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Effects of dynamic and isometric motor practice on position control, force control and corticomuscular coherence in preadolescent children

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A R T I C L E I N F O

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A B S T R A C T

In this study, we investigated the effects of motor practice with an emphasis on either position or force control on motor performance, motor accuracy and variability in preadolescent children. Furthermore, we investigated corticomuscular coherence and potential changes following motor practice.

We designed a setup allowing discrete wrist flexions of the non-dominant hand and tested motor accuracy and variability when the task was to generate specific movement endpoints (15–75 deg) or force levels (5–25% MVC). All participants were tested in both tasks at baseline and post motor practice without augmented feedback on performance. Following baseline assessment, participants (44 children aged 9–11 years) were randomly assigned to either position (PC) or force control (FC) motor practice or a resting control group (CON). The PC and FC groups performed four blocks of 40 trials motor practice with augmented feedback on performance.

Following practice, improvements in movement accuracy were significantly greater in the PC group compared to the FC and CON groups ($p < 0.001$). None of the groups displayed changes in force task performance indicating no benefits of force control motor practice and low transfer between tasks (p-values:0.08–0.45). Corticomuscular coherence (C4-FCR) was demonstrated during the hold phase in both tasks with no difference between tasks. Corticomuscular coherence did not change from baseline to post practice in any group. Our findings demonstrate that preadolescent children improve position control following dynamic accuracy motor practice. Contrary to previous findings in adults, preadolescent children displayed smaller or no improvements in force control following isometric motor practice, low transfer between tasks and no changes in corticomuscular coherence.

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1. Introduction

Development of motor control and skill learning is a necessary part of both childhood development and adult life (Greenough, Black, & Wallace, 2008) (Dayanidhi, Kutch, & Valero-Cuevas, 2013; Voelcker-Rehage, 2008.; Vollmer & Forssberg, 2009). While we continue to learn across the lifespan, de novo motor learning and refinement of existing skills is particularly important during childhood in order to expand the motor repertoire, to refine existing motor skills and to adjust mechanisms of motor control to the physical changes that occur during growth (Fandakova & Hartley, 2020; Krakauer, Hadjiosif, Xu, Wong, & Haith, 2019).

The acquisition of a new motor skill involves establishing and refining optimal motor commands to achieve our goals through continuous sensorimotor interactions. The sensorimotor interactions rely on motor planning and interactions between feedforward and feedback mechanisms when engaging in motor learning and these processes lead to modifications of the internal model (Flanagan & Wing, 1997). This processing naturally involves integration of intrinsic feedback from muscles, tendons, skin and joints while external stimuli come from visual, auditory and mechanical influences. All of these inputs are weighed, integrated and contribute to perception of our movements and their consequences (Mugge, Schuurmans, Schouten, & van der Helm, 2009). They also allow comparison to motor plans to produce an internal measure of the utility for future motor commands and thus motor learning (Flanagan & Wing, 1997; Johansson & Edin, 1993).

Numerous studies have investigated human motor learning and employed different task paradigms to study aspects of different types of motor learning including skill acquisition and retention. Different studies of motor learning have used different task paradigms depending on the research question at hand. Tasks often include (but are not limited to) adaptation tasks, serial reaction time tasks, dynamic position control tasks or isometric force control tasks. Several studies have also focused on processes of motor learning in children, but despite the extensive literature on the effects of motor practice in adults there is a lack of knowledge on the influence of motor practice paradigm for motor learning in children.

The fundamental development of functional networks within the central nervous system improves the abilities of fine motor control from childhood and into early adulthood (Dayanidhi et al., 2013; Forssberg, Eliasson, Kinoshita, Johansson, & Westling, 1991; Smith, Paton, Chakrabarty, & Ichiyama, 2017) and recent studies have indeed demonstrated age-related differences in motor control (Beck et al., 2021; Beck, Spedden, & Lundbye-Jensen, 2021; Spedden et al., 2019). Children generally display less top-down modulation during tasks that require e.g. response inhibition (Bitan et al., 2006; Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002.; Williams, Ponesse, Schachar, Logan, & Tannock, 1999) compared to adult-like higher-order cognitive control (Bitan et al., 2006). In line with this, performance in tests of executive functions contribute positively to motor performance in preschool children (Stuhr, Charmayne, & Stöckel, 2020) and the maturation of cognitive functions during childhood and adolescence seems to be associated with motor performance. We have recently found that age-related differences in motor control partly rely on the efficiency of functional communication at the cortical level (Beck, Spedden, Dietz, et al., 2021) and this resonates well with previous findings suggesting a shift from bottom-up to top-down processing as children and adolescents approach adulthood (Bitan et al., 2006).

Considering motor learning, acquisition of new motor skills seems to require more extended periods of practice for children compared to adults (Sullivan, Kantak, & Burtner, 2008; Wilhelm, Metzkow-Mészàros, Knapp, & Born, 2012). Children also display delayed gains during motor skill learning and between-session memory consolidation which is less susceptible to interference effects compared to adult motor learning (Dorfberger, Adi-Japha, & Karni, 2007). During motor practice, improved motor performance is accompanied by reduced trial-to trial variability, which is consistent with reproducibility of neural activity patterns that generate successful outcomes (Dhawale, Smith, & Ölveczky, 2017; Shmuelof, Krakauer, & Mazzoni, 2012). At the same time task-relevant motor variability also predicts faster motor learning (Wu, Miyamoto, Castro, Ölveczky, & Smith, 2014) since variability can reflect meaningful motor exploration that supports learning (Caballero et al., 2017). Interestingly, children seem to display less exploration of the movement repertoire compared to adults (Lee, Farshchiansadegh, & Ranganathan, 2018). Like adults, children do however also use feedback to optimize motor learning and learning is influenced by the feedback frequency during practice (Goh, Kantak, & Sullivan, 2012; Sullivan et al., 2008).

As mentioned above, different studies have employed different motor practice paradigms to investigate aspects of motor learning, and it is evident that different models are effective for investigating e.g. force control (Beck, Spedden, & Lundbye-Jensen, 2021; Reis et al., 2009) or position control (Christiansen et al., 2020; Larsen et al., 2016). While the character of the motor practice paradigm is not always discussed in depth in different papers, it is evident that different tasks (involving e.g. dynamic position control vs. isometric force control) have different constraints impose different demands and this is likely to influence the observed behavioral effects. In recent experiments we found distinct effects of motor practice with emphasis on dynamic position control vs. motor practice with emphasis on isometric force control in adult participants. While isometric motor practice led to improved force control, dynamic motor practice led to improved movement accuracy i.e. position control and improved force control. Furthermore, dynamic motor practice with emphasis on position control was accompanied by larger increases in corticospinal excitability (Norup, Bjørndal, Nielsen, Wiegel, & Lundbye-Jensen, 2023). While the study did not elucidate the underlying mechanisms, the distinct effects were related to the type of motor practice. While the task was similar, isometric motor practice involved augmented feedback on the exerted force relative to target while dynamic motor practice involved augmented feedback on position relative to target. Evidently, isometric and dynamic motor practice also differ in the processing of intrinsic (e.g., proprioceptive) inputs providing sensory information about both position and force during dynamic movements and about force during isometric contractions, respectively.

In children, performance in dynamic tasks improves during childhood and adolescence (Dayanidhi et al., 2013) and likewise does force control motor performance (Beck, Spedden, & Lundbye-Jensen, 2021). Although children also display motor skill learning based on short-term motor practice (Sullivan et al., 2008), it remains unknown whether motor learning based on primarily position or force control differs in children and whether effects of these types of motor practice differ in children compared to adult participants. To the best of our knowledge, this has not been investigated in previous studies. Therefore, the present study aimed to investigate behavioral effects of these distinct motor practice paradigms in preadolescent children. We investigate position control and force control and effects of dynamic and isometric motor practice. Furthermore, we investigate corticomuscular coherence during both task paradigms and potential changes in corticomuscular coherence following motor practice. It has previously been demonstrated that corticomuscular coherence increases following a single session of visuomotor accuracy practice in adult participants (Larsen et al., 2016; Perez, Lundbye-Jensen, & Nielsen, 2006). In recent experiments we have found that children display smaller magnitudes of corticomuscular coherence compared to adults (Beck, Spedden, & Lundbye-Jensen, 2021; Spedden et al., 2019). It remains however to be elucidated to which extent corticomuscular coherence changes with motor practice in preadolescent children. Based on recent findings in adult participants we hypothesized that dynamic motor practice would lead to improvements in both position control and force control in preadolescent children. We also hypothesized that transfer effects between tasks would be smaller in children based on the finding that adults and late adolescents display greater use of top-down and executive control processes during motor task performance compared to children (Beck, Spedden, Dietz, et al., 2021). Finally, we hypothesized that corticomuscular coherence increases following motor practice.

