balance control and gross motor function of children with spastic hemiplegic cerebral palsy. *Developmental Neurorehabilitation*, 16 (February), 1–11. https://doi.org/10.3109/17518423.2012.711781

Kümmel, J., Kramer, A., Giboin, L.-S., & Gruber, M. (2016). Specificity of balance training in healthy individuals: A systematic review and meta-analysis. *Sports Med*, 46(March), 1261–1271. https://doi.org/10.1007/s40279-016-0515-z

Levac, D., Mccormick, A., Levin, M. F., Brien, M., Mills, R., Miller, E., & Sveistrup, H. (2017). Active video gaming for children with cerebral palsy: Does a clinic-based virtual reality component offer an additive benefit ? A Pilot Study. *Physical & Occupational Therapy In Pediatrics*, *0*(0), 1–14. https://doi.org/10.1080/01942638.2017.1287810

Maher, C., Williams, M. T., & Olds, T. S. (2008). The six-minute walk test for children with cerebral palsy. *International Journal of Rehabilitation Research.*, 31(March 2016), 185–188. https://doi.org/10.1097/MRR.0b013e32830150f9

Mesure, S., Azulay, J., Pouget, J., & Amblard, B. (1999). Strategies of segmental stabilization during gait in Parkinson’s disease. *Experimental Brain Research*, *129*, 573–581.

Mills, R.S., Levac, D., & Sveistrup, H. (under review). Kinematics and postural muscular activity during continuous oscillating platform movement in children and adolescents with cerebral palsy. *Gait & Posture.*

Mills, R.S., & Sveistrup, H. (2018). Kinematics and postural muscular activity during continuous oscillating platform movement in children and adolescents. *Experimental Brain Research,* 236(5), 1479-1490. https://doi.org/10.1007/s00221-018-5228-0

Mombarg, R., Jelsma, D., & Hartman, E. (2013). Effect of Wii-intervention on balance of children with poor motor performance. *Research in Developmental Disabilities*, *34*(9), 2996–3003. https://doi.org/10.1016/j.ridd.2013.06.008

Oskoui, M., Coutinho, F., Dykeman, J., Jetté, N., & Pringsheim, T. (2013). An update on the prevalence of cerebral palsy: A systematic review and meta-analysis. *Developmental Medicine and Child Neurology*, *55*(6), 509–519. https://doi.org/10.1111/dmcn.12080

Palisano, R. J., Rosenbaum, P., Bartlett, D., & Livingston, M. H.. (2008). Content validity of the expanded and revised Gross Motor Function Classification System. *Developmental Medicine and Child Neurology*, *50*(10), 744–750. https://doi.org/10.1111/j.1469-8749.2008.03089.x

Pavão, S. L., Arnoni, J. L. B., de Oliveira, A. K. C., & Rocha, N. A. C. F. (2014). Impact of a virtual reality-based intervention on motor performance and balance of a child with cerebral palsy: a case study. *Revista Paulista de Pediatria : Orgão Oficial Da Sociedade de Pediatria de São Paulo*, *32*(4), 389–94. https://doi.org/10.1016/j.rpped.2014.04.005

Schmit, J. M., Riley, M., Cummins-Sebree, S., Schmitt, L., & Shockley, K. (2016). Functional task constraints foster enhanced postural control in children with cerebral palsy. *Physical Therapy*, *96*(3), 348–354. https://doi.org/10.2522/ptj.20140425

Vereijken, B., van Emmerik, R. E. A., Whiting, H. T. A., & Newell, K. M. (1992). Free(z)ing degrees of freedom in skill acquisition. *Journal of Motor Behavior*, *24*(1), 133–142. https://doi.org/10.1080/00222895.1992.9941608

Weiss, P., Sveistrup, H., Rand, D., & Kizony, R. (2009). Video capture virtual reality: A decade of rehabilitation assessment and intervention. *Physical Therapy Reviews*, *14*(5), 307–321. https://doi.org/10.1179/108331909X12488667117339

Woollacott, M., & Sveistrup, H. (1992). Changes in the sequencing and timing of muscle response coordination associated with developmental transitions in balance abilities. *Human Movement Science*, *11*(1–2), 23–36. https://doi.org/10.1016/0167-9457(92)90047-f

Figure Legends

Fig. 1 – Anchoring Index during Transition State in the Externally- and Self-Triggered Perturbation conditions in intervention and control groups. Positive values greater than 0.3 indicate a preference for Head in Space Strategy. Negative values greater than -0.3 indicate a preference for Head Stabilization on Trunk Strategy. Values around 0 indicate no preference for either strategy.

Fig. 2 – Results from the 6 Minute Walk Test (a) and GMFM-CM (b) at assessment sessions 1 and 2 for both Intervention and Control groups. Change in distance walked (6 Minute Walk Test) presented in panel (c). Positive values indicate an increase in distance walked from 1st to 2nd assessment point, while negative values indicate a decrease in distance walked. Increases (positive values) and decreases (negative values) in GMFM-CM score presented in panel (d) (figure adapted with permission from Levac et al[11]).