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## Abstract:

Background: Reactive and anticipatory postural activity has been described in single discrete perturbations in youth with cerebral palsy (CP) but not in continuous perturbation situations.

Research Question: We sought to determine how the ability to control postural responses (as reflected in the number of steps taken, postural muscle activity, and marker-pair trajectory cross-correlations) compares between typically developing (TD) youth and age-matched youth with CP when exposed to various frequencies of continuous platform oscillation. We also sought to determine if youth with CP could further modify postural activity based on knowledge of platform movement.

Methods: Eleven youth with CP and sixteen TD youth aged 7-17 years stood with eyes open on a movable platform progressively translated antero-posteriorly through four speeds in experimenter-triggered and self-triggered perturbations. Postural muscle activity and 3D kinematics were recorded. The Anchoring Index and marker-pair trajectories were used to quantify body stabilization strategies. Transition states and steady states were analysed. Mann Whitney-U tests analysed between-group differences at each frequency.

Results: At lower frequencies (0.1 and 0.25 Hz) youth with CP behaved like age-matched TD controls. At higher frequencies (0.5 and 0.61 Hz), youth with CP, took a greater number of steps, had a preference for stabilizing their head on the trunk, had low marker-pair correlations with high temporal lag, and showed increased tonic activity compared to their TD peers.

Significance: Higher frequency platform movements proved more difficult for youth with CP, however, like TD youth, they shifted from reactive to anticipatory mechanisms when the platform frequency remained constant by taking advantage of knowledge of platform movement. When given control over perturbation onset, further evidence of anticipatory mechanisms was observed following the transition to a new oscillation frequency.

**Keywords**: postural control, anchoring index, reactive and anticipatory balance mechanisms, cerebral palsy

## *Introduction*

Appropriate use of postural control strategies is required to stabilize balance and prevent falls. Typically, when faced with a small perturbation, balance is maintained through modulation of joint torques about the ankle. If a postural disturbance is larger, the center of mass must be kept within the confines of the base of support using larger movements about the hip. A large enough perturbation may require a step to avoid falling [1]. Having knowledge or previous experience of an upcoming perturbation, allows preparation for the postural disturbance by using anticipatory postural mechanisms [2–4].

Cerebral palsy (CP) is a non-progressive lesion in the central nervous system that results in heterogeneous motor disability and developmental delays. It is the most common physical disability in children [5] with individuals demonstrating motor [6] and sensory [7] deficits. These deficits contribute to impaired functional mobility and are associated with disruptions in postural control [8]. Youth with CP show increased risk of falls and their movement abilities are strongly predictive of participation in activities outside of the home [9].

Research suggests postural control plays an important role in the functional performance of children and adolescents with CP [10]. As efficient postural control is important for the performance of voluntary skills, postural abnormalities likely contribute to the delays and impairments observed in the motor skills of children with CP [11]. Anticipatory and reactive postural mechanisms have been identified as significant components necessary to maintain balance during both discrete and continuous perturbations [12,13]. These mechanisms develop gradually, but anticipatory processes are mastered much later than reactive mechanisms [14]. For example, in unloading tasks (discrete perturbation), younger typically developing children used anticipatory mechanisms to control their posture in preparation for the unloading perturbation, and older subjects were much more efficient in their use of anticipatory mechanisms. Furthermore, results from forward leg raising experiments in children 8-12 years of age confirm that expression of anticipatory mechanisms is still developing during mid-childhood, while full development of anticipatory strategy doesn't occur until approximately 12 years of age [15].

In addition to timing of postural responses, relationships between kinematic parameters of movement can illustrate how balance is maintained. Research demonstrates that cross-correlation values of the ankle, hip and head trajectories provide information on how tightly coupled (i.e., stable) segments of the body are [16], and are an indication of balance control. Since the head contains the visual and vestibular sensory systems which contribute to identifying a frame of reference, head stabilization is crucial to balance control. The Anchoring Index (AI) quantifies how the head is stabilized on the trunk during movement: a low AI suggests a head stabilization on trunk strategy (HSTS), whereas a high AI is suggestive of a preference for a head stabilization in space strategy (HSSS) [17]. During locomotion, typically developing (TD) children start to depend on HSSS, which benefits visual input to balance, around the age of 7 years. We have previously characterized the AI strategies in TD youth when exposed to repeated, predictable perturbations [12]. However, it is unclear how youth with CP stabilize their head in this situation and whether the AI is related to inferior body segment coordination.