2. Methods and materials

2.1. Participants

Forty-four children (22 boys and 22 girls) aged 9–11 years (10.2 (±0.8) from the capital area of Denmark were included in the study. The children were all naïve to the motor tasks of the experiment. This group of neurotypically developed children was included based on a general eligibility questionnaire. They had no history of either neurological or psychiatric disease, no intake of medication and had a normal or corrected-to normal vision.

We used the Edingburgh Handedness Inventory (Oldfield, 1971) to assess the handedness of the participants and according to this the participants were right-handed. This was to ensure that the prerequisites to perform the motor tasks were equal to participants across all groups. All descriptive information is presented in Table 1.

The regional committee for the Greater Copenhagen area approved the experiment (protocol H17019671) and the study was performed in accordance with the declaration of Helsinki. All participants and their parents received written and oral information about the experimental procedures and gave their written informed consent prior to taking part in the study.

2.2. Study design

We used both a within- and between-group design experiment with forty-four participants who were randomized to one of three groups; 1) Position control practice group (PC), force control practice group (FC) and resting control group (CON) (Fig. 1A). The randomization of participants was made after balancing for sex (m/f). The group allocation was not blinded to the assessors.

We measured performance in two versions of a wrist task at baseline and post motor practice; a position control task (dynamic) and a force control task (tonic). This experimental design provided the possibility to investigate the acute effects of sensorimotor practice with emphasis on position control or force control respectively on accuracy and endpoint variability of movements in both paradigms. Furthermore, we also investigate possible transfer or interference effects between paradigms.

2.3. Experimental setup

All experiments were conducted with participants seated at a table in front of a computer monitor (27″, Lenovo Thinkvision, resolution 2550*1440 pixels). For the experiment we used a custom-built armrest for the left arm of the participant (Fig. 1B). The design focused on the nondominant hand in order to ensure that the task was challenging for the participants since previous studies have found lower baseline motor performance for the nondominant hand and larger effects of motor practice i.e. room for

Table 1
Participants characteristics.

Intervention group	Position control practice (PC)	Force control practice (FC)	Control (CON)	*P*-values range
Sex (boys/girls)	15 (8/7)	15 (7/8)	14 (7/7)	
Age (years)	10.3 ± 0.5	10.2 ± 0.9	10.1 ± 0.9	0.7–0.8
Weight (kg)	38.8 ± 7.5	40.2 ± 8.8	36.5 ± 7.7	0.8–0.9
Height (m)	1.5 ± 0.06	1.51 ± 0.09	1.44 ± 0.08	0.5–0.6
Handedness (LQ)	87.0 ± 12.7	85.4 ± 22.1	63.8 ± 55.2	0.8–0.9
Sleep – night before experiment (hrs)	9.4 ± 0.68	9.72 ± 0.63	9.26 ± 0.88	0.2–0.7
Sleepiness (SSS, 1–5)	2.5 ± 0.6	2.5 ± 0.5	2.4 ± 0.5	0.5–1.0
MVC – maximal wrist flexion force (N)	34.7 ± 20.9	31.9 ± 13.0	25.3 ± 13.4	0.7–1.0
Manual Dexterity (Purdue Pegboard Score sum of tasks)	40 ± 13.9	38.9 ± 18.5	36.9 ± 12.3	0.8–0.9

Descriptive data presented as group means with standard deviations. LQ = laterality quotient, SSS = Stanford sleepiness scale (1–5), MVC wrist flexion force measured in Newton. *P*-values indicate no between-group differences in any characteristic at baseline. t-tests used to test for between-group differences at baseline.

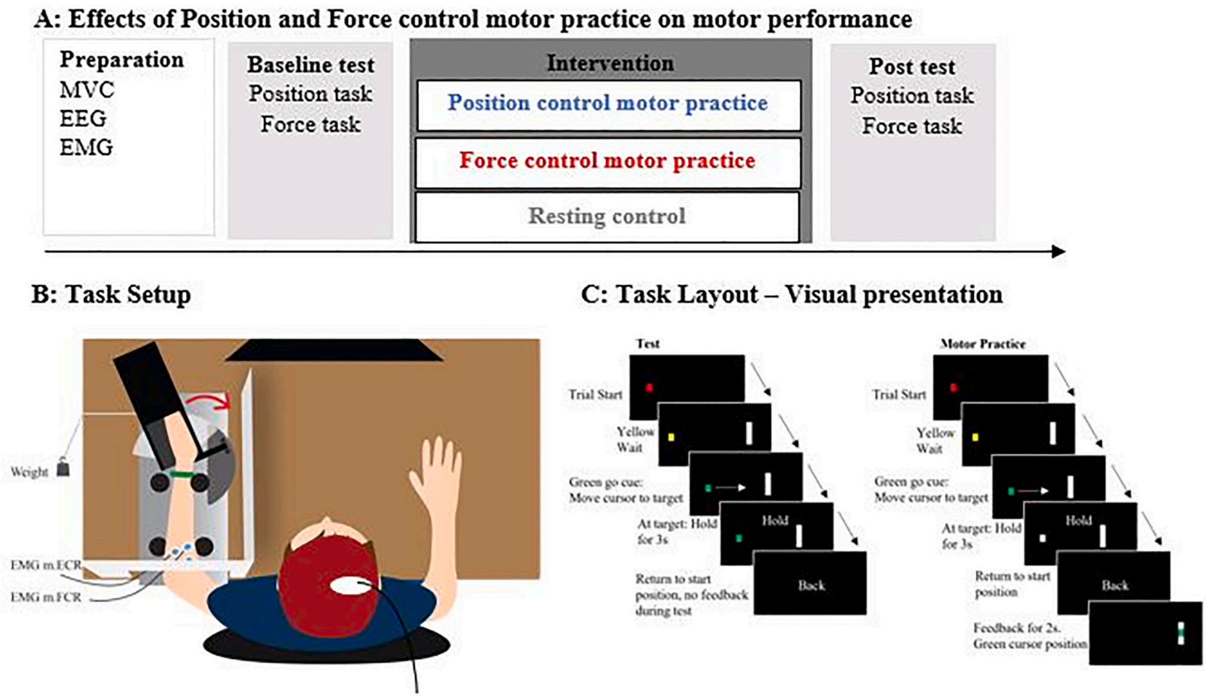

Fig. 1. Illustration of experimental design, setup and procedure. Panel A depicts the experimental protocol with the three intervention groups; Position control practice and force control practice and the control group. The experimental setup is depicted in panel B. In panel C the computerized wrist flexion task used for motor practice, baseline and post tests is depicted.

improvement with motor practice (see e.g. Ridding & Flavel, 2006). The left forearm of the participant was placed horizontally and semi-pronated in the armrest, and chair and table were adjusted to fit each participant ensuring that the shoulder was in a neutral position: lightly abducted and the elbow flexed approximately 100°. The forearm was held by velcro straps to reduce large replacements of the hand and arm during motor tasks and practice. During all motor tasks and practice the left hand was placed in a custom-made 3D printed box with all fingers passively extended. The box was attached to a lever able to rotate around the same axis as movements of the wrist. Integrated in the lever was a strain gauge and goniometer allowing measures of wrist force (when lever was fixated) and position during movements. A custom-built white wall with an angle of 90° was placed in the sagittal and frontal plane to prevent direct visual eye-hand feedback (Fig. 1B). To reduce muscle contraction of the right arm, shoulder and neck, the participants right forearm was placed on a platform in the same height as the left arm. The experimental setup was replicated from our previous study in young adults (Norup et al., 2023).

