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Electromyographic biofeedback-driven gaming to alter calf muscle activation during gait in children with spastic cerebral palsy

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ABSTRACT

Background: Children with cerebral palsy often show deviating calf muscle activation patterns during gait, with excess activation during early stance and insufficient activation during push-off.
Research question: Can children with cerebral palsy improve their calf muscle activation patterns during gait using one session of biofeedback-driven gaming?
Methods: Eighteen children (6–17 y) with spastic cerebral palsy received implicit game-based biofeedback on electromyographic activity of the calf muscle (soleus or gastrocnemius medialis) while walking on a treadmill during one session. Biofeedback alternately aimed to reduce early stance activity, increase push-off activity, and both combined. Early stance and push-off activity and the double-bump-index (early stance divided by push-off activity) were determined during baseline and walking with feedback. Changes were assessed at group level using repeated measures ANOVA with simple contrast or Friedman test with post-hoc Wilcoxon signed rank test, as well as individually using independent t-tests or Wilcoxon rank sum tests. Perceived competence and interest-enjoyment were assessed through a questionnaire.
Results: Children successfully decreased their electromyographic activity during early stance feedback trials (relative decrease of 6.8 ± 12.2 %, $P = 0.025$), with a trend during the combined feedback trials (6.5 ± 13.9 %, $P = 0.055$), and increased their electromyographic activity during push-off feedback trials (8.1 ± 15.8 %, $P = 0.038$). Individual improvements were seen in twelve of eighteen participants. All children experienced high levels of interest-enjoyment (8.4/10) and perceived competence (8.1/10).
Significance: This exploratory study suggests that children with cerebral palsy can achieve small within-session improvements of their calf muscle activation pattern when provided with implicit biofeedback-driven gaming in an enjoyable manner. Follow-up gait training studies can incorporate this method to assess retention and long-term functional benefits of electromyographic biofeedback-driven gaming.

1. Introduction

Children with spastic cerebral palsy (CP) commonly experience difficulties in gait. Those difficulties are thought to partially arise due to exaggerated velocity-dependent stretch reflexes (stretch hyperreflexia, also referred to as spasticity) [1], causing increased calf muscle activity in early stance [1,2]. This activation limits calf muscle lengthening and ankle dorsiflexion during stance, yielding decreased push-off power [1]. Moreover, calf muscle activation at push-off is often limited by muscle weakness or impaired voluntary control [1–4]. This abnormal biphasic calf muscle activation pattern has been associated with increased energy cost [5] and decreased walking speed [1]. Current medical interventions to alter the activation pattern, such as denervation through botulinum toxin or neurosurgical treatment, are often invasive, non-specific, and/or temporary [6–8] and/or tend to weaken the muscle [8,9].

Gait training is a non-invasive approach to improve mobility.

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Repetitive gait training can induce changes in corticomotor pathways [10,11] and is thereby expected to achieve long-term effects. Gait training can be supplemented with biofeedback to target specific factors of interest, such as stride length [12,13], hip and knee extension [13, 14], or muscle activation patterns [15]. Moreover, impaired ankle push-off power is an attractive target for biofeedback [1–4].

Gait training can possibly be improved when biofeedback addresses the abnormal biphasic calf muscle activation pattern of increased activity around early stance and decreased activity around push-off. Additionally, biofeedback on muscle activation, rather than kinetics, will enable translation towards physiotherapy- or home-based training, since it can be done without embedded force plates. User-friendly EMG biofeedback devices already exist [16,17], and can be complemented with step-detection algorithms, for example through accelerometer data [18]. EMG biofeedback studies on upper extremity function have already been shown successful [19,20]. Additionally, in 1994 Colborne et al. [15] already showed that children with CP can increase their push-off power during gait by 19 % when provided with electromyographic (EMG) biofeedback on the biphasic calf muscle activation pattern. However, their study presented with several limitations, such as differences in walking speed pre and post biofeedback – known to be strongly related to peak push-off power - and no quantification of actual changes in muscle activity as a result of the biofeedback [21,22]. Furthermore, they included only children with relatively mild impairments.

Over the last decades, new insights in motor learning have been developed, which may also help maximize the effects of gait training. For example, while current gait training protocols mostly use explicit forms of biofeedback [12–15,23], a growing body of literature recognizes the importance of implicit motor learning for treatment efficacy [24,25], especially in children with CP [26,27]. Explicit feedback entails specific movement instructions, such as visualization of the amount of knee extension. In contrast, while learning implicitly, children are challenged to develop their own strategies, resulting in longer-lasting improvements [28]. Furthermore, implicit biofeedback is thought to result in greater motivation, which is essential for treatment compliance [29]. Gamification is another tool to improve treatment efficacy [30–32], engagement, and motivation [33,34], and has already been successful in rehabilitation in children with CP [30,31]. Therefore, providing implicit, game-based EMG biofeedback is expected to result in a fun, engaging, effective gait training program to promote mobility.

To the best of our knowledge, training programs using game-based EMG biofeedback during gait have not been previously studied in children with CP. Given the motor learning difficulties of children with CP [35], it is essential to assess feasibility before assessing long-term training. Therefore, we aim to explore if children with CP can alter their calf muscle activation pattern within one session of implicit EMG biofeedback-driven gaming. More specifically, we evaluate if children can improve both deviating characteristics of calf muscle activation pattern; the early stance and the push-off activity. We furthermore assess if participant characteristics influence feasibility by assessing responder characteristics.

