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Original Article

Methods for evaluating motor control functions for the development of teaching materials for creating diverse movements: evaluation index for motor control function

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Abstract:
Problem Statement: Basic movement is acquired during infancy and childhood, so a variety of movement experiences are necessary during this period. In physical education classes, observational evaluation methods are used to assess a child's acquisition of movement. This method evaluates a series of movement points based on objective indicators. However, this method only evaluates the resulting external movements and the internal cognitive aspects of motor function is not assessed. When evaluating movement, it is necessary to perform both internal and external evaluations. Approach: This study examined a method for evaluating body movements from a functional perspective. The corticomuscular coherence (CMC) and intramuscular/intermuscular coherence (IMC) methods were used to evaluate the brain and nervous system, which are the basis of body movement. Purpose: This review summarizes studies that have used these evaluation methods, focusing on the examination of age-related changes. Results: CMC and performance were related, with higher CMC leading to better performance and age-related changes. The IMC showed results similar to those of the CMC, with a tendency to decrease with age and increase with development. This indicates that IMC can be used to evaluate neural function. However, since CMC evaluates neural connections between the brain and muscle and IMC evaluates neural connections between muscle and muscle, they are not exactly the same, but both are considered indicators of neural connections. Conclusions: Children can be evaluated using the IMC method, which is simple and versatile for evaluating body movements from a functional perspective. By presenting this evaluation index, we believe that it is possible to understand children's movement development from an internal perspective and show the development of movement through a child's diverse movement experiences. Thus, we believe that it can be used as an evaluation index for the development of exercise programs.
Key Words: **children, motor development, motor control function, evaluation methods, coherence**

Introduction

In recent years, it has been reported that children's physical activity has decreased in Japan, as changes in the social and natural environment have reduced the number of playgrounds and opportunities for exercise (Senda, 2007). Based on this current situation, childhood obesity is a serious challenge due to decreased physical activity. Childhood obesity is associated with obesity during adulthood (Oya et al., 2015). In other words, childhood obesity increases the risk of developing lifestyle-related diseases in adulthood and beyond. Furthermore, a decrease in physical activity decreases the opportunities to acquire movement during play and daily routines. Takai (2007) stated that "the adverse effects associated with the lack of experience in aspects such as lifestyle, social skills, and physical fitness, which were previously taken for granted, cannot be ignored, and active guidance is needed at the school education stage." Therefore, it is necessary to emphasize the development of physical fitness and motor skills through physical education. In tests of physical fitness and motor skills for children, records of "ball throwing," which is used as to evaluate skillful movement, continue to decline (Ministry of Education, Culture, Sports, Science and Technology, 2022). The development of movement was delayed compared to the past, based on movement assessment. Children who lack skillful movement abilities may exhibit issues, such as being conspicuous, stumbling, falling, and struggling to land properly when they fall down (Ministry of Education, Culture, Sports, Science and Technology, 2012). Gallahue (1999) showed that acquiring basic movements in childhood leads to more sophisticated movements in childhood and beyond.

For this reason, it is important for children to acquire basic movement skills during their early childhood and school years, and it is necessary to implement physical education classes in elementary schools and exercise play in kindergartens to provide opportunities for a variety of movement experiences. The effectiveness of these physical education classes and exercise play can be evaluated through the transformation of children's movements. A series of movements, such as running, jumping, and throwing, were objectively evaluated by an observer based on the points of each movement (Nakamura et al., 2011; Akkus et al., 2019).

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This assessment method has also been used as an indicator of children's movement development in the context of physical education classes in Japan (Matsukawa et al., 2013; Chin and Ikeda, 2014; Nanazawa et al., 2014; Hariya et al., 2017; Takizawa et al., 2017; Murai et al., 2021). This is a simple and versatile evaluation method that evaluates an index based on the perspective of observation. Another method for evaluating movement is based on image analysis of the angle and trajectory of the joints of the body (Chen et al., 2010; Kawashima et al., 2020; Yoshimi et al., 2021), which is a more objective method of evaluating movement. However, these methods primarily focus on evaluating the externally expressed aspects of movement, and may not capture internal events comprehensively.

The human body moves through neurotransmission of motor commands issued by the brain. When the body is moved, motor command information is generated in the association cortex (prefrontal cortex) of the cerebral cortex (brain) and transmitted as electrical signals to the cerebral motor cortex, spinal cord, and muscles, resulting in muscle contraction. Therefore, the foundation of physical movement lies in the brain and cranial nervous system, which transmit information between the brain and the rest of the body, including the spinal cord (Kitajo et al., 1998). In other words, when evaluating a child's movement skills, it is necessary to focus not only on the movement itself but also on the internal aspects of the body. Scammon (1927) showed that neurotypical development is evident by the age of 10 years, and we believe that it is necessary to evaluate the development of the brain and nervous system, which is the basis of physical movement, through physical activity, and that this nervous system evaluation can assess the skillfulness of physical movement.