2.4. Motor tasks

All participants performed tests of motor performance in two motor task paradigms: a dynamic task involving wrist position control and an isometric task involving wrist flexion force control. The motor tasks were inspired by the paradigm used by Wiegel & Leukel (Wiegel, Leukel, Carson, Stagg, & Wiegel, 2020) and identical to the paradigms used in our previous study (Norup et al., 2023). In both tasks, the wrist angle starting position was 40° extension from the neutral in situ position.

The participants received instruction and feedback cues on a monitor placed in front of them. The computerized task was the same in both paradigms. A black background with a grey vertical line (approximately 3 cm high) showing a target and a "traffic light" on the left side of the screen indicating preparation with a yellow dot and start signal with a green dot. Start and stop signal at each trial were given with a red dot. We used a custom script for the computerized task (Matlab R2019a, MathWorks Inc.).

Within a second after the green dot was displayed the participant had to reach the target. Subsequently a hold period of 3 s followed with "Hold" written on the screen to inform the participant to keep the current position/force level as constant as possible. The hold phase was transitioned to the end phase with the information "Back" to inform the participant to go back to the starting position and trial ended with the presentation of the red dot (Fig. 1C). All displacements on the screen were in a horizontal plane.

In the PC task, during a block of 40 trials the participant had to make a series of discrete wrist movements to five predefined targets: 15, 30, 45, 60 and 75° relative to the starting position at 40° dorsal flexion presented in a randomized order and each target was presented eight times during the 40 trials. The range of movement during the dynamic task was reduced to 2/3 of the maximum range of motion of the wrist joint equalizing a movement range of 60° palmar flexion and 40° degrees dorsal flexion. To ensure a passive movement to the starting position a wire was pulling the handle back after each trial. The force to pull back was individually adjusted using weights between 100 and 400 g.

In the FC task, the handle was fixated in 40° dorsal flexion. Participant had to reach different percentages of their individual maximal voluntary contraction during a wrist flexion. Series of 40 trials with eight randomly presented trials to each of the following force degrees: 5, 10, 15, 20 and 25% of MVC. In both tasks target 5 (75% palmar flexion in the position control task and 25% MVC in the force control task) corresponded to 2500 pixels horizontal displacement of the cursor. To measure the force necessary to reach the five distinct positions we used a Cambridge Electronic Design 1401 with a Signal Software v7.5 and transformed the force to Newton. To pull the hand back to the start position a force of 0.056 N was necessary independent of the individualized weight to pull the handle back.

2.5. Motor practice

In this study we used two distinct types of sensorimotor practice. Position control practice and force control practice. Both paradigms were built upon the same procedure and concept. The computer task was the same in both paradigms and the aim was to practice either position control or force control during the intervention. The practice in both paradigms was done without online visual feedback and no eye-to-hand coordination as the hand practicing the task was hidden behind a custom build white wall. Only augmented feedback on movements was the movement endpoint after each of the 160 trials. This way we aimed to investigate sensory motor practice relying on the internal senses: proprioception and interoception. The procedures of the sensory motor practices were almost similar to the motor tasks conducted at baseline and post interventions except from the augmented endpoint feedback given during practice.

MVC test for wrist flexion was taught to participants during the experiment via verbal instructions and a visual presentation displaying the test. To prevent the contraction of arm and shoulder muscles, participants were asked to push with their palms and only palmar flex their wrists by contracting the forearm muscles. During the trials, participants sought to exert their maximum force in 3 s while receiving verbal encouragement. In the force task, the target positions were determined using the peak force value reached in the best of the three trials, or MVC.

Baseline performance was assessed in both tasks and the order of tasks was counterbalanced between participants in all three groups. The researchers introduced the tasks verbally and visually before each of the two tasks. Following instructions, participants were familiarized with the tasks and practiced the movement to target 1, 3 and 5 three times each. During familiarization, the participants were able to follow their movement trajectories on the computer screen as a green cursor moving from left to right with increasing wrist flexion force or position respectively. The familiarization with online feedback was repeated before each of the position control and force control posttests to re-calibrate to the targets. During familiarization trials, the participants were instructed verbally to focus on the wrist flexion force level required to reach the specific force targets and during familiarization to the position task, the participants were instructed to focus on the hand position (wrist flexion) required to reach the specific position targets.

The familiarization was followed by the actual baseline tasks consisting of 40 trials in each task and in contrast to the familiarization tasks the position control and force control tasks were conducted with no augmented feedback on performance and only the target position was displayed during the tasks.

The sensorimotor practice interventions consisted of four blocks of 40 trials each. The participants practiced a sensorimotor task with emphasis on either position control or force control. During the sensorimotor practice, the participants received augmented visual feedback in the form of a green cursor displayed after each trial and was the mean of a 3 s hold phase at the end of each trial. This way participants were able to incorporate the endpoint position or force level. During the 160 practice trials the experimenter gave encouragements as “good job”, “well done”, “keep up the good work” at every 10th trial to keep the participants motivated.

The control group was resting for 30 min to equalize the practice time in the two intervention groups.

Post-tests were done after completed sensorimotor practice with the same procedures as at baseline testing. These procedures included counter-balancing test order, familiarization trials and instructions to tasks before completing the two sensorimotor tasks. At baseline, halfway through practice and post practice the participants' sleepiness was evaluated. The Stanford Sleepiness Scale was used for this purpose (Hoddes, Zarcone, Smythe, Phillips, & Dement, 1973).

2.6. Electrophysiological recordings

During all baseline and posttest as well as during motor practice electroencephalographic (EEG) was obtained using 64 electrodes plugged into a headcap (BioSemi) positioned in accordance with the international 10/20 system (Journal & Technology, 1961). Electromyographic (EMG) recordings were also obtained during the experiment from flexor carpi radialis (FCR) of the participants left arm using surface electrodes (BioSemi, Amsterdam, The Netherlands). Both EEG and EMG were recorded in ActiView software (v7.07). All EEG electrodes were recorded with an offset below 30 mV and with electrode reference (common mode sensor and driven right leg) from BioSemi system during the data acquisition. Signals in the ActiView software were sampled at 2048 Hz and participants were instructed to relax face and neck muscles and to avoid excessive movement that could affect the EEG signals.

2.7. Data processing and statistical analysis

We measured error (pixels) and calculated the variability of error and variability in endpoint position and force for the position task and the force task. The variability is presented as standard deviation and coefficient of variance of distance from the center of the target across all trials. In addition to error, variability was also quantified for movement endpoint and presented as standard deviations and coefficients of variation across all trials within each participant.

R (Team, 2022) was used for all statistical analyses, with the R-package lmerTest (Kuznetsova, Brockhoff, & Christensen, 2017) being used to construct linear mixed effects models to the averaged datapoints (Winter, 2013). We modelled dependent variables (performance scores: error (pixels), SD (pixels) and coefficient of variance (COV) (%)) separately for the two tasks (force and position task) with the fixed factors INTERVENTION (PC; FC; CON) and BLOCK (repeated measure: Baseline; Post practice), we further included an interaction term (INTERVENTION x BLOCK). We introduced intercepts for each participant as a random effect to account for inter-individual variability in performance; this was also done for trials within each block. With the BLOCK condition, similar models were employed to test for performance increases during practice (practice block 1–4). QQ-plots and residual plots were used to test the assumptions of normality and homogeneity of variance of residuals. For pairwise comparisons based on our hypothesis, we used the multcomp R-package (Hothorn, Bretz, & Westfall, 2008). Multiple statistical comparisons were adjusted using the Holm-Sidak procedure. The significance level for all statistical analyses was set at $p < 0.05$. When applicable, model estimates are supplied with standard error (SE) and confidence intervals (CI).