2. Methods and procedures

2.1. Participants

A convenience sample of eighteen children with spastic CP and related forms of spastic paresis participated in this observational cross-sectional feasibility study (Table 1). Twelve age-matched typically developing children were included for reference values. Exclusion criteria were: orthopedic leg surgery (<12 months ago), lower limb botulinum toxin-A injections (<6 months ago), selective dorsal rhizotomy, visual deficits limiting interpretation of visual feedback, frequent epilepsy, behavioral problems, or comorbidities affecting gait. The study protocol was approved by the local medical ethics committee (NL65846.029.18). All participants aged twelve years and older provided written informed consent, as well as all parents of participants under sixteen.

Table 1
Participant characteristics.

	Children with cerebral palsy		Typically developing children	
Characteristic	Inclusion criteria	Values (mean ± std or n)	Inclusion criteria	Values (mean ± std or n)
Age (y)	6–17	10.5 ± 2.9	6–17	10.4 ± 3.7
Gender (F/M)	-	(8 F, 10 M)	-	(3 M, 9 F)
Height (m)	-	1.45 ± 0.16	-	1.45 ± 0.23
Body mass (kg)	-	39.0 ± 14.6	-	40.9 ± 19.2
GMFCS	I-II	I: 9, II: 9	-	-
Distribution	-	Uni: 10, Bi: 8	-	-
Side	-	Left: 6, Right: 12	-	-
SPAT GM	≥ 1 *	1:4, 2:1, 3:3, CL:10	-	-
SPAT SO	≥ 1 *	0:1, 1:3, 2:2, CL:12	-	-
Walking speed (m/s)	-	0.72 ± 0.14	-	1.02 ± 0.14

Abbreviations: GMFCS, Gross Motor Function Classification System [36]; GM, m. gastrocnemius medialis, SO: m. soleus; SPAT, scores reflect values of spasticity according to the SPAT test; [37] with the leg bent (SO) or extended (GM); CL, clonus. *One of these values should be 1 or higher.

2.2. Study design

All measurements were performed on an instrumented treadmill in a semi-immersive virtual reality environment (Fig. 1A). EMG electrodes were placed on the gastrocnemius medialis and soleus muscles according to SENIAM guidelines [36], and reflective markers were placed according to the Human Body Model marker set [37,38]. EMG signals were measured at 1000 Hz via a wireless system (Wave, Cometa, Italy), motion data at 100 Hz using a motion capture system (Vicon Motion Systems, Oxford, UK), and ground reaction forces at 1000 Hz by sensors underneath both treadmill belts (R-Mill, Forcelink, The Netherlands).

Children started with at least six minutes of habituation to treadmill walking. They wore a non-weight bearing safety harness, and handrails were present for additional safety. Comfortable walking speed was determined by gradually altering belt speed until comfortable, as indicated by children and parents, and maintained throughout the experiment. Next, a comfortable walking trial of 30 s without biofeedback was recorded for all participants, while walking within an environment with optic flow (for typically developing children and participants 1–8 with CP) or the gaming environment (participants 9–17 with CP). Pilot analyses showed that walking in the gaming environment alone, did not alter the gait pattern. Thereafter, biofeedback trials were performed for children with CP only. Breaks were provided when necessary.

EMG-driven biofeedback was presented implicitly through a game (Fig. 1), as explained in detail in Supplementary Material 1. In short, a monkey had to travel through a game, and children were instructed that the gait pattern of their most affected leg controlled the monkey. This control was based on the gastrocnemius medialis or soleus EMG of the most affected leg. Traveling of the monkey was achieved in all steps in which children successfully decreased average early stance activity (0–50 % or 15–50 % of stance phase; FB_{early_stance}; see Supplementary Material 1), increased push-off activity (60–90 % of stance phase; $FB_{push\text{-}off}$), or both simultaneously ($FB_{combined}$). The soleus was targeted for most children, but the gastrocnemius medialis was targeted when the SPAT score was higher than for the soleus (n = 4). Feedback was provided in real-time during every stride for eighteen minutes; resulting in 700–1000 feedback occurrences per session. The session started with either early stance (n = 10) or push-off (n = 8) feedback as randomly