While reactive and anticipatory mechanisms of postural control have been described in single discrete perturbations in youth with CP (perturbation via limb movement [10] and platform movement [1]), they have not been characterized in continuous (i.e. repeated) perturbation situations. The oscillating platform paradigm is an experimental approach whereby both reactive and anticipatory postural control mechanisms are generated in order to deal with the same perturbation. Specifically, the initial perturbation elicits a reactive response mechanism and as the platform continues to oscillate, the participant can switch to an anticipatory mechanism [12,3]. Adaptations to the predictable oscillations can occur within just a few cycles of sinusoidal platform translations [18,3]. Sudden changes in the frequency of platform oscillation results in a new perturbation and the participant must use a reactive mechanism to respond to this change before switching again to the anticipatory mechanism once stabilized. Furthermore, when given control over when a change in frequency occurs, it is possible to make the appropriate changes to balance through the use of anticipatory postural control mechanisms *prior to* the onset of perturbation [12,3]. However, it remains unclear how postural impairments in youth with CP impact their ability to maintain balance and their ability to shift from one mechanism to the other.

The primary aim of this study was to determine how the ability to control postural responses (as reflected in the number of steps taken, postural muscle activity, and marker-pair trajectory cross-correlations) differs between TD youth and age-matched youth with CP when exposed to various frequencies of continuous platform oscillation. Secondary aims were to determine if youth with CP were able to 1) take advantage of knowledge of platform movement in order to modify postural responses, and 2) further modify their postural responses when given control of when the perturbation occurs. We hypothesized that youth with CP would be less able to shift from reactive to anticipatory mechanisms 1) as compared to their TD counterparts and 2) both after having been exposed to the platform oscillation, and when given control of the timing of platform perturbation.

## *Methods*

### *Participants*

Eleven youth (N=11; 6 boys and 5 girls), aged 7-17 years with confirmed diagnosis of CP Gross Motor Function Classification System (GMFCS) levels I or II [19] participated in this study (full participant demographics available in the table accessible in the supplementary online material). Two participants were diagnosed as right hemiplegic, three were left hemiplegic, and six were spastic diplegic. All participants and/or parents provided written informed consent. Ethical approval was granted through the University of Ottawa research ethics board. Exclusion criteria were visual, cognitive or auditory impairment that would interfere with understanding of and/or ability to carry out instructions, and lower limb orthopedic surgery or Botox injections in the previous twelve months.

### *Experimental Protocol*

The experimental paradigm is described in detail in [3,12]. Briefly, participants stood barefoot (no ankle foot orthoses) with eyes open and feet shoulder-width apart on a platform that translated in the anterior/posterior direction with an amplitude of 20cm peak-to-peak. They were told to maintain their balance while avoiding taking steps. Participants performed two trials in each of two test conditions: 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) was required before advancing to the next frequency. Frequencies were presented in order from lowest to highest (0.1 Hz to 0.61 Hz).

Motion analysis software (Vicon, Oxford, UK) recorded full body kinematics (100 Hz). Bilateral surface electromyography (EMG; Delsys Inc., Natick, USA) was recorded for tibialis anterior (TA), gastrocnemius (G), quadriceps (Q), and hamstring (H) muscles, with the reference electrode placed on the iliac crest. The EMG signals were pre-amplified and sampled at 1000 Hz.

The first three to five consecutive cycles without stepping at each frequency were considered 'transition-state' (TS) and were analyzed separately [12,3]. In the last half of each frequency following TS, a period of 3 to 5 consecutive cycles without stepping at 0.1 Hz and a period of 8 to 10 consecutive cycles without stepping at the remaining frequencies were considered 'steady-state' (SS) during which the movement of the platform has been shown to be predictable [3].

*Place figure 1 (methodology figure) near here*

*Outcome Measures*

The number of steps taken was counted for each frequency. The anchoring index (AI) was used to determine the stabilization of the head with respect to both external space and the trunk [12, 20] and was calculated as follows:

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

where $\sigma_a$ is the angular dispersion of the head with respect to the absolute (external space), and $\sigma_r$ is the angular dispersion of the head relative to the trunk.

In addition to the AI, kinematic information illustrates maintenance of balance using cross-correlations between joint markers [21,22]. Cross-correlations (CC) of anterior-posterior linear displacements of the ankle-head, hip-head, and ankle-hip marker pairs were calculated by shifting one signal relative the other to find maximum correlation ($CC_{max}$). The time at which the $CC_{max}$ occurred ($CC_{lag/lead}$) was also recorded. As absolute cycle duration varied with each frequency, the timing of each $CC_{max}$ was determined for up to one half cycle time (±50% time shift of one cycle): a positive value indicates the second segment is leading, while a negative value indicates the second segment is lagging.