2.8. Coherence analysis

Corticomuscular coherence (CMC) analysis was performed in MATLAB (Version R2022a, MathWorks, MA, USA). EEG and EMG data was first preprocessed using EEGLAB toolboxes (v2022.1). Data was stepwise preprocessed. The digital signal was sampled at 2048 Hz and down sampled to 256 Hz and bandpass filtered from 5 Hz to 45 Hz because our analysis focused on the beta band (15 + 35 Hz). Bad EEG channels were identified though visual inspection. Subsequently the average reference of the signal was computed. Independent Component Analysis (ICA) was then used to remove components that were identified as eye blink and muscle activity within the EEG signals. This was done using the “runica” algorithm. Prior to coherence estimation, EMG signals were full-wave rectified to maximize the information regarding timing of motor unit actions potentials (MUAP) and to suppress information of MUAP waveform shape (Halliday & Farmer, 2010). Signals were linearly detrended and normalized to have unit variance. The single electrode (C4) above primary motor cortex (M1) located contralaterally to the contracting muscle had the highest CMC (Fig. 5A and D) and was chosen due to the fact that coherence is topographically organized (Mima, Simpkins, Oluwatimilehin, & Hallett, 1999). Power spectra were assembled from sections of data taken from a fixed offset time given from the trigger points in each trial. The analysis was constructed from the “hold phase” sections within each trial, consisting of a 3 s period in 40 trials (total of 120 s).

The framework presented from Halliday, Conway, and Farmer (1995) provides a useful framework for calculation of coherence function between two signals. The quantification of coherence is estimated from the correlation structure of two signals (EEG-EMG). First, estimates of the power spectra were computed by averaging periodograms across all trials and represent the auto spectra calculated by the Fourier transformation of processes x, and y, at a given frequency. The cross spectrum between x and y is denoted by divided by the two auto spectra (Fig. 5 B and E).

Coherence estimates are bounded measures of association defined over the range from zero to one describing the absence or presence of a linear correlation between the two signals. Individual data were pooled to provide a single frequency domain coherence

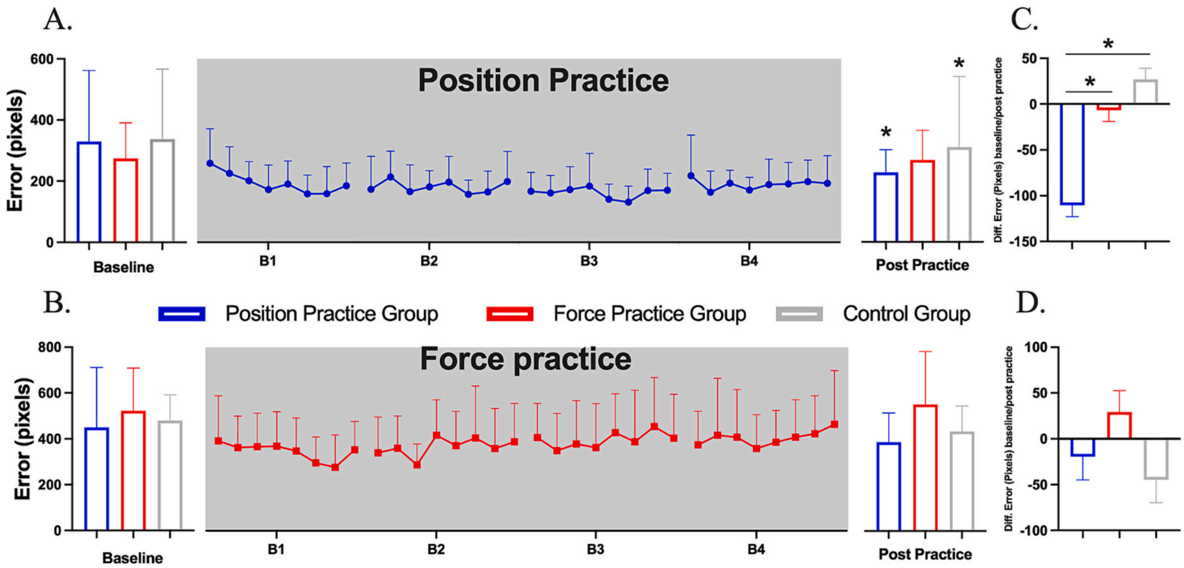

Fig. 2. Mean errors at baseline, during practice and post practice in the position control task and in the force control task A: depicts error in the position task at baseline and post tests for all groups; PC (blue), FC (red) and CON (grey). Error during four blocks of position control practice is also shown in panel A. Correspondinly, mean error in the force control task is depicted in panel B. Mean changes in error from baseline to post tests are shown in panel C for the position control task and in panel D for the force control task. All errors are reported in pixels. * denotes a significant difference ($p < 0.05$) within group in panel A and between groups in panel C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

measure reflecting the average of each group (Halliday & Rosenberg, 2000). Coherence was investigated with a main focus on the beta frequency band (15–35 Hz) since previous studies that have found increased coupling in the particular frequency band during low to moderate isometric contractions (Conway et al., 1995; Farmer, Bremner, Halliday, Rosenberg, & Stephens, 1993; Reyes, Laine, Kutch, & Valero-Cuevas, 2017).

Statistical inference between two independent coherence estimates can be assessed using the extended difference test (Amjad, Halliday, Rosenberg, & Conway, 1997). Extended difference is a nonparametric test that provides insight into the difference in coherence both within a large population and at individual level. Therefore, the pooled coherence used in this study summarizes the strength in the coupling within the population and the test provides the difference between pooled coherence at given frequencies. The test was used to compare pooled coherence at baseline between the PC and FC tasks and the effect of motor practice within each group.

3. Results

Participant characteristics are presented in Table 1. The three groups were comparable in all parameters (range of p values: 0.5–1).

3.1. Motor performance in the position task

Motor performance for the position task is depicted in Fig. 2A. Planned comparisons from the linear mixed effect model showed no significant differences in baseline position task error and SD (pixels) between the PC (329.17 ± 232.62), FC (274.37 ± 116.18) and CON (337.12 ± 229.13) groups (range of p-values: 0.65–0.99). From baseline to post practice there was a significant decrease in error for the PC group (−110.48 ± 12.38, CI: [−134.73; −86.22], $p < 0.001$) (Fig. 2C). There was no change in position task error following force practice in the FC group (−6.73 ± 12.24, CI: [−30.72; 17.26], $p = 0.58$). The CON group, however, demonstrated a small but significant decrease in error from baseline to post practice in the position task (−26.91 ± 12.25, CI: [−50.92; −2.9], $p = 0.028$) (Fig. 2C). Comparisons between groups demonstrated that error in the PC group decreased significantly more in the PC group compared to both the FC and CON groups: PC vs. FC (−103.75 ± 17.41, CI: [−144.53; −62.96], $p < 0.001$), and PC vs. CON (−83.57 ± 17.42, CI: [−124.37; −42.77], $p < 0.001$). No significant difference in delta changes was observed between the FC and the CON group (−20.18 ± 17.32, CI: [−60.76; 20.4], $p = 0.244$).

3.2. Error and endpoint variability in the position task

The quantification of variability based on standard deviations of the mean error in pixels at baseline and post practice showed that participants in the PC group did not change variability (1.47 ± 12.64, CI: [−23.31; 26.24], $p = 0.91$). The additional assessment of error variability calculated as COV did however demonstrate a significant increase from baseline to post practice in the PC group (7.63 ± 3.88, CI: [0.03; 15.24], $p = 0.049$). There were no significant changes in SD or COV in the FC group (SD:19.14 ± 12.52, CI: [−5.41; 43.68], $p = 0.13$, COV: FC: 2.9 ± 3.85, CI: [−4.64; 10.44], $p = 0.45$;). On the contrary, the CON group showed significantly lower standard deviation from baseline to post practice but no changes in the coefficient of variation (SD: −26.32 ± 12.52, CI: [−50.87; −1.78], $p = 0.037$; COV: −1.47 ± 3.85, CI: [−9.01; 6.08], $p = 0.7$). There was a significant difference in SD between the CON and FC group in the observed changes from baseline to post practice. The CON group decreased SD significantly more than FC (FC-CON: −45.46 ± 17.71, CI: [−86.96; −3.96], $p = 0.031$). No significant differences were observed between PC and CON or PC and FC in the SD in error. There were no significant differences between groups in the observed changes in the COV from baseline to post practice when comparing the groups.

The assessment of movement variability calculated as SD and COV based on cursor endpoint in the position task demonstrated no significant change in the PC group following the practice session but a significant decrease in COV (SD: −12.17 ± 13.34 pixels, CI: [−38.32; 13.99], $p = 0.36$; COV: −4.61 ± 1.48, CI: [−7.51; −1.72], $p = 0.001$). In the FC group, there were no changes in either SD or COV (SD: 21.12 ± 13.81 pixels, CI: [−5.95; 48.18], p = 0.13; COV: 1.02 ± 1.53, CI: [−1.97; 4.02], $p = 0.5$). For the CON group, there was a significant decrease in SD and COV from baseline to post practice (SD: −37.76 ± 13.81 pixels, CI: [−64.83; −10.69], $p = 0.006$; COV: −3.7 ± 1.58, CI: [−6.81; −0.59], $p = 0.016$).