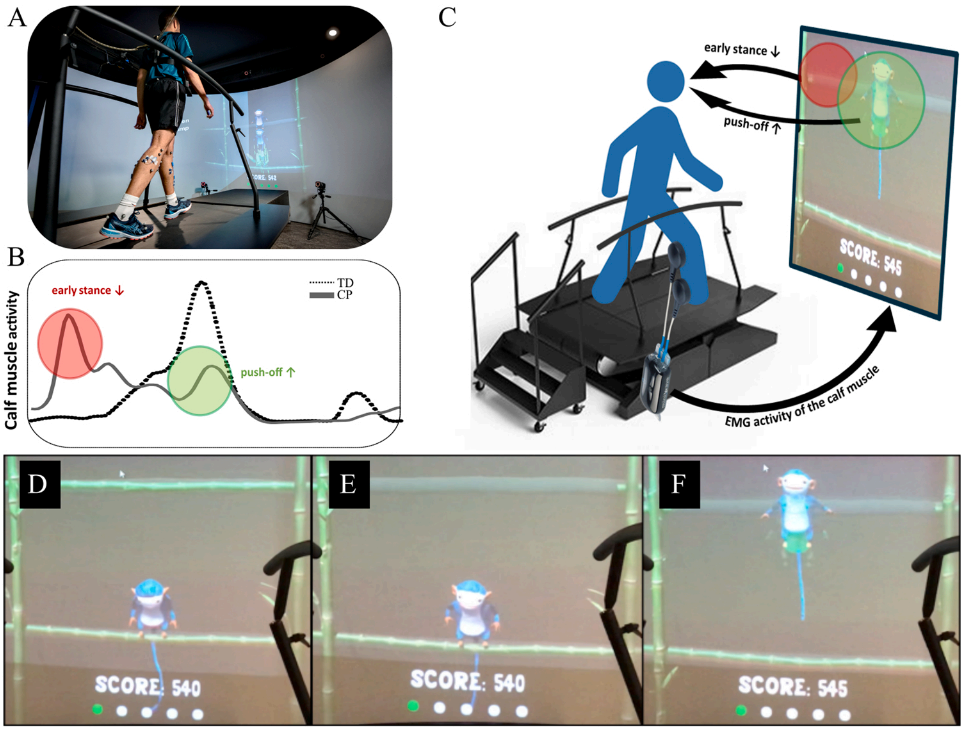

Fig. 1. Measurement set-up and game. Panel A depicts the participant walking in the Gait Real-time Analysis Interactive Lab (Motek ForceLink, Amsterdam, Netherlands; Photo by DigiDaan). The calf muscle activity is measured, see panel B for a typical example, and used as input for the biofeedback game, which is depicted in panels C-F: The goal is to make a monkey jump to as many branches as possible. If children decrease their early stance electromyographic (EMG) activity (panel B) the branch above the head of the monkey opens up (panels D→E), enabling a jump. The size of their EMG activity during the push-off (panel B) determines the height of the jump (panels E → F). These conditions were trained separately (EMG_{early_stance} and $EMG_{push\text{-}off}$ condition), and then combined. During early stance feedback, there was always a jump of sufficient height to reach the next branch in case it opened and during push-off feedback the branch was always open and if the jump was sufficiently high, the monkey would reach the next branch.

assigned, and ended with combined feedback. Each condition lasted six minutes and feedback trials were recorded during the last 30 s of walking with feedback. Feedback was set at 67 % positive feedback initially and manually adjusted if necessary to maintain motivation and maximize improvements. Motivation and perceived competence were assessed through an intrinsic motivation questionnaire [39] administered directly after the game, consisting of eight questions using a 1–10 Likert scale (Supplementary Material 3).

2.3. Data analysis

EMG signals were high-pass filtered (bidirectional 4th order Butterworth at 20 Hz), rectified, and low-pass filtered (5 Hz). The EMG envelopes were normalized to the mean over the entire gait cycle averaged over all baseline strides [40]. Kinematics (pelvis, hip, knee, and ankle angles) and kinetics (ankle moment and power) were calculated using the human body model [37], and kinetics were normalized to body weight. Data were time-normalized to gait cycles using initial contact following Zeni [41]. Strides were manually excluded when movements were present that generally do not belong in gait (e.g., kicking, sliding, stepping sideways, or standing still). Furthermore, clear outliers were excluded with excessive deviations (>±3 SD from the median [13] over the trial) in maximum ankle plantar- or dorsiflexion or EMG peaks at early stance or push-off.

To quantify the improvements in EMG activity, the average peak during early stance (0–50 % of stance phase), the average peak during push-off (60–90 % of stance phase), and the double bump index [2] (DBI; early stance peak divided by push-off peak; see Fig. 2) were calculated over all steps within a recording. Furthermore, peak ankle power during push-off and ankle work during early stance and push-off were calculated. The following kinematic variables were assessed: maximum dorsiflexion during stance – expected to increase with decreased early stance EMG activity; maximum plantarflexion around push-off (60–120 % of stance phase) – expected to increase along with increased push-off EMG activity; and knee extension in 20–100 % of stance - expected to increase due to the plantarflexor knee extensor coupling in stance. Furthermore, the gait profile score (GPS [42]) was calculated to assess overall kinematic deviations from normal. Finally, for intrinsic motivation, answers within two dimensions (interest-enjoyment and perceived competence) were averaged to obtain one overall score for each dimension.

2.4. Statistical analysis

All outcome parameters were compared between baseline and the three feedback types using repeated measures ANOVA with simple contrast and Friedmans test and post-hoc Wilcoxon signed rank test for parameters without normal distribution. Normality was tested by Shapirow-Wilk tests. Improvements were quantified using the percentage change, calculated as values after feedback minus baseline values divided by baseline values. For kinematics, improvements were quantified by subtracting the joint angles before and after biofeedback. Parameters at baseline and during the three feedback conditions were compared to typically developing children using an ANOVA with Dunnet's post-hoc testing. To identify responders to the three types of feedback, independent t-tests, or Wilcoxon sum rank when appropriate, were performed for each subject individually, comparing early stance EMG peaks (for FB_{early_stance}), push-off EMG peaks ($FB_{push\text{-}off}$), and DBI ($FB_{combined}$) for all feedback strides with all baseline strides. To determine if responder characteristics could be identified, we calculated correlation coefficients between improvements in DBI and subject characteristics, using Pearson correlation for age and baseline DBI, Spearman correlation for GMFCS and SPAT, and a partial eta squared for uni/bilateral involvement and most affected side. Furthermore, we correlated baseline early stance and push-off EMG peaks to changes in early stance and push-off EMG peaks. Given the explorative nature of this study, p-values below 0.10 were considered trends and p-values below 0.05 as significant.