Raw electromyography signals were full-wave rectified. Bursts were identified as activity greater than two standard deviations above the raw baseline lasting for at least 50 ms. Postural muscle burst frequencies were expressed as a percentage of cycles in which bursts occurred. Tonic activity levels were expressed as percentage of baseline tonic activity at ETP SS 0.1 Hz.

### *Statistical Analysis*

We did not undertake power analyses for this study since our aim was to initially characterize these outcome measures in the CP population for subsequent studies. CP participant demographics and stepping data were summarized using descriptive analyses. Trials where participants continued to step throughout all cycles of a frequency were not analyzed as periods consisting of the required number of step-free cycles were needed to calculate the AI and cross-correlations for TS and SS periods. Dependent variables were averaged between the two trials, and all outcome measures were compared to TD youth values obtained from a previous study [12].

Statistical analysis was performed using SPSS v 23.0.0.2 (IBM Corp.). The data were determined to be non-normal through inspection of skewness and kurtosis, histograms, and Shapiro-Wilk tests of normality. Non-parametric inferential testing using the Mann Whitney-U test for between group (TD vs CP) differences was undertaken. These tests were performed for stepping, AI, $CC_{max}$ and $CC_{lag/lead}$, and EMG tonic and bursting activity outcome measures at each frequency with an adjusted (Bonferroni) accepted significance level of $p < 0.0125$.

## ***Results***

All TD participants were able to complete all frequencies in both trials for ETP and STP conditions. In contrast, youth with CP had difficulty completing higher frequencies. One participant with hemiplegia (JS04) would not attempt 0.5 Hz and 0.61 Hz for both trials in the ETP condition, and declined to complete any STP trials. Three participants with spastic diplegia (JS08, JS10, and JS11) attempted but could not complete the 0.5 Hz and 0.61 Hz in ETP or STP without continuous stepping; JS09 was GMFCS level II and could only complete 0.1 Hz in either condition. JS10 also declined any STP trials.

### *Stepping Responses*

The number of steps taken by CP participants was compared to the TD average at each frequency in ETP and STP conditions. Although statistical testing did not reveal any significant differences between groups, the children with CP tended to step more frequently and/or were unable to complete trials without stepping throughout. Generally, the lowest frequencies (0.1 Hz and 0.25 Hz) did not elicit stepping responses from either group. The highest frequencies (0.5 Hz and 0.61 Hz) tended to result in stepping responses in the majority of CP participants and more steps were elicited in ETP than in STP. Specifically, four of the eight children with CP who attempted trials at the higher frequencies used a stepping response for a total 78 steps at 0.5 Hz in ETP (not including trials that were attempted, but unable to complete without stepping). This is compared to only four (of 7) who stepped for a total of 19 steps at the same frequency in STP (again, not including trials that were attempted, but unable to complete without stepping). While all TD youth were able to complete the attempted trials without major stepping responses, five of the eleven youth with CP were unable to complete trials without stepping at 0.5 Hz and 0.61 Hz in ETP, and 0.5 Hz in STP, and four were unable at 0.61 Hz in STP. Full stepping response data can be found in the supplementary material online.

### *Anchoring Index*

Typically developing youth had a tendency to adopt a higher AI (HSSS), compared to similarly aged participants with CP. Group differences were significant in the ETP condition at the higher frequencies (TS at 0.61 Hz: $U = 12$, $p = 0.012$; SS approached significance at 0.61 Hz: $U = 13$, $p = 0.015$). There were no significant differences between groups in STP at any frequencies.

*Place figure 2 (anchoring index) near here*

### *Cross Correlations*

No significant differences were found between groups in the cross-correlation comparisons for ankle-head and ankle-hip trajectories. Time-lag comparisons for the ankle-hip revealed the CP group had a greater hip lag during TS at 0.25 Hz in the ETP condition ($U = 31.5$, $p = 0.009$). During TS at the higher frequencies, the TD group tended to have a greater hip lag than the CP group. This approached significance at 0.5 Hz in the ETP condition ($U = 29.5$, $p = 0.032$) and at 0.61 Hz in the STP condition ($U = 24$, $p = 0.047$).

*Place figure 3 (ETP/STP ankle-head kinematics) near here*

The TD group tended to have a greater correlation between hip-head marker trajectories during TS in ETP at 0.5 Hz (approached significance, $U = 28$, $p = 0.027$), however no differences were found at any other period or frequency in either condition. No significant differences were detected for hip-head time lag.