There was a significant difference between the CON and FC groups in the observed changes from baseline to post practice in SD. The CON group decreased SD significant more compared to FC from baseline to post practice (CON-FC: −58.87 ± 19.53, CI: [−104.63; −13.11], $p = 0.008$). No significant differences were observed between PC and CON or PC and FC. The PC group reduced COV more compared to the FC (PC-FC: −5.64 ± 2.12, CI: [−10.61; −0.66], $p = 0.024$). There were no significant differences between PC and CON or FC and CON in change from baseline to post practice.

3.3. Motor performance in the force task

Motor performance in the force task is depicted in Fig. 2B. There were no significant differences between groups in the force task performance at baseline in mean error or SD (pixels), FC (522.53 ± 185.94), PC (449.42 ± 261.76), and CON (479.36 ± 112.13) (range of p-values: 0.6–0.81).

The PC group did not change error significantly from baseline to post practice in the force task (−19.42 ± 25.58, CI: [−69.55; 30.71], $p = 0.45$) (Fig. 2D). In the FC group there was also no change in error from baseline to post force control practice (29.3 ± 23.28, CI: [−16.32; 74.92], $p = 0.21$) nor in the CON group (−44.55 ± 25.27, CI: [−94.07; 4.97], $p = 0.08$) (Fig. 2D).

Paired comparisons between groups did not reveal any differences between delta changes from baseline to post practice (PC-FC:

−48.72 ± 34.58, CI: [−129.77; 32.34], $p = 0.32$, FC-CON: −73.85 ± 34.35, CI: [−154.37; 6.66], $p = 0.09$, PC-CON: 25.14 ± 35.95, CI: [−59.13; 109.4], $p = 0.48$).

3.4. Error and endpoint variability in the force task

The assessment of performance variability in force level error SD and COV showed no change from baseline to post practice in the FC group (SD: 20.09 ± 27.12, CI: [−33.06; 73.24], $p = 0.46$; COV: −4.53 ± 4.13, CI: [−12.51; 3.56], $p = 0.27$) nor in the PC group (SD: 8.5 ± 29.39, CI: [−49.1; 66.1], $p = 0.77$; COV: −2.27 ± 4.43, CI: [−2.27; 10.95], $p = 0.61$). In the CON group a significant decrease in SD was observed from baseline to post practice with no significant change in COV (SD: −58.53 ± 29.48, CI: [−116.32; −0.75], $p = 0.047$, 1.54 ± 4.48, CI: [−7.25; 10.33], $p = 0.73$). There were no significant differences between groups in observed changes from baseline to post practice.

Considering force level endpoint variability, there were no significant changes in SD or COV from baseline to post practice in the FC group (SD: 9.5 ± 28.62, CI: [−46.59; 65.6], $p = 0.74$; COV: 6.36 ± 6.51, CI: [−6.4; 19.11], $p = 0.33$) nor in the PC group (SD: −37.3 ± 27.65, CI: [−91.49; 16.89], $p = 0.18$; COV: −5.51 ± 6.29, CI: [−17.84; 6.81], $p = 0.38$). The CON group also did not demonstrate changes in SD, but COV decreased significantly (SD: −33.5 ± 29.7, CI: [−91.71; 24.71], $p = 0.26$; COV: −14.89 ± 6.75, CI: [−28.12; −1.65], $p = 0.028$). There were no significant differences between groups in changes in SD or COV from baseline to post practice.

3.5. Change in performance for specific targets

In all three groups (PC, FC and CON) we tested change in error for the specific targets from baseline to post practice (see Fig. 3).

In the position task, the PC group demonstrated reduced errors from baseline to post practice for target 3 (−65.89 ± 27.03, CI: [−135.33; 3.54] $p = 0.04$), 4 (−183.59 ± 27.17, CI: [−253.39; −113.78], $p < 0.001$) and 5 (−240.14 ± 27. 17, CI: [−310.07; −170.21], $p < 0.001$) (Fig. 3A). There were no significant changes for specific targets in either the FC or CON groups (range of p-values: 0.12–1).

In the force task, the PC group did not demonstrate significant changes for any specific target from baseline to post practice ($p > 0.7$). In the FC group there was a significant increase in error for target 5 (178.17 ± 48.72, CI: [53.01; 303.33], $p = 0.001$) but no change at any other target ($p > 0.05$). In the CON group there were no significant changes at any of the targets ($p > 0.6$) (Fig. 3B). In addition to error for the specific targets illustrated in Fig. 3, we also calculated movement endpoint for all trials. These results are depicted in Fig. 4.

3.6. Differences in performance with and without augmented feedback

For the two intervention groups we additionally tested if there was a change in mean error between the baseline test (B0) and the first motor practice block (B1). We also tested if there was a change in error between the last motor practice block (B4) and the posttest block (B5). Since baseline and posttests were performed without augmented feedback and motor practice was performed with

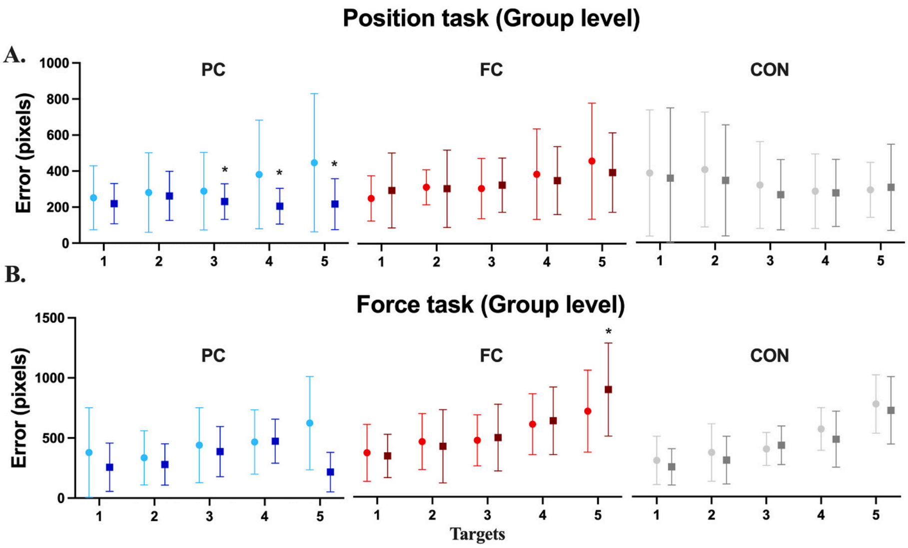

Fig. 3. Mean error for all specific targets at baseline and post practice. Panel A depicts the mean error and SD for the five targets in the position control task and panel B depicts the mean error and SD for the five targets in the force control task; PC (blue colours), FC (red colours) and CON (grey colours). * denotes a significant difference ($p < 0.05$) between baseline and post practice for the specific target. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