3. Results

All participants were able to perform the biofeedback game and perceived the game as highly motivating (interest-enjoyment score 6.2–10, average 8.4). All but one subject felt competent (perceived-

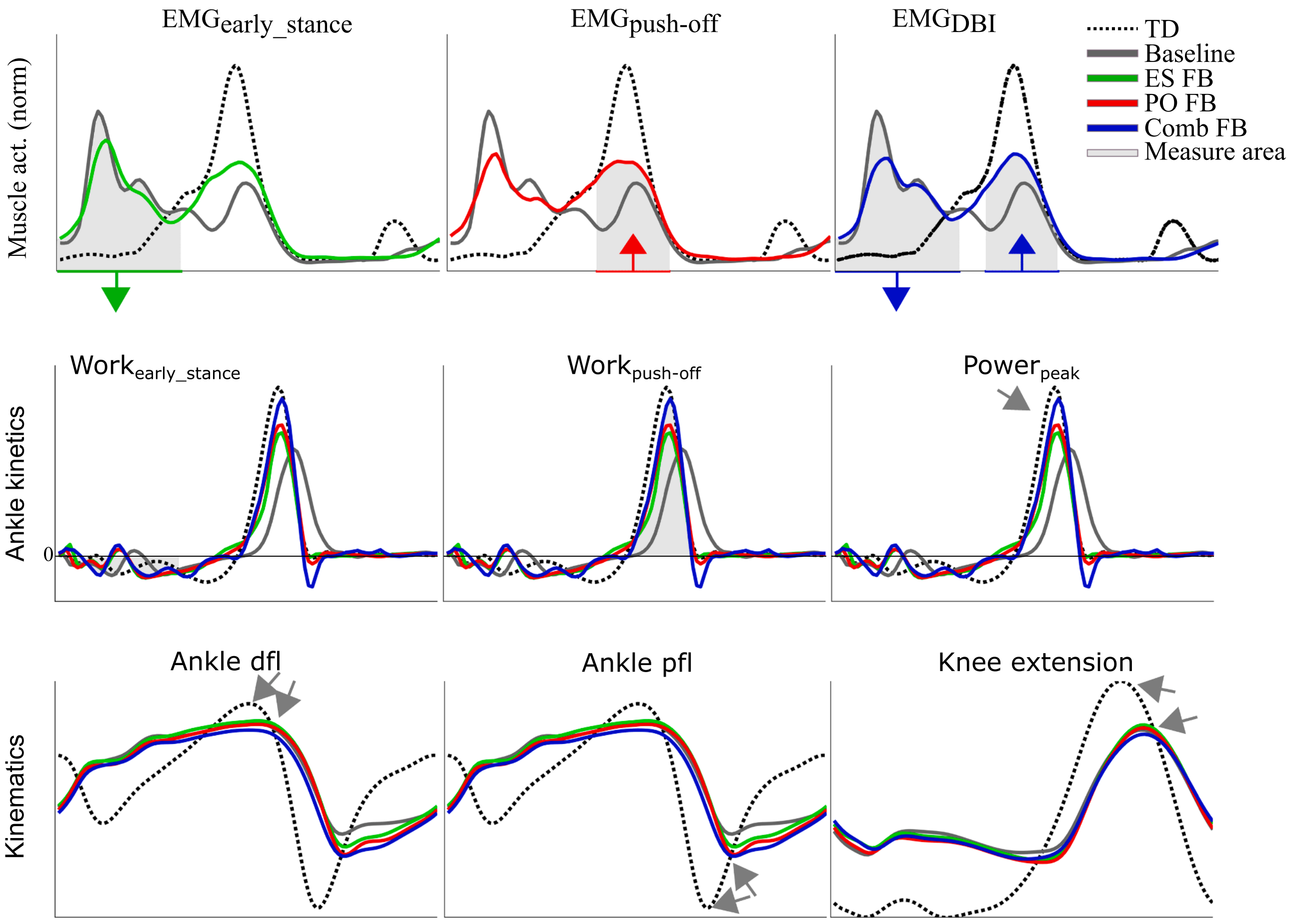

Fig. 2. Example data from one typically developing child (dotted line) and one child with CP (solid lines) at baseline and during the three different feedback trials. The top row presents the EMG signals, with the shaded gray areas depicting the areas over which the RMS EMG were calculated which were used as input for the biofeedback and as outcome parameters. The arrows corresponding to the areas indicate the desired direction of improvement, e.g., early stance activity should be decreased. The second row represents the work around the ankle, with shaded areas and arrows representing the calculated outcome parameters. The third row represents the ankle and knee kinematics with arrows indicating the calculated outcome parameters.

competence score 6–10, average 7.9; with one outlier of 3.3). Two participants did not complete the combined feedback trials and five participants only performed four to five minutes of biofeedback per session due to fatigue. One subject experienced an unexpectedly large increase in early stance peak once the game started and was therefore left out of group level analysis, as explained in detail in Supplementary material 2.