An evaluation method called cortico-muscular coherence (CMC) has been developed to assess the function of the central nervous system. This method evaluates the coherence between electrical signals and rates it between 0 and 1, indicating neural activity of the brain and muscle in the β-frequency band of 13–35 Hz during voluntary contraction of the muscle (Halliday et al., 1995). Synchrony between two electrical signals indicates neural coupling between the cortex and motor neurons (Farmer et al., 1993; Conway et al., 1995). Therefore, this method has been used to assess the motor control function. Furthermore, intermuscular coherence and intra-muscular coherence (IMC), which is based on the analysis of the synchrony of signals from motor neurons to motor neuron neural activity, indicates motor neuron-to-motor neuron neural coupling. IMC show similar results to CMC and are considered related (Grosse et al., 2002).

As this method can be measured using only surface electromyography, the use of wireless electromyography minimizes behavioral restrictions and can be applied in the field. Farmer et al. (2007) showed that age variation in Inter-muscular coherence (Inter-MC) of the hand increased with age. The difference is particularly pronounced between children aged 4–6, 7–9 and 12–14 years. In addition, Petersen et al. (2010) found significantly higher intra-muscular coherence (Intra-MC) in the lower leg during walking at ages 7–9, 10–12, and 13–15 years compared to 4–6 years across age groups. However, there are only a few reports on children, and there is insufficient data on the development of the nervous system using CMC and IMC.

Therefore, the purpose of this study was to organize the reports using the CMC and IMC evaluation methods as a coherent set of age changes and subject characteristics and to show the possibility that this evaluation index can be applied as an index to evaluate nervous system development and during exercise in children.

Material and methods

*Collection of article*s

This study targeted academic papers using the coherence method, which has been shown to be useful in evaluating motor control functions. The target articles were collected and selected using the following method. Articles were collected using PubMed, an article search service for medical journals. Coherence methods search terms included "cortico-muscular coherence (CMC)," which is evaluated based on brain-muscle synchrony; "intermuscular coherence (Inter-MC)," which is evaluated based on synchrony between different muscles; and "intramuscular coherence (Intra-MC)," which is evaluated based on synchrony between the same muscle. Data were collected on August 19, 2022. The search identified 323 articles on "cortico-muscular coherence," 119 articles on "intermuscular coherence", and 83 articles on "intramuscular coherence".

Selection of articles

Among the articles identified, 103 references were found for "cortico-muscular coherence," 46 for "intermuscular coherence," and 32 for "intramuscular coherence." We extracted literature aimed at evaluating motor control functions related to physical movements and selected articles that used the muscles of the extremities as measurement sites.

Results and Discussion

Cortico-muscular coherence (CMC)

Table 1 summarizes the results of the studies on CMC, showing the CMC method as an evaluation index for healthy adults, the elderly, and children. In healthy adults, Safri et al. (2007; a1) showed that β-band (13–30 Hz) CMC increased when visual stimulation was applied during hand muscle contraction, indicating that visual stimulation during muscle activity affects the function of strengthening neural connections between the brain and muscle. It has been shown that the CMC varies depending on the manner of muscle activity, with the β-band (15–30 Hz) CMC increasing as the force level of muscle exertion increases (Chakarov et al., 2009; a3). In squatting movements, the CMC is higher during eccentric and concentric contractions than during isometric contractions (Kenville et al., 2020a; a8). During a walking exercise, higher CMCs in the high β-band (21–30 Hz) were shown in ground walking compared to treadmill walking (Roeder et al., 2018; a7), indicating that the same gait has different effects on neural control depending on the walking style. In contrast, Lunbye-Jensen and Nielsen (2008; a2) showed that CMC in the β-band (15–35 Hz) is decreased by muscle inactivity due to fixation. However, when the fixation was subsequently released, the CMC returned to normal when similar measurements were performed 1 week later, indicating that changes in neuroplasticity occur with physical activity habits. Larsen et al. (2016; a6) also showed an increase in CMC in the β-band (15–30 Hz) after an intervention with hand training, indicating changes in the neural connections in the cortical muscles.