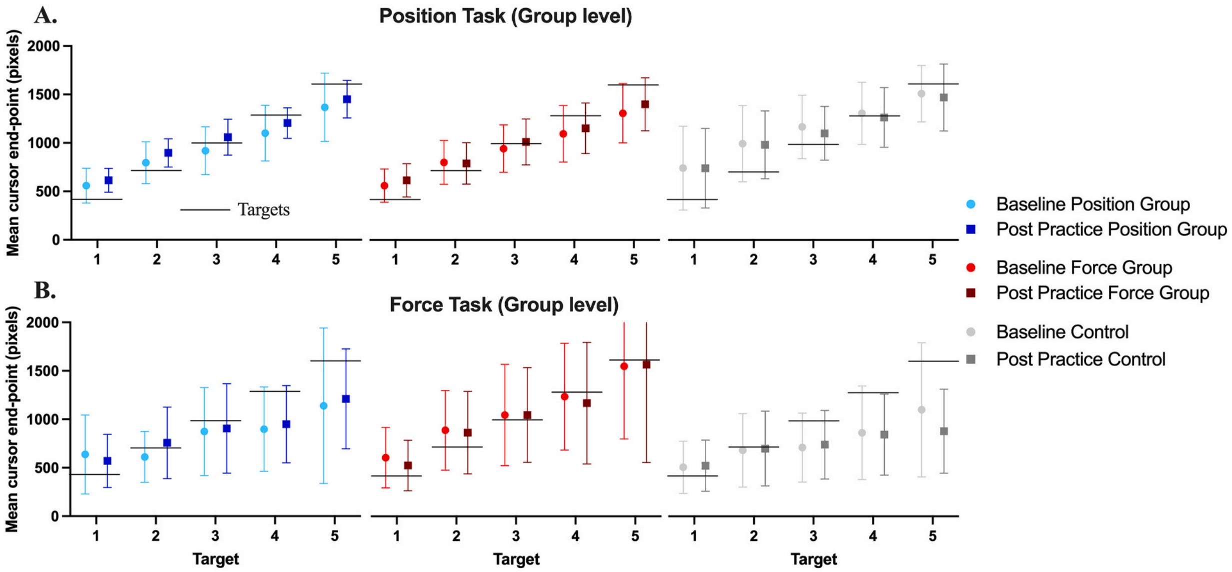

Fig. 4. Mean cursor endpoint and SD for all specific targets at baseline and post practice. Panel A depicts the mean endpoint and SD for the five targets in the position control task and panel B depicts the mean endpoint and SD for the five targets in the force control task; PC (blue colours), FC (red colours) and CON (grey colours). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

augmented feedback, these comparisons aimed to investigate effects of augmented feedback.

In the PC group we found a significant decrease in error between B0 to B1 (-143.57 ± 12.33, CI: [-171.1; -122.6], $p < 0.001$). The same comparison made between B4 and B5 in the position task (with and without augmented endpoint feedback) demonstrated a

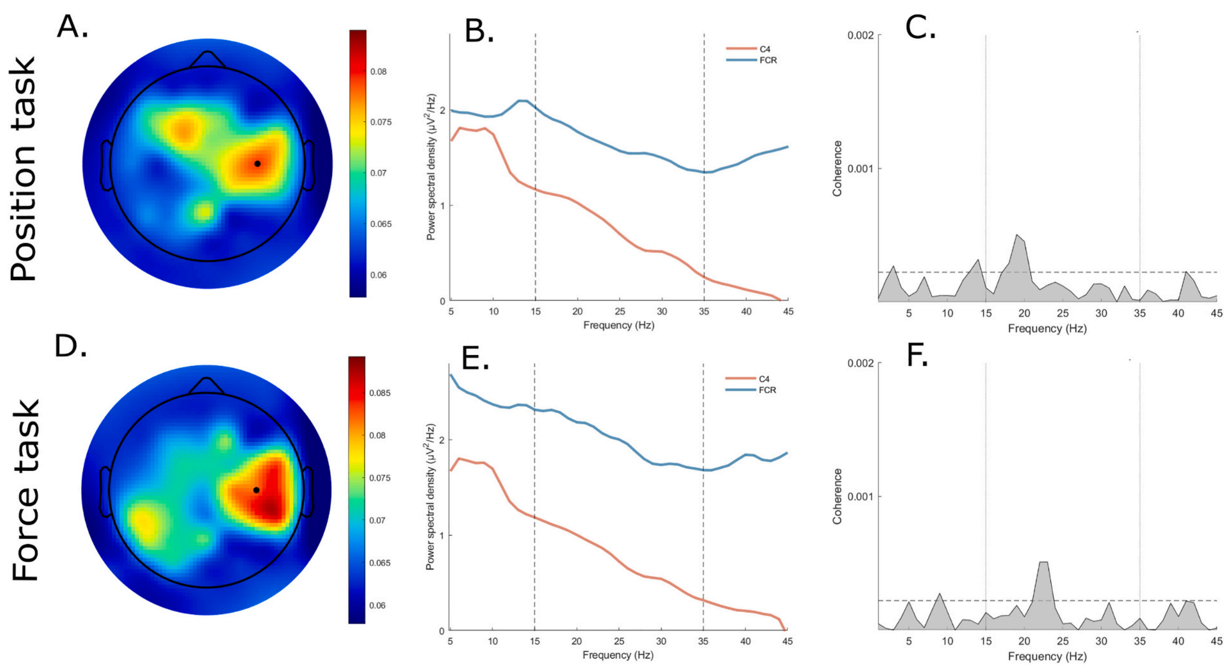

Fig. 5. Corticomuscular coherence and spectral density at baseline in hold phase of the position-control task and the force-control task. Panels A and D depict headplots i.e. the spatial localization of summed beta band (15–35 Hz) corticomuscular coherence across all participants during the hold phase of the position task (A) and the force task (D). In both panels, the C4 EEG electrode is highlighted. Panels B and E depict power spectral density for the FCR EMG (blue) and C4 EEG during the hold phase of the two tasks. Panels C and F depict pooled corticomuscular coherence plots for C4-FCR EMG during the hold phase of the position task (C) and the force task (F). The horizontal dashed line denotes the criterium for significant coherence (i.e. $p < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

significant increase in error (38.28 ± 12.46, CI: [13.86; 62.7], $p = 0.002$) in the practiced task. In the FC group we found a significant decrease in error from B0 to B1 (−182.82 ± 22.97, CI: [−227.83; −137.81], $p < 0.001$). When comparing B4 to B5 in the force task there was also a significant increase in error (148.09 ± 22.96, CI: [−103.08; −193.1], $p < 0.001$). When comparing the observed changes between the PC and FC group, the changes B0–B1 ($p < 0.001$) and B4–B5 ($p < 0.001$) were significantly larger in the FC group.

3.7. Effect of task order on performance

The test order performed at baseline and post practice was counterbalanced within all three groups. Planned comparisons demonstrated an effect of baseline test order in the position task. Participants who performed the force task first and secondly the position task demonstrated lower error in the position task compared to those who started with the position task (Position task after Force task contra Force task after Position task: 74.21 ± 20.03, CI: [34.95; 113.47], $p < 0.001$). For the force task, planned comparisons showed no effect of task order at baseline (Force task after Position task contra Force task before Position task: 30.41 ± 36.71, CI: [−41.52; 102.28], $p = 0.41$). Post practice none of the groups demonstrated order effects in the position task (range of p-values: 0.98–0.29) nor in the force task (range of p-values: 0.28–0.94).

3.8. Corticomuscular coherence

At baseline, corticomuscular coherence pooled across all participants demonstrated significant but low coherence peaks (0.0005) within the beta frequency range 15–35 Hz for the hold phase of both the position task and the force task (Fig. 5C and F). The extended X^2-test demonstrated equal amounts of coherence in the position-control task and force-control task at baseline.

Pooled coherence for each group at baseline and post-practice was consistently low in the position and force-control tasks (coherence ranging from 0 to 0.0016) (Fig. 6A–F). The X^2 test demonstrated no significant differences between baseline and post practice in any of the three groups for either the position-control task or the force-control task.

4. Discussion

4.1. Dynamic motor practice leads to improved movement accuracy while isometric motor practice is not accompanied by improved force control in preadolescent children

We found that dynamic motor practice with emphasis on position control led to improvements in performance in the position task, and the preadolescent children who practiced the position task displayed smaller movement errors measured across all five targets following motor practice. This result is in agreement with our recent findings in young adult participants (Norup et al., 2023).