### *EMG Tonic and Bursting Activity*

In the ETP condition, TA tonic activity levels were higher in the CP group during TS at 0.25 Hz ($U = 24.5$, $p = 0.002$), while the G tonic activity approached significantly higher levels in TS at 0.61 Hz ($U = 17$, $p = 0.021$). The TA also had approached significantly higher tonic activity levels in the CP group during TS in the STP condition, especially at the higher frequencies (0.25 Hz: $U = 27$, $p = 0.034$; 0.5 Hz: $U = 17$, $p = 0.029$; and 0.61 Hz: $U = 18$, $p = 0.036$). No significant differences were found between groups in Q and H muscles.

Briefly, the gastrocnemius muscle was consistently activated more often in the TD group than in the CP group across all frequencies and conditions except for in STP TS at 0.25

Hz. Similarly, the hamstrings were found to be more active in the TD group at the higher frequencies (0.5 Hz and 0.61 Hz) for both conditions. No significant differences were found between groups for TA and Q at any frequency or condition. Summary information are presented in Table 1.

*Place Table 1 (test summary) near here*

*Place figures 4 (tonic activity) and 5 (burst activity) near here*

## ***Discussion***

This is the first study to characterize postural strategies in response to and in anticipation of oscillatory platform movement in children and adolescents with cerebral palsy.

### *1. Youth with CP are less able to maintain balance at high oscillation frequencies*

Youth with CP were most similar to TD youth at low frequencies and differed most at higher frequencies. The increase in number of steps recorded in both groups at the higher frequencies reflects the large increase in difficulty in the task and the CP group were clearly unable to maintain balance at this stage. This is consistent with reported findings for older adults [3,23,24] and adults with Parkinson's disease [25]. In these adult groups, the foot-in-place response was inadequate to compensate for the increased risk of falling resulting in a stepping response strategy to control movement of the centre of mass. While at the lower frequencies both groups made use of the 'ride' pattern [26] (i.e., standing straight), the youth with CP were unable to switch to 'head fixed' (i.e., allowing the lower body to pass under trunk/head) with the increased platform velocity. This may function as an attempt to remain stiff (evidenced by HSTS, increased muscle tone) resulting in segment temporal lag, an inability to disconnect the upper and lower segments to absorb the platform movement, and ultimately, more stepping responses. The higher level of baseline tonic activity exhibited by the CP group compared to the TD group is to be expected as a function of the hypertonia associated with spastic CP [11]. With the increasing frequency of the platform movement, and thus the increased duration of each trial, the increased tonic activity could be due to the prolonged activation due to spasticity [27].

### *2. Youth with CP are able to modify strategy with experience*

Like the TD group, the CP group demonstrated evidence of a shift in postural response strategy from reactive mechanisms during TS to anticipatory mechanisms in SS. This is evidenced in a shift towards HSSS and reduced segmental temporal lags, and was exhibited in both ETP and STP conditions. This modification corresponds to previous studies in which it has been shown there is a period of postural adaptation to meet the requirements of a new motor task [2,18]. One possible explanation is Bernstein's motor equivalence problem in which the body's degrees of freedom are 'frozen' to reduce redundancy when learning a new motor task [28,29]. This allows for initially keeping a rigid system with stiff joints, which can then be re-integrated with experience of the task, allowing the optimization of movement through the use of all available degrees of freedom [30]. The higher levels of tonic activity during TS in both groups can be interpreted as a functional method of joint stiffening [31] which is then decreased, as evidenced through lower tonic activity levels and reduced segmental temporal lag in SS. The reduction in temporal lag indicates an ability to shift from the previously mentioned inability to effectively use the 'ride' strategy, to the more effective ‘head fixed’ strategy. This is further supported by the shift to no preference for either HSTS or HSSS in the AI at the higher frequencies.

*3. Youth with CP make better use of anticipatory mechanisms in self-triggered perturbations*

The third aim of our study was to determine if youth with CP were able to modify their postural responses when given control over a change in frequency. Similar to other studies [10,13], our data suggest that youth with CP have the ability to use directionally specific anticipatory mechanisms of postural control when faced with continuous perturbation. We have previously documented [12] the ability of TD youth to make use of anticipatory control mechanisms when given control over a change in oscillation frequency. In this study, we compared the CP youth with the TD youth in the various conditions: like the TD youth in [12], youth with CP are able to take advantage of the knowledge/cueing of the upcoming change in frequency when given control over perturbation onset. The most compelling difference observed in the CP group between the ETP and STP conditions was the reduction in total number of steps taken, especially at the higher frequencies. This ability to take advantage of the knowledge of frequency change is further supported by a large reduction in tonic activity in G, specifically in TS, less temporal lag between marker-pair trajectories, and a shift to preference for HSSS in the AI.