These findings indicate that physical activity causes changes in corticomuscular neural coupling, especially during movements with high eccentric or concentric contractions, using the CMC method index. However, Murnaghan et al. (2014; a4) found no change in CMC with or without postural sway, suggesting that there is no association between brain and muscle coupling and postural maintenance. In a comparison of β-band (15–35 Hz) CMC in athletes, Ushiyama et al. (2010; a9) showed that weightlifters and ballet athletes had lower CMC than non-athletes, especially in the lower leg muscles. Vries et al. (2016; a5) showed that the lower the motor coordination, the lower the CMC, suggesting that the body's muscle activity influences the CMC. It has been hypothesized that CMC is influenced by muscular activity in the body.

In studies examining the effects of aging on brain-muscle neural coupling from the perspective of isometric contraction movements, Kamp et al. (2013; a11) found that the CMC peak, Bayram et al. (2015; a12) found that the CMC average, and Spedden et al. (2018; a14) found that CMC integral ratings were lower in older subjects. It has also been reported to be lower during bottom dorsiflexion exercise (Yoshida et al., 2017; a13) and walking exercises (Roeder et al., 2020; a15) in elderly individuals. On the other hand, it has been shown that β-band (15–32 Hz) CMC peaks are higher in the elderly during isometric exercise (Jonson & Shinohara, 2012; a10), and that CMC peaks do not change according to age during walking exercises (Yokoyama et al., 2020; a17). Although it has been shown that CMC may decrease or increase with aging, since physical activity affects neural connectivity, and Ushiyama et al. (2010; a9) showed that CMC is higher in people without exercise habits; moreover, it is likely that CMC will differ among the same healthy elderly people depending on whether they have exercise habits or not and on their physical activity.

The CMC is thought to differ among healthy elderly people depending on their exercise habits and physical activity. These factors likely influenced the higher and lower CMC observed in some cases. In the future, it will be necessary to examine changes in neural connections with age, taking physical activity into consideration. In addition, regarding visual feedback adjustment, it has been shown that the CMC increases only in the elderly as the range of the magnitude of the force of adjustment to the visual line increases (Watanabe et al., 2020; a16).

This was not observed in younger participants, which may indicate an age-related effect on task performance. It is a known fact that motor function decreases with age. However, it is not clear how this decline is related to changes in brain and nervous system functions. Further studies are needed to examine age-related changes in neural connections in the corticospinal tract. In reports on children, CMC peaks are lower in children than in adults (Garaziadio et al., 2010; a18), and Beck et al. (2021; a20) showed that, in the descending neural drive, adults have a higher CMC than children. It can be inferred that neural oscillation from the cortex to muscle are weaker in children and are still developing.

It also shows a strong positive correlation with age in the β-band (15–35 Hz) CMC area (Spedden et al., 2019; a19), suggesting that neural connections become stronger as age increases and development progresses. Ritterband-Rosenbaum et al. (2016; a21) examined infants aged 1–66 weeks and divided them into 1–8 weeks, 9–25 weeks, and >25 weeks age groups, and reported a significantly higher β-band (20–40 Hz) CMC area in infants aged 9–25 weeks compared to other infants.

Scammon (1927) showed that neurotypical development is prominent up to approximately 10 years of age and that further age-specific changes are required to characterize development at different ages and time points. In order to show the developmental characteristics of the cortex and nervous system, it may be possible to show the developmental process of neural connections by looking at more detailed age-specific changes in the cortex and nervous system.

Relationship between CMC and performance

We believe it is necessary to demonstrate how the increase in CMC actually affects the actual behavior as a result of physical movement by the increase in CMC, along with the performance results. Jonson and Shinohara (2012; a10) demonstrated a negative correlation between errors in force adjustment and β coherence during hand muscle exertion in adults.

Table 1 Previous studies assessing neural function using cortico-muscular coherence methods