When practicing the dynamic task with emphasis on position control, the available sensory information relates to changes in the

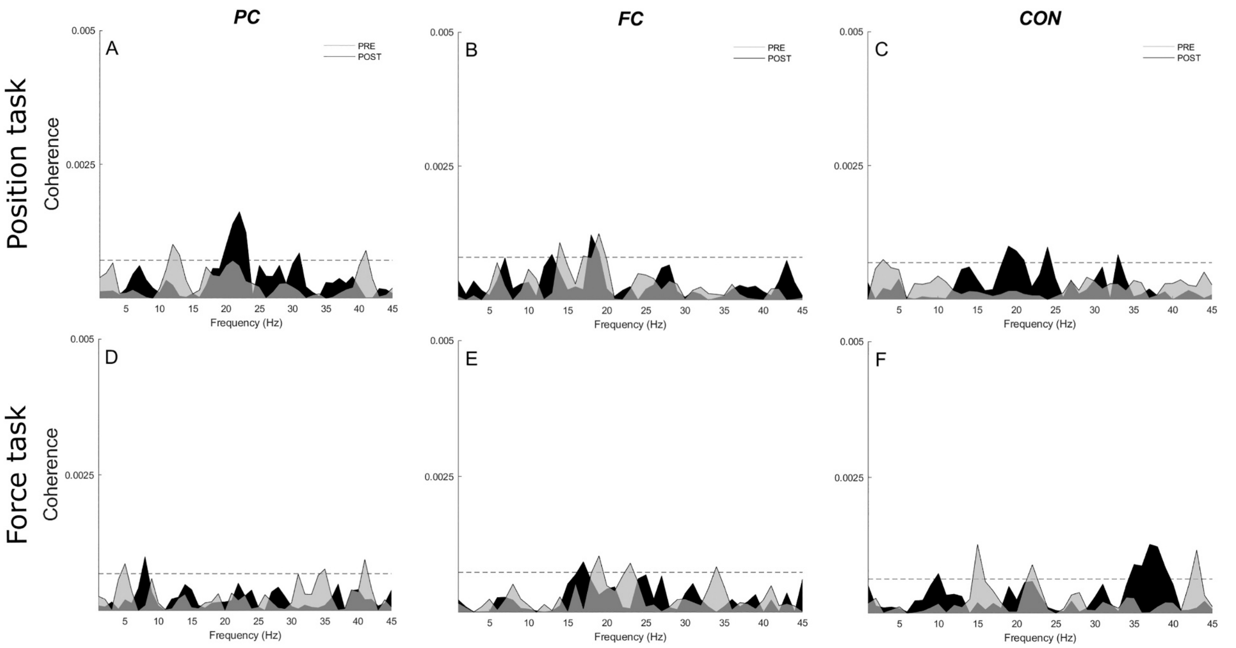

Fig. 6. Pooled corticomuscular coherence for the three groups at baseline and post practice. Pooled coherence estimates between C4 EEG and FCR EMG for baseline (light grey areas) and post-practice (black areas) in each group during the position control task (A,B,C) and the force control task (D,E,F). The horizontal dashed line in each panel denotes the criterium for significant coherence (i.e. $p < 0.05$).

wrist joint and this proprioceptive information is added to the intrinsic sensory information originating from muscle spindles and Golgi apparatus about changes in muscle length and forces and to cutaneous inputs. This means that rich intrinsic sensory information is available during dynamic movements. Although in the present study participants did not have online visual feedback, they did receive augmented feedback on endpoint position. Although in adult participants, Lauber, Keller, Leukel, Gollhofer, and Taube (2013) previously demonstrated that motor cortical activity increases when participants are provided feedback on joint position (Lauber et al., 2013) and we have recently found that position control motor practice leads to increased corticospinal excitability compared to isometric motor practice (Norup et al., 2023). In the present study, we show that also preadolescent children are able to learn a new dynamic motor skill and improve position control when relying on intrinsic feedback and augmented feedback on movement endpoint position (Sharma, Faisal Chevidikunnan, Rahman Khan, & Allah Gaowgzeh, 2016). Milner and Hinder (2006) have suggested that the CNS uses position error rather than force error information when adapting to changes in environmental dynamics (Milner & Hinder, 2006).

In contrast to dynamic motor practice, isometric motor practice with emphasis on force control was not accompanied by improved force control in preadolescent children. This finding is different from our recent finding in young adult participants who demonstrated improved force control in an identical paradigm (Norup et al., 2023). This lack of change in force control is evident from the practice session (Fig. 2) and the result is surprising as it has previously been shown that children improve their performance following motor practice (Sullivan et al., 2008). On the other hand, improvements accompanying motor learning in children have been observed primarily as offline effects (Ashtamker & Karni, 2013) (Krakauer et al., 2019; Reber, 1989) and children may need an offline consolidation period following practice for improving isometric force control (Du, Valentini, Kim, Whitall, & Clark, 2017; Robertson, 2005). The present study only involves assessment of immediate and not delayed retention effects, but the results demonstrate that in contrast to adult participants, preadolescent children do not improve force control following isometric motor practice.

Another reason that we did not find an effect of the isometric practice in this study could be that children need more feedback during such motor practice paradigms, which is supported by earlier studies investigating visuomotor practice and demonstrating increased performance following isometric motor practice (de Havas et al., 2022; Perez et al., 2006; Reis et al., 2009). The task was scaled to each participant individually based on their maximal voluntary contraction force during wrist flexion and the task included targets at 5–25% of the MVC and no visual feedback during the tests and only end point feedback during motor practice. While identical feedback conditions applied to the position control task, we speculate that the demands of the force task involving less rich intrinsic feedback and no augmented feedback during tests may have been too high for this age group. The target order during practice was random which gives the learner an opportunity to engage more cognitively compared to blocked practice (Kantak & Winstein, 2012). Random order practice promotes inter-task comparison while blocked practice promotes the possibility to reuse the previously constructed action plan. With random order the learner must continuously reconstruct the action plan, which requires more cognitive resources (Kantak & Winstein, 2012). While these conditions apply to both the dynamic and isometric task, and the results demonstrate positive effects of dynamic motor practice, we nevertheless speculate that the requirements may have been too high for the participants in the force task and in the force control group. Sullivan et al. (2008) found that children were more dependent on augmented feedback to improve task performance compared to young adults (Sullivan et al., 2008). In the present protocol, the participants could not see their hand and augmented feedback was only provided as endpoint feedback at the completion of each trial during motor practice blocks. This is different from previous studies in which visual feedback has been provided continuously and thus allowed online visuomotor tracking. De Havas and colleagues have described knowledge of result as guiding a cognitive strategy when engaging in motor learning (de Havas et al., 2022). They showed that restricted visual feedback facilitated use of cognitive control strategies. The present paradigm involving restricted visual feedback may have been too challenging in particular for isometric force control motor practice. Nevertheless, the results demonstrate that preadolescent children are able to improve movement accuracy with dynamic motor practice but not force control with isometric motor practice.

Besides mean errors across all targets, we also investigated effects of motor practice on performance for specific targets (1–5) i.e., 15, 30, 45, 60 and 75° movements in the position task and 5, 10, 15 and 25% of MVC in the force task. We found that position control practice led to improved performance at target 3, 4 and 5 in the position control task. We recently observed that this motor practice paradigm led to improved performance for all targets in young adult participants. Following force control motor practice, the only difference was increased error for target 5 in the force task, no other changes were observed. This is also in contrast to results from young adults, who demonstrated decreased error for target 4 and 5 (Norup et al., 2023). Thus, the present results demonstrate that preadolescent children display specific improvements only following position control motor practice and only for the three targets which required the largest movements.

4.2. Changes in variability with motor practice

In the present study we measured variability as standard deviation (SD) and coefficient of variation (COV) of distance to target (error) and endpoint. Following position control motor practice, we found no significant changes in error SD and significantly increased COV. COV illustrates the extent of variation relative to the mean and the observed increase in COV following position control motor practice is thus explained by lower mean error but no change in SD. For movement endpoint variability a decreased COV was found, but SD was unchanged after training. In other words, decreased movement variability was not essential for the improvements in motor performance observed following position control motor practice. Wiegel, Spedden, Ramsenthaler, Beck, and Lundbye-Jensen (2022) recently demonstrated that during motor practice, trial-to-trial variability is modulated and influenced in particular by recent behavioral success. While reduced variability accompanied improved movement accuracy following motor practice in adults, this was seemingly not the case in preadolescent children. Previous studies have demonstrated higher movement variability in children compared to adults (Deutsch & Newell, 2005) which may related to differences in the sensorimotor control processes and task-related factors such as feedback characteristics (Deutsch & Newell, 2005; Sullivan et al., 2008). It should however be taken into account, that in the present study, behavioral variability was assessed not during but prior to and following motor practice and in trials without augmented feedback on performance.

