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Corticospinal Excitability and Muscle Synergies during Visually-Guided Walking Task

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1. Introduction

Cerebral palsy (CP) is the most common motor disability in children, often caused by brain lesions. It leads to sensorimotor deficits, particularly affecting walking due to impaired neural circuits like the corticospinal tract (Kuo et al. 2017) as well as an altered motor control. The corticospinal tract is a key pathway of voluntary motor control, and damage to it in CP individuals results in weaker signals from the brain to muscles, making movement initiation and control difficult. Despite the known importance of descending control in adapting gait to the constraints of the environment (Barthélemy et al. 2012), no study of corticospinal excitability has been conducted in CP.

In real world, humans often must adapt their gait to environmental challenges. Unpredictable disturbances, such as any deviation from normal walking, can lead to falls and injuries. Much of the existing research has focused on the automatic control of walking studying repetitive movements in highly controlled conditions like walking in a straight line or on a treadmill. These simple walking tasks predominantly engage automatic neural circuits, like spinal structures, and rely less on descending voluntary gait control circuits which are crucial for daily-life task adaptations. Measuring corticospinal excitability and extracting muscle synergies during walking under different conditions may provide deeper insights into how the brain controls leg movements.

The main objective of this study was to assess whether a complex walking task promote an increase in corticospinal excitability and a reorganization of muscle synergies compared to natural walking task in individuals suffering from CP.

2. Methods

2.1. Participants

Fourteen individuals with CP [age=27.3±10.1 years, sex=5♀] and 14 healthy controls [age=25.2±3.3 years,

sex=8♀] were included in this study. The participants with CP had a GMFCS level ranging from I to III.

2.2. Experimental protocol

Individuals with CP eligible for transcranial magnetic stimulation (TMS) underwent two evaluation sessions. The first session included Magnetic Resonance Imaging to guide coil placement for TMS in the second session. During the second session, neurophysiological measurements were taken while participants performed two walking tasks on a treadmill at comfortable speed: a simple task (natural walking, SW) and a complex task (requiring to adapt step length to walk on virtual targets, CW). Healthy participants only attended the second session. Firstly, muscle synergies were extracted from surface electromyographic (sEMG) signals acquired from seven key lower-limb muscles (Tibialis Anterior (TA), Soleus (SOL), Gastrocnemius Lateralis (GL), rectus femoris (RF), vastus lateralis (VL), SemiTendinosus (ST), and Biceps Femoris (BF)). Then, corticospinal excitability of the TA muscle was measured using single-pulse TMS, with stimulation timed to the late stance phase of walking. sEMG electrodes were positioned on the most affected leg (for CP) and non-dominant (leg for healthy participants).

2.3. Data analysis

Muscle synergy. Raw sEMG signals were band-pass filtered between 10 and 450 Hz, full-wave rectified, and then low-pass filtered at 10 Hz to obtain sEMG envelopes. These envelopes were amplitude-normalized by the peak amplitude of the average sEMG profile during walking. Non-Negative Matrix Factorization was applied to extract muscle synergies. The number of synergies was determined as the minimal value for which the total VAF was greater than 90% (Cherni et al. 2021). Corticospinal excitability. Trials in which TMS was delivered with a hotspot-to-coil distance larger than 5 mm were removed from analysis. The area under the curve was calculated for each rectified motor evoked potentials (MEP) and then averaged for each task and participant. The error in coil placement was assessed by a neuronavigation software as the distance between the coil location and the hotspot for each stimulation. Additionally, the mean background sEMG amplitude was measured (using a window of 50 ms preceding each stimulation).