No	Reference	Participant	Coherence	Task	Result
a1	Safri et al., 2007	adult 20–24 years (10)	EEG-EMG(FDI)	Visual stimulation present during isometric contraction of pinching motion	β (13–35 Hz) band CMC increases by visual stimulation
a2	Lundbye-Jensen et al., 2008	adult 24±6 years （M6, F4）	EEG-EMG(FCR) EEG-EMG(APB)	Cast immobilization along the forearm from the proximal point of the forearm Remove the fixation after one week.	β (15–35 Hz) band CMC decreases immediately after unfixing One week after infixation CMC returns to pre-fixation
a3	Chakarov et al., 2009	adult 23.8±3.1 years （F7）	EEG-EMG(FDI)	Isometric contraction to the line of force levels MVC 8%, 16%, and 24% MVC	β (15–30 Hz) band CMC increases with the force of muscle exertion
a4	Murnaghan et al., 2014	adult 23.8±3.9 years （F7）	EEG-EMG(LG) EEG-EMG(MG) EEG-EMG(SOL)	Maintaining standing posture during floor stability and instability	No change in CMC with or without limitation of postural oscillations
a5	Vries et al., 2016	adult 25.5±4.3 years （M4, F8）	EEG-EMG(R-FPB) EEG-EMG(L-FPB) EMG(R-FPB)-EMG(L-FPB)	Force adjustment by visual feedback through coordinated movements of both hands	Negative correlation between RV and CMC correlation Positive correlation between RV and CMC α band (5–12 Hz) IMC increases with bimanual coordination
a6	Larsen et al., 2016	adult 21–29 years （F16）	EEG-EMG(APB) EEG-EMG(FDI) EMG(APB)-EMG(FDI)	Test: Isometric contraction force adjustment by visual task Intervention exercise: training to perform a task by application that captures a target at the fingertips	β (15–30 Hz) band CMC and IMC increased after intervention Improved test scores
a7	Roeder et al., 2018	adult 25.9±3.2 years （M12, F12）	EEG-EMG(R-TA) EEG-EMG(L-TA)	Ground walking and treadmill walking	β (21–30 Hz) band CMC increased during ground walking compared to treadmill walking
a8	Kenville et al., 2020a	adult 27.9±5.1 years (M11)	EEG-EMG(R-VL) EEG-EMG(L-VL) EEG-EMG(R-VM) EEG-EMG(L-VM) EEG-EMG(R-TA) EEG-EMG(L-TA) EEG-EMG(R-ES) EEG-EMG(L-ES)	Squatting movement (eccentric, isometric, concentric contraction pattern)	eccentric and concentric contractions significantly greater than isometric contractions
a9	Ushiyama et al., 2010	untrained 21–31 years (M12, F12) ballet dancer 19–29 years (F12) weightlifter 19–22 years (M10)	EEG-EMG(FDI) EEG-EMG(FCR) EEG-EMG(ECR) EEG-EMG(BB) EEG-EMG(TB) EEG-EMG(SOL) EEG-EMG(TA) EEG-EMG(BF) EEG-EMG(RF)	Isometric contraction movement	Athletes have lower β (15–35 Hz) band CMC than non-athletes, especially in lower extremity muscles
a10	Jonson et al., 2012	adult 18–38 years (M6 F10) old 61–75 years (M6 F7)	EEG-EMG(FDI)	Isometric contraction movements of the fingers with visual feedback	The elderly have higher α (8–14 Hz) band and β (15–32 Hz) band CMC Negative correlation between muscle output error and beta coherence only in younger subjects
a11	Kamp et al., 2013	adult 22–77 years （27）	MEG-EMG(EDC)	Abduction movement of human stabbing finger by visual feedback	CMC peak decreases with age
a12	Bayram et al., 2015	adult 22.60±0.90 years (M10, F10) old 74.96±1.32 years (M8 F20)	EEG-EMG(BB) EEG-EMG(BR) EEG-EMG(TB)	Elbow flexion isometric contraction at MVC 20%, 50%, and 80% force levels	Elderly have lower β (15–35 Hz) band CMC than adults
a13	Yoshida et al., 2017	adult 27±7 years (M15) old 66±7 years (M9)	EEG-EMG(R-TA) EEG-EMG(R-MG) EEG-EMG(L-TA) EEG-EMG(L-MG)	Alternating dorsiflexion and plantar flexion of the ankle	Elderly have lower CMC than adults
a14	Spedden et al., 2018	adult 20–26 years (M7 F8) old 65–73 years (M7 F8)	EEG-EMG (TAp) EEG-EMG (TAd) EEG-EMG (SOL) EEG-EMG (MG) EMG (TAp) -EMG (TAd) EMG (SOL) -EMG (MG)	Ankle dorsiflexion-base flexion isometric contraction for 10% force level of MVC	The elderly have lower β (15–35 Hz) band CMC and IMC than younger subjects The elderly have greater RMSerror than younger subjects
a15	Roeder et al., 2020	adult 25.9±3.2 years （M12, F12） old 65.1±7.8 years (M12, F12) PD old67.4±7.3 years (M12, F8)	EEG-EMG(R-TA) EEG-EMG(L-TA)	Ground walking and treadmill walking	Adults have higher β (13–21 Hz) band CMC than the elderly and PD
a16	Watanabe et al., 2020	adult 21–30 years (17) old 68–78 years (16)	EEG-EMG(FDI) EEG-EMG(APB) EMG(FDI)-EMG(APB)	Isometric contraction adjusting the force to the target line of the hand	Older adults have increased β (15–30 Hz) band CMC band when force adjustment in visual feedback is greater than when it is less IMC is lower in younger and older adults when visual feedback force adjustment is greater than when it is less
a17	Yokoyama et al., 2020	adult 26.7±7.5 years (M15) old 64.9±6.3 years (M9) PD old 61.6±6.3 years (M10)	EEG-EMG(TA) EEG-EMG(MG)	Ground walking	PD patients have lower β (16–32 Hz) band CMC than healthy adults and healthy elderly
a18	Garaziadio et al., 2010	children 4–12 years (M6, F6) adult 21–35 years (M5 F5) old 55–80 years (M3 F7)	EEG-EMG(R-OP) EEG-EMG(L-OP)	Isometric contraction of pinching motion	Children have lower CMC peaks than adults
a19	Spedden et al., 2019	children 7–9 years (M2 F4) 10–12 years (M3 F3) 13–15 years (M6 F1) 16-18yr (M3 F3) adult 19-23yr (M2 F6)	EEG-EMG(TA) EEG-EMG(SOL) EMG(TAp)-EMG(TAd) EMG(SOL)-EMG(MG)	Dorsiflexion-base flexion isometric contraction to match MVC 10% force	Strong positive correlation with age in β (15–35 Hz) band CMC and IMC Performance on ankle dorsiflexion and plantar flexion tasks positively correlated with age
a20	Beck et al., 2021	children 8–10 years (M14 F9) 12–14 years (M12 F11) 16–18 years (M10 F10) adult 20–30 years (M20 F25)	EEG-EMG(FDI) EEG-EMG(APB)	MVC 10% fingertip isometric contraction	Adults have higher descending CMC peaks compared to 8- to 10-year-olds and 12- to 14-year-olds
a21	Ritterband-Rosenbaum et al., 2016	infant 1–66 weeks (M26 F33)	EEG-EMG(TA) EMG(TAp)-EMG(TAd)	Sitting posture	β (20–40 Hz) band CMC and IMC are higher in 9–25 weeks infants than in younger (< 9 weeks) and older (> 25 weeks) infants