Although we would expect some variability due to differences in task conditions and to noise in the neuronal structures that generate motor commands (Sternad, 2018), we still expected reduced variability in the position task following position practice and in the force task following force practice. The FC group did, however, not display changes in SD or COV. It is noteworthy however, that the CON group demonstrated a decrease in SD from baseline to post for both error and endpoint in the position task and a decrease in SD of error supplemented by a decrease in endpoint COV for the force task. This finding of reduced error and end point variability for both tasks in the control group is interesting because it indicates that repeated test procedures of position and force control leads to reduced variability in motor performance in preadolescent children. Since these changes were not observed in the intervention groups, it may suggest that the motor practice paradigms including augmented feedback could have introduced specific behavioral effects which overrule the reduced variability, which was observed in the CON group. Earlier studies have demonstrated that reducing the level of augmented feedback can lead to overshooting or undershooting of the force and position during motor skill tasks and this could cause increased variability compared to that observed when augmented feedback is provided (Ilic, Corcos, Gottlieb, Latash, & Jaric, 1996). This could have been the case for children in the two intervention groups. It is nevertheless noteworthy that variability decreased in the preadolescent control group with repeated testing of position and force control.

4.3. No between-task transfer effects in preadolescent children

When investigating effects of the two types of motor practice on performance in the other task i.e. between-task transfer, we found no effects of position control motor practice on force control or vice versa. We have recently found that adult participants display positive transfer effects from dynamic position control practice to force control (Norup et al., 2023). Although other types of transfer effects following motor practice have been investigated in young adults (Lauber et al., 2013), it has to our knowledge not previously been investigated in children if practicing a dynamic task benefits force control or vice versa. We hypothesized that such transfer effects would be smaller in children based on the finding that other transfer effects e.g. interlimb transfer are facilitated by use of a cognitive strategy in adults (de Havas et al., 2022). Since adults and late adolescents display greater use of top-down and executive control processes during motor task performance compared to children this could lead to lower task flexibility in children compared to adults (Beck, Spedden, Dietz, et al., 2021; Beck, Spedden, & Lundbye-Jensen, 2021). While the tasks were identical in the present study and the previous study in adult participants, it may also be possible that the relative task difficulty has been higher for the preadolescent children, and that this may have limited the potential transfer effects.

4.4. Effects of augmented visual feedback during motor practice

To investigate the effects of augmented visual feedback during task execution we compared baseline performance to performance in the first block of practice. We saw that the performance improved significantly when the tasks were performed with augmented visual endpoint feedback. In addition to augmented feedback, this positive effect can be attributed to initial learning effects from the first 40 trials to the next 40 trials.

When comparing performance in the fourth practice block to the post test condition without augmented feedback we found a significant increase in error in both intervention groups. This indicates that removal of the augmented feedback caused a drop in performance for both the PC and FC groups. The results demonstrate that children perform better when augmented feedback is provided meaning that they utilize the information inherent in the augmented feedback to guide their motor behavior and/or that the augmented feedback influences motor performance through an effect on motivation. The effect of provision and removal of augmented feedback was larger in the force task compared to the position task. This demonstrates, that augmented feedback had a larger effect on performance in the force task, potentially due to a higher relative task difficulty. It is noteworthy that which indicates that could indicate the CON group showed decreased variability in the post tests contrary to the motor practice groups. This could indicate an interference effect in the motor practice groups potentially caused by the transition from motor practice with augmented feedback to tests without augmented feedback.

4.5. Preadolescent children display corticomuscular coherence during position and force control but coherence is unchanged after motor practice

The results demonstrate that during the hold-phase of both the position-control and force control tasks, the preadolescent children display low but significant corticomuscular coherence in the beta band with no significant difference between tasks. The finding of weak corticomuscular coherence in preadolescent children is in line with previous studies investigating age-related differences in participants aged 7–30y. These studies found stronger corticomuscular and intermuscular coherence with increasing age (Beck, Spedden, & Lundbye-Jensen, 2021; Petersen, Kliim-Due, Farmer, & Nielsen, 2010; Spedden et al., 2019). Nevertheless, our results showed peak values of corticomuscular coherence in the lower range of the spectrum compared to previous reports (James, Halliday, Stephens, & Farmer, 2008). Our primary aim was however to investigate effects of motor practice in preadolescent children. Our results showed no significant changes in corticomuscular coherence following neither position or force control motor practice, which is at odds with previous results in adult participants demonstrating increased corticomuscular and intermuscular coherence following short-term motor practice (Larsen et al., 2016; Perez et al., 2006). While Perez et al. (2006) assessed coherence during 2 min. Tonic contractions, Larsen et al. (2016) assessed coherence during the steady-state hold-phase of repeated ramp and hold contractions. This corresponds to the present experiment in many ways since this protocol also involved repeated ramp and hold contractions for each motor paradigm and coherence was analyzed during the hold-phase. The only notable difference was that participants in the present experiment did not have online visual feedback during the hold-phase, which may have caused some variability, that could lead to lower coherence.

While the FC group did not improve performance from baseline to post practice, this could explain the lack of change in corticomuscular coherence following practice. The PC group did improve position control with motor practice, but nevertheless no difference was found in corticomuscular coherence from baseline to post-practice. These findings indicate that although short-term motor practice can lead to improved motor control in preadolescent children, these changes are not accompanied by increased strength of the functional corticomuscular coupling. This contrasts with what has previously been observed in adult participants and it may indicate that preadolescent children display different learning mechanisms compared to older adults or that more practice is necessary in order to induce corresponding behavioral changes and changes in the functional coupling between the cerebral cortex and the motoneuron pools of the contracting muscles (Suzuki & Ushiyama, 2020). These questions may be addressed in future studies.

4.6. Limitations

We acknowledge that the study has limitations. During baseline and posttest conditions the participants did not receive augmented feedback. This was in contrast to the motor practice where the participants received endpoint feedback following each trial. This decision was made in order to assess genuine changes in position control and force control respectively and to rule out effects of visual, augmented feedback during baseline and post assessments. Although all participants were familiarized to the tasks before each test, this design does however carry the risk that the participants could forget required target levels or lose motivation in the absence of augmented feedback, which they experienced during motor practice. Indeed, for both motor practice paradigms, the results demonstrated increased error between the end of motor practice and post test performance i.e. when augmented feedback was removed.

Furthermore, all participants performed both motor tasks at baseline and post motor practice to assess potential transfer effects. Because of this, the test order was counterbalanced within all three groups. This means that for half of the participants in the motor practice groups, the first post test would be in the task they did not practice. Although we did not observe any order effects for post test performance in the motor practice groups, it is noteworthy that the CON group showed decreased variability at posttest conditions compared to the two motor practice groups. This could indicate an interference effect in the motor practice groups potentially caused by the transition from motor practice with augmented feedback to tests without augmented feedback since the CON group cannot have experienced this effect. Finally, it should be acknowledged that the results of the present study are based on the non-dominant hand. We therefore cannot conclude on potential effects for the dominant hand.

5. Conclusion

The results demonstrate that children who practice position control improve performance from baseline to post practice. Furthermore, their movements become more accurate for specific targets. To our surprise, motor practice with emphasis on force control was not accompanied by improvements in force control. While recent experiments have demonstrated that position control motor practice can improve force control in young adult participants, this effect was not observed in preadolescent children i.e., there was no between-task transfer. In agreement with our hypothesis, we found significant corticomuscular coherence during the hold phase of both the position and force control task. However, corticomuscular coherence did not change following motor practice as it has been observed in young adults.

In conclusion, children seem to benefit from learning based on position control rather than force control. Furthermore, the dynamics of learning are different from those observed in young adults, and this is also the case for the corticospinal mechanisms including oscillatory functional coupling, which may underly motor learning. Despite the extensive literature on motor practice, there is a paucity of literature investigating effects of distinct motor practice paradigms and feedback domains in children. The seeming importance of both intrinsic and augmented feedback is noteworthy and future studies should explore the neurophysiological mechanisms underlying motor learning in children further.

Author contributions

MN, PW & JLJ planned the experiments PW & JLJ established the computerized task setup. MN, JRB & ALN performed the experiments. MN, JRB, MES & ALN analyzed the data. MN and JLJ wrote the initial draft of the manuscript. All authors contributed to writing the final version of the manuscript.

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Data availability

Data will be made available on request.

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