While able to make the shift to anticipatory mechanisms at lower frequencies, youth with CP still struggled to maintain their balance during higher frequency perturbations when compared to TD youth. At the higher frequencies, the youth with CP may not have been able to overcome the difficulty of the platform translation and instead relied on reactive mechanisms, suggesting an inability to generate the appropriate muscle activity, whereas the

TD youth were able to make the shift to anticipatory mechanisms. This was evidenced in the CP youth having lower percentages of postural muscle bursting activity in the posterior muscles. While there were no differences observed in the tibialis anterior and quadriceps between CP and TD groups, this may be a result of leaning forward to counteract the movement of the platform and allow the inertia of the body to return the center of mass to a stable position [20]. Previous research has also established youth with CP to have poorly organized muscle activation [11,32]. Together with our data, this suggests that physiotherapists could target muscle weakness and appropriate muscle order activation and timing to deal with larger perturbations. Future studies should make smaller increments in the platform oscillation to determine at which velocity youth with CP cease to shift to anticipatory mechanisms. Because of the relatively small sample sizes and natural variability of youth with CP, future studies should also aim to include more participants.

In summary, the data from the present study demonstrated that when subjected to a continuous platform perturbation, mildly impaired youth with CP behave like age-matched TD controls at low frequencies. Higher frequency perturbations proved to be more difficult for the CP group, as evidenced through a greater number of steps taken, a preference for HSTS, low marker-pair correlations with high temporal lag, and increased tonic activity. Like the TD group, however, CP participants were able to take advantage of the knowledge of platform movement during SS, and while able to make appropriate postural changes when given control of the perturbation, continued to struggle with large perturbations. The results from this study suggest targeting muscle timing and weakness, and inappropriate muscle activation in mildly impaired youth with CP (GMFCS levels I/II) by practicing muscle sequencing and reactive/anticipatory postural response activities within intervention programs focused on improving postural control.

## Compliance with Ethical Standards:

Funding: This study was funded through the Ontario Federation for Cerebral Palsy and the University of Ottawa Faculty of Health Sciences.

Conflict of interest: None.

Ethical approval: All procedures performed involving human participants were in accordance with the institutional research committee standards.

## References

[1] P.A. Burtner, M.H. Woollacott, G.L Craft, MN Roncesvalles, The capacity to adapt to changing balance threats: a comparison of children with cerebral palsy and typically developing children, Dev. Neurorehabil. 10:3 (2007) 249-260. doi:10.1080/17518420701303066.

[2] A. Kennedy, N. Bugnariu, A Guevel, H. Sveistrup, Adaptation of the Feedforward Postural Response to Repeated Continuous Postural Perturbations, Neurosci. & Med. 4:1 (2013) 45-49. doi:10.4236/nm.2013.41007.

[3] N. Bugnariu, H. Sveistrup, Age-related changes in postural responses to externally- and self-triggered continuous perturbations, Arch. Gerontol. Geriatr. 42:1 (2006) 73-89. doi:10.1016/j.archger.2005.05.003.

[4] J.S. Frank, M. Earl, Coordination of Posture and Movement, 1990;70(12):855-863.

[5] N. Badawi, J.M. Keogh, Causal pathways in cerebral palsy, J. Paediatr. Child. Health. 49:1 (2013) 5-8. doi:10.1111/jpc.12068.

[6] A.L. Albright. Spasticity and movement disorders in cerebral palsy, J. Child. Neurol. 11 (1996) Suppl 1:S1-S4.

[7] J. Cooper, A. Majnemer, B. Rosenblatt, R. Birnbaum, The determination of sensory deficits in children with hemiplegic cerebral palsy, J. Child. Neurol. 10:4 (1995) 300-309. doi:10.1177/088307389501000412.

[8] J.M. Schmit, M. Riley, S. Cummins-Sebree, L. Schmitt, K. Shockley, Functional task constraints foster enhanced postural control in children with cerebral palsy, Phys. Ther. 96:3 (2016) 348-354. doi:10.2522/ptj.20140425.

[9] M.K. Bult, O. Verschuren, E. Lindeman, et al, Predicting leisure participation of school-aged children with cerebral palsy: Longitudinal evidence of child, family and environmental factors, Child Care Health Dev. 39:3 (2013) 374-380. doi:10.1111/j.1365-2214.2012.01391.x.