EEG: Electroencephalography, EMG: Electromyography, FDI: First dorsal interosseous, FCR: flexor carpi radialis
APB: abductor pollicis brevis, LG: lateral gastrocnemius, MG; Medial gastrocnemius, SOL: soleus
FPB: Flexor pollicis brevis, TA: tibialis anterior, VL: vastus lateralis, VM: vastus medialis, ES: erector spinae
ECR: extensor carpi radialis, BB: biceps brachii, TB: triceps brachii, BF: biceps femoris, RF: rectus femoris
EDC: extensor digitorum communis, BR: brachioradialis, OP: opponens pollicis, MVC: Maximal voluntary contraction

The smaller the error, the higher the CMC, indicating that a higher CMC increases the accuracy of the force adjustment. In contrast, Spedden et al. (2018; a14) found no correlation between the CMC of the β-band and errors in force adjustment during bottom dorsiflexion isometric contractions in older and younger adults. However, this report showed that older adults had greater errors in force adjustment and lower CMC in the β-band compared to younger adults. We believe that this can be considered evidence that performance accuracy and nervous system function are indirectly related. Moreover, in children, Spedden et al. (2019; a19) showed that errors in muscle force coordination during plantar-dorsiflexion isometric contraction of the ankle decrease with age change and β-band CMC is higher with age change. This is thought to be due to increased neural oscillations in the corticospinal tract during development, which stabilize muscle coordination. These results suggest that CMC decreases with decreasing performance with age and increases with increasing performance with development and that CMC can be used as a method to evaluate motor functions that control physical function.

CMC and IMC

Electroencephalography is used to evaluate IMC. This makes it difficult to measure in pediatric subjects owing to behavioral limitations. To perform additional measurements in the future, it will be necessary to utilize more versatile methods. The IMC method is used as a simple evaluation method. Because this method uses only electromyography (EMG), it is simpler to measure than the CMC and is expected to be a more versatile evaluation method.

Several reports examining the CMC and IMC values simultaneously have been published. Comparisons between younger and older adults have shown that IMC as well as CMC are lower in older adults (Spedden et al., 2018; a14), that IMC as well as CMC are strongly positively correlated with age in children (Spedden et al., 2019; a19), and that in infants, as with CMC, IMC is significantly higher in infants aged 9–25 weeks (Ritterband-Rosenbaum et al., 2016; a21). Furthermore, training interventions have been shown to increase post-intervention IMC and CMC (Larsen et al., 2016; a6). Similar trends in CMC and IMC suggest that the IMC values reflect the state of neural connectivity. In contrast, Vries et al. (2016; a5) showed a negative correlation between the muscle coordination index and CMC, and a positive correlation with IMC. They attributed this result to CMC, which reflects the corticospinal projections involved in the control of individual muscles, and IMC, which reflects the branching pathways involved in the coordination of multiple muscles. Watanabe et al. (2020; a16) also showed that greater changes in the magnitude of force in visual feedback were higher in CMC and lower in IMC. Thus, the CMC and IMC exhibit different neural couplings. Although CMC and IMC exhibit different characteristics, they reflect the coupling of the nervous system and can be used as indices to evaluate nervous system activity during physical movement. Therefore, we summarized and characterized studies conducted on healthy adults, the elderly, and children using the IMC evaluation index in Table 2.