2.4. Statistical analysis

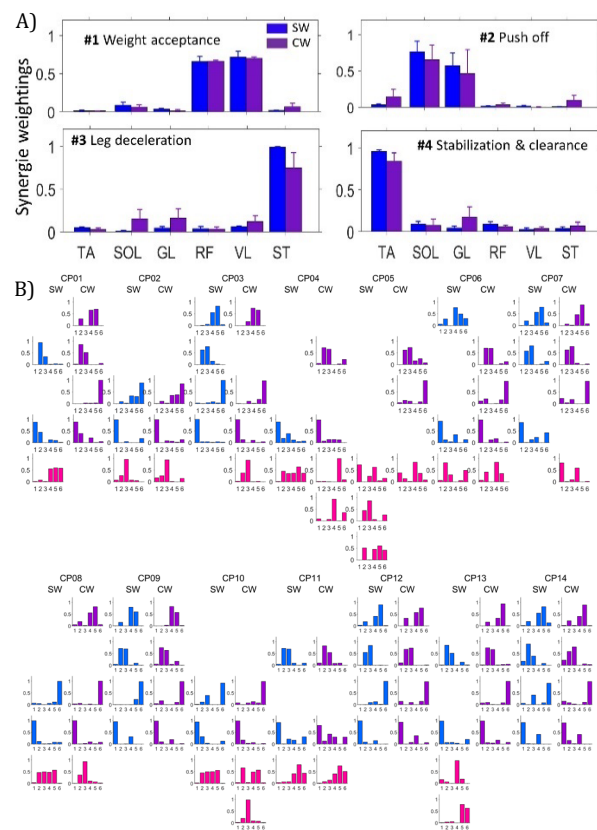
To compare muscle synergies across both groups, the cosine similarity was used to compare the similarity between weighting of each CP with the reference (average muscle synergies over healthy individuals). The cosine similarity value ranges from 0 (totally dissimilar) to 1 (totally similar). A muscle synergy was considered specific if the similarity score was lower than 0.8. Wilcoxon tests were used to compare the as

the number of synergies in CP during SW and CW. The nparLD test, a non-parametric equivalent of a repeated-measures ANOVA was applied to MEP results, with the within-subject factor Condition (simple and complex) and the between-subject factor Group (CP and CTL).

3. Results and discussion

3.1. Muscle synergies

Reference synergies weighting from healthy individuals are shown in **Fig 1A**. Given the results variability in CP, individual synergy results are presented in **Fig 1B**. An increase in the number of synergies was observed during CW in CP group ($p < 0.05$). The similarity between the muscle synergies observed in CP participants and the reference was analyzed in each participant with CP. The results indicate the presence of specific synergies in 11 out of 14 participants.



1 : TA, 2 : SOL, 3 : GL, 4 : RF, 5 : VL, 6 : ST

Figure 1. (A) Reference synergies from healthy individuals during SW (blue) and CW (purple). (B) Muscle synergies number and structure during SW and CW. Y axis represents muscle weightings (range=0 to 1). x-axis represents muscles included. The four first lines are synergies shared with the control group (cosine similarity ≥ 0.8). In pink are specific synergies that are not present in the control group (cosine similarity < 0.8).

Three participants with CP (i.e., 09, 12, 14), classified as GMFCS I, exhibited four synergies with a high level of similarity (range= 0.87 – 0.99) compared to the reference (**Fig 1B**). Overall, CP participants recruited less muscle synergies during SW. These results are in line with the literature highlighting that individuals with CP often employ a simpler motor control strategy during gait compared to their typically developing peers (Bekius et al. 2020).

3.2. Corticospinal excitability

In CP participants, only 11 participants were eligible for TMS, thus for assessment of corticospinal excitability during the two locomotor tasks. The NparLD results showed significant effect ($p < 0.0001$) for the condition factor (SW vs. CW), but no significant effect for the group factor (CP vs Control, $p > 0.05$) nor at the interaction level (condition x group, $p > 0.05$). Thus, the CW task induced a significant increase in MEP in both groups CP and control.

4. Conclusions

CP participants showed that either the number or the structure of synergies are modulated by the CW. Moreover, our preliminary results elucidated the involvement of corticospinal control during walking in CP and healthy individuals which increase with challenging walking tasks. Thus, challenging tasks may be considered as interesting training modality to improve gait control in CP.

Competing interests: The authors declare that they have no competing interests.

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