At group level, participants showed a significant decrease in early stance muscle activity during early stance feedback (−6.8 ± 12.2 % $p = 0.025$) and a trend during combined feedback (−6.5 ± 13.9 %, $p = 0.055$; Figs. 2,3). Muscle activity around push-off improved during push-off feedback (+8.1 ± 15.8 %, $p = 0.039$), but not during early stance or combined feedback. There was no overall effect on the DBI ($p = 0.102$–0.186). All EMG parameters remained significantly different from TD values ($P < 0.001$–0.002; see Supplementary table 4).

Peak ankle power increased during push-off feedback trials (10.6 ± 19.0 %, $p = 0.037$). Knee extension in stance increased by 1–2° during all forms of feedback ($P = 0.009$–0.032), but the GPS did not change ($P = 0.185$–0.686). There were no significant changes in ankle kinematics ($p = 0.193$–0.978) or work during early stance ($P = 0.295$–0.831) and push-off ($p = 0.185$–0.354). Ankle dorsiflexion during stance, and plantarflexion and work during push-off were already not significantly different from TD at baseline ($P = 0.108$–0.900) and also not during feedback. Peak push-off power remained significantly different from TD during all trials ($P < 0.018$). However, ankle work during early stance was no longer significantly different from TD during combined feedback trials ($p = 0.081$). Similarly, maximum knee extension during both combined ($p = 0.053$) and push-off feedback trials ($p = 0.064$) was no longer significantly different from TD, but these parameters did show a trend towards differences ($p < 0.10$).

Twelve of eighteen participants were categorized as responders for at least one feedback type (Table 2), with 6/18 ($\mathrm{FB}_{\mathrm{early\_stance}}$), 7/18 ($\mathrm{FB}_{\mathrm{push\text{-}off}}$), and 5/18 ($\mathrm{FB}_{\mathrm{combined}}$) significantly improving EMG activity (Fig. 2). Three participants showed significant worsening in DBI, of whom two were able to improve their push-off activity. Improvements in DBI correlated with higher DBI at baseline ($r^2 = 0.309$; $P = 0.031$), lower peak ankle power at baseline ($r^2 = 0.392$, $P = 0.012$), total power during push-off ($r^2 = 0.342$, $P = 0.031$) and a trend for the right leg as the most affected side ($\eta^2 = 0.240$; $P = 0.096$) (Fig. 4; Supplementary table 4).

4. Discussion

This study explored the possibilities of improving calf muscle activation in children with CP through biofeedback-driven gaming. At group level, we found that children can change their activation pattern when receiving early stance and push-off biofeedback. Twelve of eighteen participants showed an immediate response to at least one type of biofeedback. Improvements were generally small (5–10 %), while participants with more deviating baseline EMG patterns – according to the double-bump-index - achieved larger improvements. Furthermore, changes in muscle activity were accompanied by some improvements in