Inter-MC and Intra-MC

In healthy adults, Nguyen et al. (2017; b3) showed that β-band (13–35 Hz) Inter-MC differ between tasks with visual feedback coordination, with Inter-MC increasing with increasing difficulty and stronger neural oscillations between left- and right-hand homologous muscles. On the other hand, simultaneous performance of multiple tasks involving elbow extensor and flexor movements simultaneously during contraction of the hand muscles shows a decrease in α-band (6–15 Hz) Inter-MC (Lee et al., 2014; b1). From these results, it can be concluded that the neural coupling is different for each exercise. In addition, squatting movements show a higher Inter-MC during dynamic contractions than during isometric contractions (Mohr et al., 2015; b2). The Inter-MC is higher during shortening and stretching contractions than during isometric contractions (Kenville et al., 2020b; b4). These results indicate that muscle contraction depends on the muscle pattern. Furthermore, in a walking task, the Inter-MC between the upper and lower limbs increases from the middle to the end of the stance phase (Weersink et al., 2021; b6). The faster the pedaling rotation during the bicycle pedaling movement, the higher the IMC during the backward phase than during the forward phase (Lee et al., 2020; b7). From these results, we believe that there are specific timing points in a series of movements where the Inter-MC increases. However, in the balance task, no change in Inter-MC was observed, although the balance ability was improved by the training intervention, indicating no change in neuroplasticity in balance ability (Bakker et al., 2021; b5). Based on these reports, we believe that the Inter-MC assessment method can be utilized to show changes in neural connectivity related to movement patterns and the timing of movement.

Using Inter-MC as an assessment index, age-related changes have been reported in inter-subject comparisons. Walker et al. (2020; b9) demonstrated greater postural sway in standing balance in the elderly compared to younger adults, with higher α-band (8–14 Hz) Inter-MC during eye opening in the elderly and higher β-band (16–30 Hz) Inter-MC during eye closing in younger adults (16–30 Hz). In that study, standing balance during eye closure was shown to be related to somatosensory-neural coupling, indicating changes in neural coupling with age. In contrast, Jaiser et al. (2016; b8) showed no significant differences between age in the upper- and lower-extremity Inter-MC during the simultaneous contraction of the upper and lower extremities. A report on patients with neurological diseases showed that patients with moderate-to-mild disease had higher IMC during gait than patients with severe disease, and that IMC increased before and after training (Norton & Gorassini, 2006; b10). This report states that exercise-induced neural connections occur in patients with moderate-to-mild disease and that exercise can strengthen neural connections. They also reported that the Inter-MC was lower in healthy subjects who reported the same slow speed as in patients with the disease. Ushiyama et al. (2010; a9) reported that athletes have a lower CMC than adults who are not habitual exercisers, suggesting that the Inter-MC may not be higher because healthy adults routinely perform walking exercises and have a sophisticated neural drive for movement altered by long-term professional use. Mizuta et al. (2020; b11) showed that the IMC between the tibialis anterior (TA) and medial gastrocnemius (MG) muscles on the paralyzed side was higher in post-stroke patients with mild motor paralysis and slow walking speed. They stated that this was thought to be due to the large co-contraction of the lower extremity muscles, which prevents full utilization of potential neural function. These findings indicate the

Table 2 Previous studies assessing neural function using inter- and intramuscular coherence methods