[10] G.L Girolami, T. Shiratori, A. Aruin, Anticipatory postural adjustments in children with hemiplegia and diplegia, J. Electromyogr. Kinesiol. 21:6 (2011) 988-997. doi:10.1016/j.jelekin.2011.08.013.

[11] M.H Woollacott, P. Burtner, J. Jensen, J. Jasiewicz, N. Roncesvalles, H. Sveistrup, Development of postural responses during standing in healthy children and children with spastic diplegia, Neurosci. Biobehav. Rev. 22:4 (1998) 583-589. http://www.ncbi.nlm.nih.gov/pubmed/9595573.

[12] R.S. Mills, H. Sveistrup, Kinematics and postural muscular activity during continuous oscillating platform movement in typically developing children and adolescents, Exp. Brain. Res. 236:5 (2018)1479-1490. doi:10.1007/s00221-018-5228-0

[13] W.-Y. Liu, C.A. Zaino, S.W. McCoy, Anticipatory postural adjustments in children with cerebral palsy and children with typical development, Pediatr. Phys. Ther. 19:3 (2007) 188-195. doi:10.1097/PEP.0b013e31812574a9.

[14] L. Hay & C. Redon, Feedforward versus feedback control in children and adults subjected to a postural disturbance, Exp. Brain. Res. 125 (1999) 153-162. doi:10.1007/s002210050670

[15] E. Palluel, H. Ceyte, I. Olivier, V. Nougier, Anticipatory postural adjustments associated with a forward leg raising in children: Effects of age, segmental acceleration and sensory context, Clin. Neurophys. 119 (2008) 2546-2554. doi: 10.1016/j.clinph.2008.08.001

[16] A. Nardone, M. Grasso, M. Schieppati, Balance control in peripheral neuropathy: Are patients equally unstable under static and dynamic conditions?, Gait Posture, 23:3 (2006) 364-373. doi:10.1016/j.gaitpost.2005.04.002.

[17] C. Assaiante, S. Mallau, S. Viel, M. Jover, C. Schmitz, Development of postural control in healthy children: A functional approach, Neural. Plast. 12:2-3 (2005) 109-118. doi:10.1155/NP.2005.109.

[18] M. Schmid, A. Bottaro, S. Sozzi, M. Schieppati, Adaptation to continuous perturbation of balance: Progressive reduction of postural muscle activity with invariant or increasing oscillations of the center of mass depending on perturbation frequency and vision conditions, Hum. Mov. Sci. 30:2 (2011) 262-278. doi:10.1016/j.humov.2011.02.002.

[19] P.L. Rosenbaum, R.J. Palisano, D.J. Bartlett, B.E Galuppi, D.J. Russell, Development of the Gross Motor Function Classification System for cerebral palsy, Dev. Med. Child Neurol. 50:4 (2008) 249-253. doi:10.1111/j.1469-8749.2008.02045.x.

[20] F. Cignetti, P.-Y. Chabeauti, H. Sveistrup, M. Vaugoyeau, C. Assaiante, Updating process of internal models of action as assessed from motor and postural strategies in children, Neurosci. 233 (2013) 127-138. doi: 10.1016/j.neuroscience.2012.12.040

[21] S. Corna, J. Tarantola, A. Nardone, A. Giordano, M. Schieppati, Standing on a continuously moving platform: is body inertia counteracted or exploited?, Exp Brain Res. 124 (1999) 331-341. doi:10.1007/s002210050630

[22] A.M. de Nunzio, M. Schieppati, Time to reconfigure balancing behaviour in man: changing visual condition while riding a continuously moving platform, Exp Brain Res. 178 (2007) 18-36. doi:10.1007/s00221-006-0708-z

[23] C.P. Carty, N.J. Cronin, D. Nicholson, et al, Reactive stepping behaviour in response to forward loss of balance predicts future falls in community-dwelling older adults, Age Ageing. 44:1 (2015) 109-115. doi:10.1093/ageing/afu054.

[24] B.E. Maki, W.E. McIlroy, Control of rapid limb movements for balance recovery: Age-related changes and implications for fall prevention, Age Ageing. 35:Suppl.2 (2006) 12-18. doi:10.1093/ageing/afl078.

[25] C. Schlenstedt, M. Mancini, F. Horak, D. Peterson, Anticipatory postural adjustment during self-initiated, cued, and compensatory stepping in healthy older adults and patients with Parkinson Disease, Arch. Phys. Med. Rehabil. 98 (2017) 1316-24. doi:10.1016/j.apmr.2017.01.023

[26] J.J. Buchanan, F.B. Horak, Emergence of postural patterns as a function of vision and translation frequency, J. Neurophysiol. 81:5 (1999) 2325-2339.