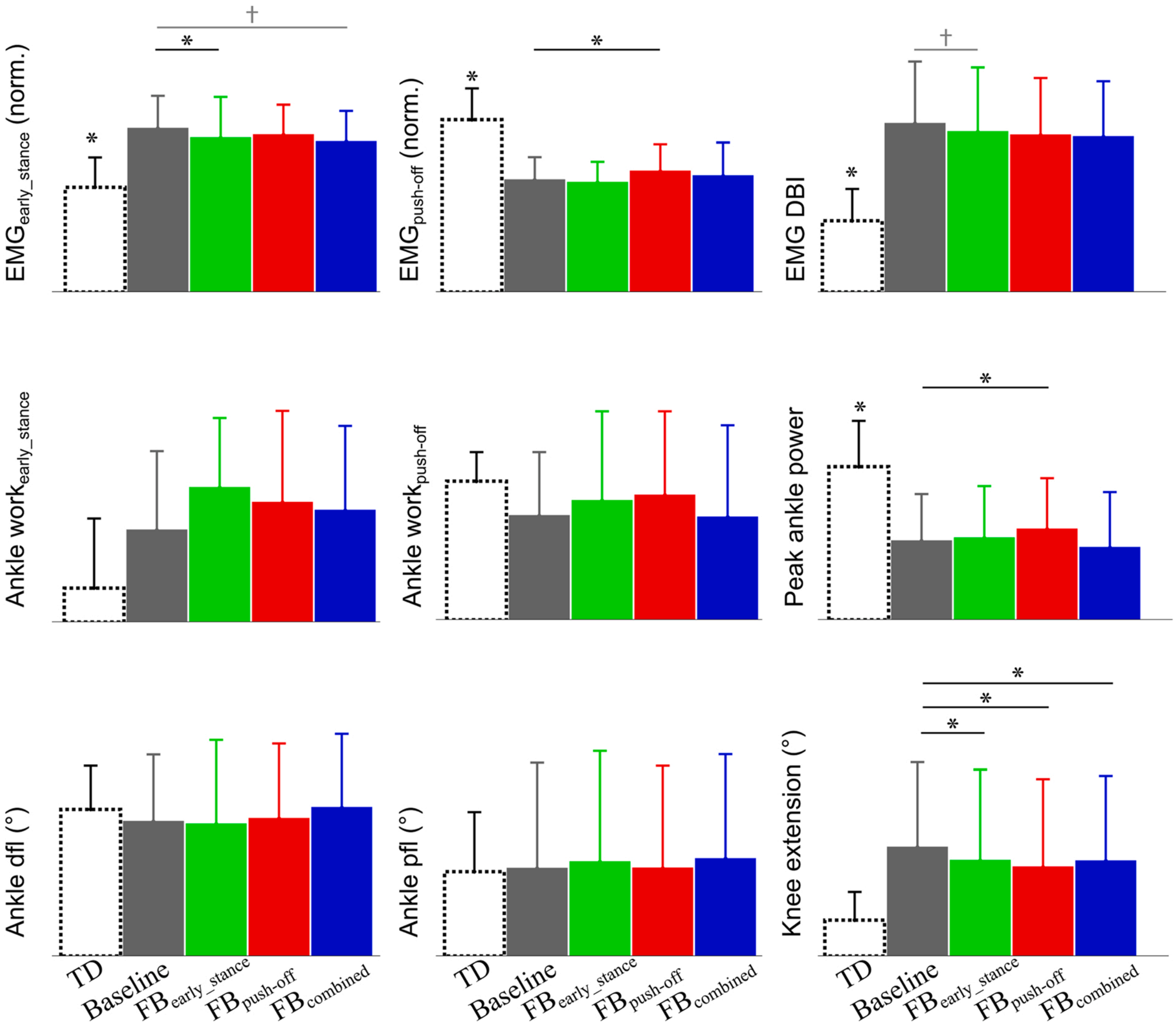

Fig. 3. Changes in outcome parameters due to biofeedback. Means and standard deviations as described in the previous figure are shown for the different conditions, for EMG (top row), ankle work (middle row) and ankle and knee angles (bottom row). Bars are presented for typically developing (TD) children and children with cerebral palsy (CP) at baseline and during the three types of biofeedback (FB_{early_stance}, $FB_{push\text{-}off}$, $FB_{combined}$). Stars above typically developing (TD) data indicate parameters that were significantly different from all conditions of the children with CP. Trends ($p < 0.10$) are visualized with a cross. Stars between baseline and biofeedback conditions represent improvements due to the biofeedback. Baseline values, improvements and p-values can be found in Supplementary material 4. Max ankle dorsiflexion (dfl) is measured during stance, plantarflexion (pfl) around push-off (60–120% of stance phase), and max knee extension during 20–100% of the stance phase. Abbreviations: DBI, double-bump-index, dfl, dorsiflexion; pfl, plantarflexion.

kinetics and kinematics. GPS did not change during biofeedback, suggesting that children did not show large improvements but also no major compensations in other joints. Importantly, all children enjoyed playing the game and scored high on perceived competence.

Results of our study add to the limited available evidence [15,43] that children with CP can alter their muscle activation patterns when walking with EMG biofeedback. Improvements were small, with 7–8 % relative improvement in push-off and early stance activity during their corresponding feedback. Furthermore, we saw a trend toward 7 % improved DBI during early stance feedback. Similar to Colborne et al. [15], who found a 19 % increased ankle power ($p < 0.10$), push-off biofeedback resulted in improved peak ankle power, but other kinetic variables did not improve.

Some overlap but also some discrepancies with previous studies became apparent. Colborne et al. [15] provided similar biofeedback but over eight sessions instead of one. Despite more sessions, changes were not considerably larger than in our study, as they only found a trend towards improved ankle power. This may be because their study was performed in an overground lab, limiting the number of strides (60–70 per session, compared to 700–1000 in our study) and thereby the amount of biofeedback. Additionally, the discrepancy could be caused by the less pathological baseline values in the study of Colborne et al. [15] (e.g., average peak ankle push-off power was 91 % of our norm data, compared to 50 % in our study). The inclusion of less affected individuals likely limits the effect size, as we found that children with more deviating EMG patterns and lower ankle push-off power generally achieved larger improvements. This is consistent with previous findings, as Van Gelder et al. [14] found an association between baseline GPS and improvements from kinematic biofeedback in children with CP. Therefore, it appears that more severely affected patients achieve greater improvements when targeting gait with biofeedback. Supporting this, Booth et al. [13] included more severely affected children (ankle push-off 41% of norm) and provided biofeedback directly on ankle push-off power during treadmill walking. They found large increases in peak ankle push-off power (38 %) already after two minutes of biofeedback.

Compared to Booth et al. [13], the improvements found in our study (7–8%) were relatively modest. Furthermore, a recent study by Conner

Table 2
Individual participants improvements and characteristics.