No	Reference	Participant	Coherence	Task	Result
	inter-muscular coherence				
b1	Lee et al., 2014	adult 27.1±5.0 years (M6 F5)	EMG(EDC) - EMG(FDS) EMG(EDC) - EMG(FPB) EMG(EDC) - EMG(FDI) EMG(FDS) - EMG(FPB) EMG(FDS) - EMG(FDI) EMG(FPB) - EMG(FDI)	Fingertip isometric contraction during elbow contraction	Fingertip IMC decreases when performed simultaneously with elbow contraction
b2	Mohr et al., 2015	adult 26±5 years (M12 F4)	EMG(VL)-EMG(VM)	Squatting (bilateral, unilateral, isometric contraction, unilateral balance)	IMC increased for both the bilateral squat and unilateral squat tasks compared to the isometric contraction task IMC decreased unilateral balance squat compared to isometric contraction task
b3	Nguyen et al., 2017	adult 19–34 years (12)	EMG(R-BB)-EMG(L-BB) EMG(R-TB)-EMG(L-TB)	Isometric contraction in visual feedback adjustment at three levels of difficulty	α (8–12 Hz) band IMC increases as the difficulty of the task increases.
b4	Kenville et al., 2020b	adult 27.9±5.1 years (M11)	EMG(R-VL)-EMG(L-VL) EMG(R-VM)-EMG(L-VM) EMG(R-TA)-EMG(L-TA) EMG(R-ES)-EMG(L-ES)	Squatting movement （eccentric, isometric, concentric contraction pattern）	Eccentric squatting has higher α (12–30 Hz) band IMC than isometric squatting and concentric squatting Eccentric squatting has higher γ (30–44 Hz) band IMC than isometric squatting
b5	Bakker et al. 2021	adult 20.9±1.9 years (M18 F18)	EMG(SOL)-EMG(LG) EMG(SOL)-EMG(PL) EMG(TA)-EMG(LG) EMG(RF)- EMG(BF) EMG(TA)-EMG(SOL) EMG(TA)-EMG(LG) EMG(RF)-EMG(BF)	Test: balance Intervention exercise Balance training Cycling training	Improved balance ability No change in IMC in any training
b6	Weersink et al., 2021	adult 67±6.8 years (M10 F10)	EMG(BF)-EMG(DA) EMG(BF)-EMG(DP) EMG(RF)-EMG(DA) EMG(RF)-EMG(DP) EMG(SOL)-EMG(DA) EMG(SOL)-EMG(DP) EMG(TA)-EMG(DA) EMG(TA)-EMG(DP)	Ground walking	Increased IMC of upper and lower extremities from mid to end of stance phase
b7	Lee et al., 2020	adult 20–75 years (M7 F9)	EMG(RF)-EMG(BF)	Pedaling movement (forward and backward rotation)	At high rotational speeds (45RPM, 60RPM), IMC is increases for backward than forward.
b8	Jaiser et al., 2016	adult 20–80 years (M58 F41)	EMG(MG)-EMG(EDB) EMG(MG)-EMG(EDB) EMG(EDC)-EMG(FDI) EMG(FDS)-EMG(FDI)	Upper limb: isometric contraction exercises with tubing Lower limb: dorsiflexion isometric contraction exercise of the ankle joint Simultaneous contraction of upper and lower extremities	No association between IMC and age between upper and lower extremities
b9	Walker et al., 2020	adult 18–31 years (M4 F12) old 66–73 years (M8 F9)	EMG(MG)-EMG(TA) EMG(SOL)-EMG(TA)	Test: Standing postural balance in open and closed eyes Intervention exercise: muscle training	Postural oscillations are smaller in adults than in the elderly in both open and closed-eye conditions. Eye-opening balance is increased α (8–16 Hz) band IMC in the elderly. Eye-closing balance is increased in β (16–30 Hz) band IMC in adults No change in IMC with strength training
b10	Norton et al., 2006	healthy adult 28–38 years (M1 F2) spinal cord injury adult 18–78 years (M11 F1)	EMG(Hamstrings)-EMG(VL)	Test: Treadmill walking Intervention exercise: treadmill walking	Patients with moderate neurological disease have higher β (24–40 Hz) band IMC than those with severe disease Patients with moderate disease have significantly higher β (24–40 Hz) band IMC after intervention
b11	Mizuta et al., 2020	post-stroke patients 65.9±13.7 years (M34 F8)	EMG(TA)-EMG(MG)	Walking at comfortable speed on 10 m sidewalk and 2 m auxiliary sidewalk	Higher IMC during walking in patients with mild cerebral palsy and slow walking speed
	intra-muscular coherence				
b12	Sato et al., 2019	adult 20–37 years (M9 F9)	EMG(pTA)-EMG(dTA)	Split belt walking at separate left and right speeds	β (15–30 Hz) and γ (30–45 Hz) band IMC higher in fast legs β (15–30 Hz) band IMC decreases from early to late adaptation in the fast leg
b13	Willerslev-Olsen et al., 2015	cerebral palsy children 5–14 years (M11 F5)	EMG(pTA)-EMG(dTA)	Test: treadmill walking, ground walking Intervention exercise: treadmill walking	IMC increases after intervention The magnitude of change in IMC before and after intervention was negatively correlated with age, with the largest effects observed in children younger than 10 years old