[27] L. Bar-On, G. Molenaers, E. Aertbeliën, et al, Spasticity and its contribution to hypertonia in cerebral palsy, Biomed. Res. Int. 2015 (2015) doi:10.1155/2015/317047.

[28] A. Shumway-Cook, M. Woollacott, Motor Control: Translating Research into Clinical Practice, third ed, Lippincott Williams & Wilkins, Washington, 2007.

[29] N. Caillou, D. Delignieres, D. Nourrit, T. Deschamps, B. Lauriot, Overcoming spontaneous patterns of coordination during the acquisition of a complex balancing task, Can. J. Exp. Psychol. 56:4 (2002) 283-293. doi:10.1037/h0087404.

[30] B. Vereijken, R.E.A. van Emmerik, H.T.A. Whiting, K.M. Newell, Free(z)ing degrees of freedom in skill acquisition, J. Mot. Behav. 24:1 (1992) 133-142. doi:10.1080/00222895.1992.9941608.

[31] A.R. Needle, J. Baumeister, T.W. Kaminski, J.S. Higginson, W. B. Farquhar, C.B. Swanik, Neuromechanical coupling in the regulation of muscle tone and joint stiffness, Scand. J. Med. Sci. Sport. 24:5 (2014) 737-748. doi:10.1111/sms.12181.

[32] E.B. Carlberg, M. Hadders-Algra. Postural dysfunction in children with cerebral palsy: Some implications for therapeutic guidance, Neural. Plast. 12:2-3 (2005) 221-228.

Table 1 – Results of Mann-Whitney U comparisons between typically developing and cerebral palsy groups for muscle bursting activity

| | | | Frequency | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0.1Hz | | | | 0.2Hz | | | | 0.5Hz | | | | 0.61Hz | | | |
| | | | MWU | Z | p | r | MWU | Z | p | r | MWU | Z | p | r | MWU | Z | p | r |
| ETP | TS | TA | 83.5 | -0.24 | 0.827 | -0.05 | 61 | -0.961 | 0.363 | -0.19 | 42.5 | -0.409 | 0.693 | -0.09 | 47 | -0.075 | 0.971 | -0.02 |
| | | GAS | 38.5 | -2.535 | 0.013 | -0.49 | 38.5 | -2.204 | 0.027 | -0.43 | 25 | -1.71 | 0.098 | -0.36 | 31 | -1.272 | 0.231 | -0.27 |
| | | *Q* | 55 | -2.24 | 0.11 | -0.43 | 44 | -2.003 | 0.06 | -0.39 | 41.5 | -0.486 | 0.641 | -0.10 | 29 | -1.419 | 0.178 | -0.30 |
| | | HAM | 77.5 | -0.672 | 0.61 | -0.13 | 66 | -0.843 | 0.484 | -0.17 | 16.5 | -2.339 | 0.017 | -0.50 | 11 | -2.769 | **0.005** | -0.59 |
| | SS | TA | 86 | -0.118 | 0.942 | -0.02 | 54 | -1.381 | 0.182 | -0.27 | 37.5 | -0.777 | 0.449 | -0.17 | 40 | -0.593 | 0.59 | -0.13 |
| | | GAS | 33 | -2.829 | **0.006** | -0.54 | 37.5 | -2.246 | 0.023 | -0.44 | 15.5 | -2.412 | 0.013 | -0.51 | 22 | -1.922 | 0.059 | -0.41 |
| | | Q | 56 | -2.555 | 0.121 | -0.49 | 48 | -1.877 | 0.097 | -0.37 | 44 | -0.3 | 0.802 | -0.06 | 31 | -1.26 | 0.231 | -0.27 |
| | | H*AM* | 72 | -0.979 | 0.451 | -0.19 | 74.5 | -0.305 | 0.776 | -0.06 | 7 | -3.038 | **0.001** | -0.65 | 7.5 | -2.998 | **0.001** | -0.64 |
| STP | TS | TA | 56.5 | -0.783 | 0.519 | -0.16 | 54.5 | -0.365 | 0.728 | -0.08 | 33 | -0.942 | 0.381 | -0.35 | 44 | -0.078 | 0.97 | -0.02 |
| | | *GAS* | 16 | -3.134 | **0.001** | -0.64 | 13.5 | -3.026 | **0.001** | -0.63 | 16.5 | -2.252 | 0.023 | -0.49 | 19.5 | -2.005 | 0.045 | -0.44 |
| | | Q | 61.5 | -0.551 | 0.726 | -0.11 | 37.5 | -2.48 | 0.149 | -0.52 | 44.5 | -0.039 | 0.97 | -0.01 | 44.5 | -0.04 | 0.97 | -0.01 |
| | | HAM | 63.5 | -0.367 | 0.815 | -0.07 | 54 | -0.428 | 0.728 | -0.09 | 10 | -2.755 | **0.005** | -0.60 | 9.5 | -2.78 | **0.003** | -0.61 |
| | SS | TA | 66.5 | -0.071 | 0.953 | -0.01 | 53.5 | -0.431 | 0.681 | -0.09 | 24.5 | -1.6 | 0.112 | -0.02 | 24 | -1.643 | 0.112 | -0.36 |
| | | GAS | 13 | -3.342 | **0.001** | -0.68 | 7 | -3.447 | **0** | -0.72 | 7 | -2.971 | **0.002** | -0.65 | 10.5 | -2.696 | **0.005** | -0.59 |
| | | Q | 61.5 | -0.551 | 0.726 | -0.11 | 51 | -0.662 | 0.591 | -0.14 | 36 | -0.706 | 0.519 | -0.15 | 39.5 | -0.43 | 0.677 | -0.09 |
| | | HAM | 63.5 | -0.367 | 0.815 | -0.07 | 53.5 | -0.445 | 0.681 | -0.09 | 6 | -3.052 | **0.001** | -0.67 | 8 | -2.89 | **0.002** | -0.63 |