	Early stance (*P*-values)	Push-off (*P*-values)	Combined(*P*-values)	Muscle	Distribution	Side	Motivation	Competence
P01	**0.002**$^{+}$	**0.050**	-†	SO	Bi	R	-†	-†
P02	0.622	**0.005**	0.002 *	SO	Uni	L	9.3	8.0
P03	**0.028**	0.351	0.695^{+}	GM	Uni	L	9.1	9.9
P04	0.266	**< 0.001**	**< 0.001**$^{+}$	SO	Uni	R	9.3	9.3
P05	**0.056**	0.803	0.533	GM	Uni	R	8.0	9.0
P06	**< 0.001**	0.218	0.609^{+}	SO	Uni	R	6.2	7.9
P07	**< 0.001**$^{+}$	**0.082**	0.108	SO	Bi	L	10.0	9.2
P08	< 0.001 *$^{+}$	**0.003**	< 0.001 *$^{+}$	SO	Bi	L	7.5	6.0
P09	0.563	0.813	0.015 *$^{+}$	SO	Bi	R	7.5	9.0
P10	**< 0.001**	**< 0.001**	**< 0.001**	SO	Bi	R	9.5	8.0
P11	0.882	0.107	**0.009**	SO	Uni	R	7.5	10
P12	0.273	0.656^{+}	0.437^{+}	GM	Uni	R	9.4	9.0
P13	0.110	**0.046**$^{+}$	**0.025**$^{+}$	SO	Bi	R	7.9	3.3
P14	**0.088**$^{+}$	**< 0.001**$^{+}$	-†	GM	Bi	R	9.4	7.8
P15	0.544^{+}	0.675	**0.028**$^{+}$	SO	Bi	L	8.2	9.2
P16	0.364	0.667	0.866^{+}	SO	Bi	R	-†	-†
P17	**0.013**	0.516	0.801^{+}	SO	Uni	R	9.3	8.6
P18	0.899	0.355	0.290^{+}	SO	Bi	L	7.7	7.1

This table presents if individual participants were able to decrease their early stance EMG activity during the early stance biofeedback trial, increase their push-off activity during the push-off biofeedback trial and decrease their double-bumb-index during the combined feedback trial. P-values are presented for all individual participants (P#). Furthermore, the assessed muscle is shown, being the soleus (SO) or gastrocnemius medialis (GM) muscle. Distribution of the subject is presented, with uni, unilateral and bi, bilateral. Side indicates the (most-) affected side upon which feedback was provided. The final columns depict the individual scores on the intrinsic motivation inventory for both subscales motivation and perceived competence. Bold values indicate significant improvements or trends, *indicate significant worsening. +Indicates non-parametric Wilcoxon sum rank test was used. †indicate missing values, which were therefore left out of the analyses.

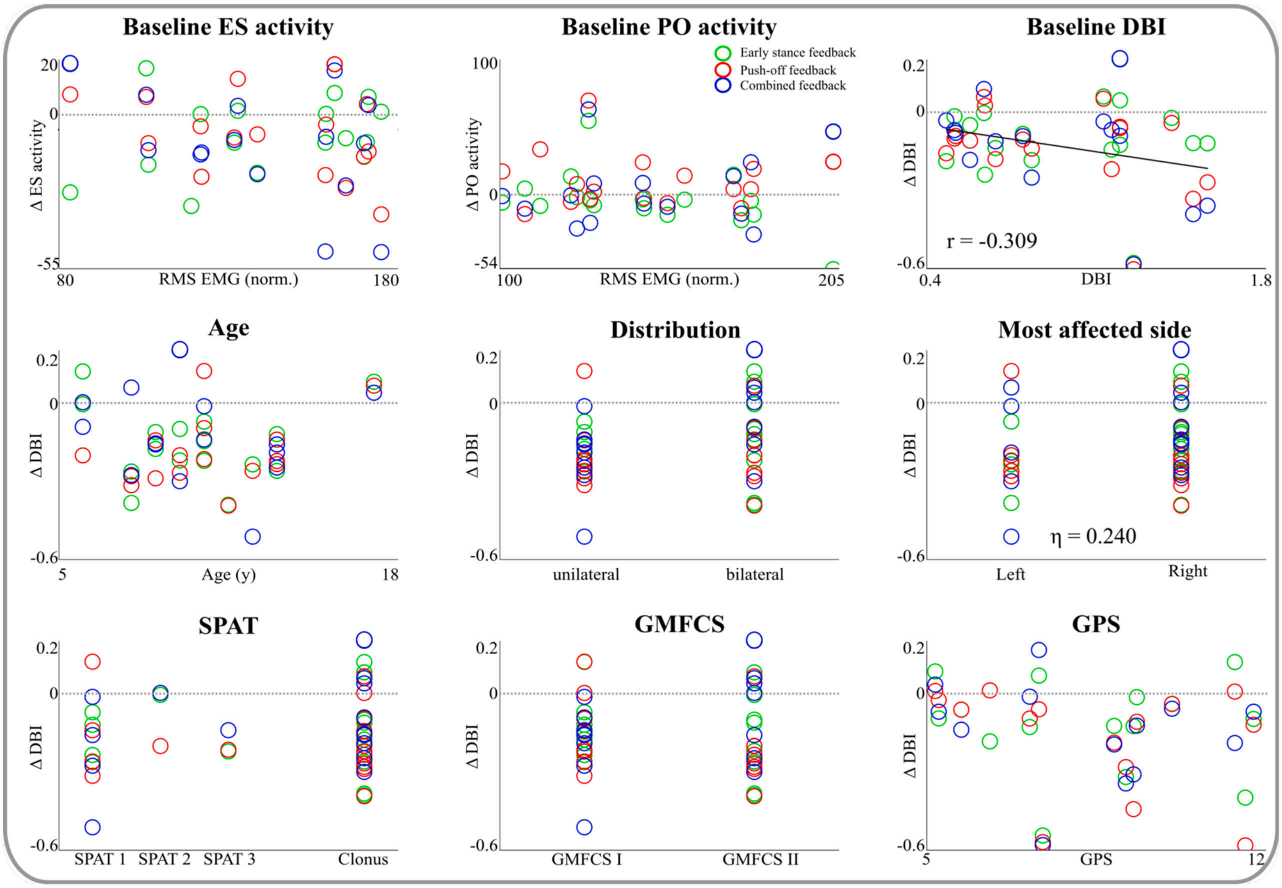

Fig. 4. Correlation analysis to identify responder charactetristics. The regression line is only presented for the variables 'baseline DBI', and the partial eta score for 'most affected side', as these were the only significant correlations. Other correlation values and the corresponding p-values can be found in Supplementary Table 3. DBI is the double-bump-index, calculated as the ES activity/PO activity, with lower values indicating improvements. The negative correlation in Baseline DBI versus ΔDBI indicates that children with larger DBI (i.e. more deviating activity patterns) show larger improvements (DBI decreases with feedback). Abbreviations; ES, early stance; PO, push-off; SPAT, spasticity assessment; GMFCS, gross motor function classification system; GPS, gait profile score.

and Lerner [44] found large increases of 46% in soleus activation in a single session of robot-resisted gait training when adding push-off feedback. Several factors could explain this difference. First, most previous gait training studies [13,15,44] used explicit biofeedback, whereas we applied implicit biofeedback. It is noteworthy that several children already showed changes within one session, as implicit feedback is expected to take longer to yield results [28]. Although it should be confirmed in future studies for our specific application, implicit learning in general yields longer-lasting results [24,25] and increases engagement and motivation [29]. Another advantage of implicit learning is that it requires less working memory, which is often impaired due to left hemisphere lesions, as is common in children with right unilateral CP [26]. Although weak, we found a trend towards a greater response in children whose right side was more severely affected, further underlining the efficacy of implicit biofeedback for this group.

A second factor that could explain the relatively small improvements regards the requirement of consecutively decreasing and increasing the activation of the same muscle within a short time window of 400–600 ms. Even though the implicit nature of the biofeedback allows for such a task, this may be complex to perform. Mastering the separate components first and only providing combined feedback later might increase improvements. Thirdly, since we kept walking speed constant, this might have impeded further increases, knowing that calf muscle activation is highly dependent on walking speed. Long-term training studies can use self-paced walking during the biofeedback conditions, allowing for greater effects. However, improvements should be assessed at matched walking speeds for a fair comparison [21]. Finally, we noticed that subjects experienced both more and less successful periods of feedback, for example due to a sudden loss of effective strategy, bursts of frustration, loss of attention, or the occurrence of fatigue. Children were on average not able to comply with the combined feedback, which might be caused by these factors. We expect that larger within-session improvements can be achieved by fine-tuning the gaming techniques.

Although it is debatable whether the changes found in this study represent a clinically relevant improvement and effects are limited to immediate effects during biofeedback, it is promising that improvements could be seen in most children already within one session. For successful implementation in clinical care, it is important that children already achieve success during early stages of training. Therefore, within-session improvements are a first step, and translation toward general gait should be studied in long-term studies. Furthermore, future studies can analyze if improvements are specific to the biofeedback imposed, and what types of feedback would work best. For instance, it could be that only the focus on improving gait, regardless of the type of feedback, already leads to improvements in muscle activation. Yet, our finding that reductions in early stance activity and increases in push-off activity were specific to their respective feedback type, strengthens the idea that changes are indeed feedback-specific.

EMG biofeedback is likely easier to implement in physiotherapy- or potentially even home-based training, compared to for example kinetic biofeedback [13], as it omits the need for expensive 3D motion tracking devices with embedded force plates. User-friendly devices already exist to provide EMG biofeedback at home [16,17]. Adding a step-detection algorithm, for example through accelerometer data [18], can make these devices suitable to target specific phases of the gait cycle. Additionally, gamification increases long-term treatment efficacy [30–32] as well as engagement and motivation [33,34], and indeed we measured high levels of motivation. Besides these positive effects, moving away from clinical settings towards physiotherapy or home settings will increase clinical applicability.

This explorative study assessed improvements within just one session. No post-testing was performed as retention was not expected after the short feedback session. Follow-up training studies are required to evaluate the long-term effects. Additionally, even though multiple outcome parameters normalized towards typical, we did not assess functional outcomes, such as energy expenditure or walking speed, which should be a target in a long-term study [45]. Another limitation is the single muscle currently addressed for biofeedback, whereas future applications might need to target more muscles for optimal improvements.

In conclusion, this exploratory study indicates that most participants with CP can achieve within-session improvements in their muscle activation pattern during walking with implicit EMG biofeedback-driven gaming. Furthermore, the gaming was well-tolerated and motivating for children with CP. These results indicate that it is worthwhile to assess the long-lasting functional effects of implicit EMG biofeedback-driven gaming.

Conflict of interest

Motek ForceLink is involved as a partner in the TTW project. Motek ForceLink was involved in the development of the gaming application, for which Motek ForceLink received payment. Furthermore, all partners of the TTW project provided consent for the publication of the manuscript. None of the partners were involved in any other part of the research design, measurements, or development of the manuscript.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2023.02.012.

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