NOTE: Tibialis anterior (TA), gastrocnemius (GAS), quadriceps (Q) and hamstring (HAM); Transition State (TS); Steady State (SS); externally-triggered (ETP); self-triggered (STP). N for ETP = 27, 26, 22, 22, for 0.1Hz, 025Hz, 0.5Hz, 0.61Hz respectively. N for STP = 24, 23, 21, 21, for 0.1Hz, 025Hz, 0.5Hz, 0.61Hz respectively; Significant results represented by bold table values.

## Figure captions

Figure 1 - Perturbation protocol depicting platform oscillation and corresponding EMG signals (a) from tibialis anterior (TA), gastrocnemius (G), quadriceps (Q), and hamstring (H) muscles during the transition and steady state periods at 0.5Hz. Panel (b) depicts a participant's posture during backward platform displacement at 0.5Hz in transition (left) and steady (right) states. Expanded head-neck stick figure shows an example of a shift from Head Stabilized on Trunk (AI = -0.1) to Head Stabilization in Space Strategy (AI = 0.3). Panel (c) A participant with markers and EMG electrodes. (Adapted with permission from [12])

Figure 2 - Anchoring Index (mean +/- SD) obtained from typically developing (TD) youth and youth with cerebral palsy (CP). Transition State (TS) and Steady State (SS) periods across four frequencies are presented in Externally (left) and Self-triggered (right) perturbations. Positive values indicate a preference for a Head Stabilization in Space Strategy (HSSS), while negative values indicate a preference for a Head Strapped to Trunk Strategy (HSTS). Values around 0 indicate no preference for either strategy. Values are offset horizontally for clarity purposes.

Figure 3 - Mean cross-correlation function peak values (CCmax – left panels) and time lags (CClag/lead – right panels) in typically developing (TD) and cerebral palsy (CP) youth. Values are offset horizontally for clarity purposes. The ankle-head correlations are presented for transition (TS) and steady (SS) states in Externally- (top panels) and Self- (bottom panels) Triggered conditions. Error bars indicate standard deviations.

Figure 4 – Tonic activity (mean +/- SD) for (top to bottom panels) tibialis anterior (TA), gastrocnemius (G), quadriceps (Q), and hamstring (H) muscles in ETP (left side) and STP (right side) conditions. Comparisons were made to baseline tonic activity of each muscle in the steady state period at 0.1Hz in ETP. Transition (TS) and steady (SS) states presented for typically developing (TD) and cerebral palsy (CP) youth. Values are offset horizontally for clarity purposes.

Figure 5 – Muscle bursting activity (mean +/- SD) for (top to bottom panels) tibialis anterior (TA), gastrocnemius (G), quadriceps (Q), and hamstring (H) muscles in Externally- (left panels) and Self- (right panels) triggered perturbation conditions. Transition (TS) and steady (SS) states presented for typically developing (TD) and cerebral palsy (CP) youth. Values are offset horizontally for clarity purposes.