FDS: flexor digitorum superficialis, DA: deltoideus anterior, DP: deltoideus posterior, EDB: extensor digitorum brevis effectiveness of interventions for neural control through rehabilitation and suggest that walking may be an effective interventional exercise for instability and excessive cortical control. In contrast to the Inter-MC method, which evaluates the coherence between different muscles, the Intra-MC method evaluates the coherence in the same muscle. It mainly shows coherence between distal and proximal sites within the TA muscle, and its evaluation in gait has been reported. Sato & Choi (2019; b33) used the Intra-MC method as an evaluation for walking movements with different left and right speeds, with the β and γ bands of the Intra-MC showing a slower speed and a decrease from early to late adaptation, indicating that neural drive decreases with motor adaptation. This is lower in athletes and healthy adults than in those with neurological diseases at the same walking speed, suggesting that walking is an adaptation to daily movements that alters the function of the nervous system. Furthermore, in Intra-MC, Willerslev-Olsen et al. (2015; b13) showed an increase in Intra-MC after gait training in children with cerebral palsy. The effect of this training was negatively correlated with age, indicating that the largest effects were observed in children younger than 10 years. The effect size varies with age, suggesting a developmental effect. This is similar to the report of Ritterband-Rousenbaum et al. (2016; a21) in infants, where it is thought that there is a period of significant neural connectivity during the developmental process, which occurs under the age of 10 years. This corroborates Scammon’s developmental curve, in which neurotypical development is prominent by the age 10 (Scammon, 1927).

Based on these results, we believe that the trends in the functional aspects of the brain and nervous system during exercise are becoming clearer, as several reports have been presented in adults. In children who are still developing, the CMC and IMC are lower than in adults, but there are periods of markedly increased IMC. This suggests that there is a period of significant development in the neural connections that can be evaluated using the IMC method. As there are few data on children, more data on children should be obtained in the future to demonstrate the developmental process. The clarification of human developmental processes is essential when considering events related to physical activity. Therefore, it is necessary to demonstrate the developmental processes of the cranial nervous system, such as neural connections and neural drive, in children using the IMC evaluation method, which is simpler than the versatile CMC method.

Conclusions

Changes in the social environment surrounding children have resulted in fewer opportunities for physical activity, and children experience developmental delays in their ability to control their own bodies skillfully. In this social environment, preschools and schools have become places where children can experience a variety of physical activities, and it is important to enhance physical play and physical education classes in preschools. To enhance these activities, it is necessary to have an index to evaluate the children's ability to control their bodies skillfully. The method of evaluating movement skills by observing points of movement has been used in schools. However, since body movements are caused by the activity of the brain/nervous system, we believe that the evaluation of this nervous system is also an important indicator when evaluating the skillfulness of body movements. Therefore, in this study, we summarized the literature that evaluates brain and nerve activity during muscle activity using CMC and IMC evaluation methods, which have been shown to be indices for evaluating neural function, and examined the possibility of utilizing this evaluation method as an index for evaluating neural activity during exercise, when developing exercise programs. We found that CMC and IMC change with age and that different results have been reported for different neurological diseases. Patients with neurological diseases showed significantly different results than healthy individuals, indicating that CMC and IMC can be used as indices to evaluate the activity of the nervous system during exercise. In addition, CMC and IMC differed depending on the timing of the motor task and muscle activity, indicating that brain-nervous system entrainment differs depending on physical and muscle activity. We believe that these results indicate the possibility of evaluating neural functions using different motor tasks and linking them to the presentation of effective exercise. For example, we believe that it is possible to evaluate not only the single walking task on the ground but also the neural activity during the exercise that requires muscle coordination based on visual feedback, such as avoiding obstacles while walking, stepping on, or avoiding marks on the floor.

Movements evaluated by CMC were mainly static muscle activities such as isometric contractions. In contrast, IMC evaluated dynamic movements such as walking during exercise tasks involving dynamic movements. The evaluation by IMC may indicate the possibility of a more applicable evaluation during field-like exercise. In addition, since this method can be evaluated using only electromyography, there are fewer physical limitations, and more pediatric data will be collected in the future.

IMC evaluation is an indicator of the coordinated neural drive of muscles and is used to evaluate the neural drive between muscles or the spinal cord tract. The IMC method is an index for evaluating the nervous system of the body, development of motor function, and skill in physical movement in children from a functional perspective. This method does not evaluate movement itself, but is an indicator of the degree of inter-neural coupling based on neural entrainment during exercise. In other words, since this method evaluates the degree of neural connections in a variety of movements, it is expected to be used as an evaluation index to show the effectiveness of exercise when proposing exercise programs in early childhood and early school age when a variety of movement experiences are required.

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References

Akkus, P.Z., Hizal, M. G., Bahadur, E. L., Ozmert, E. N., Polat, S. E., Ozdemir, G., Karahan, S., Yalcin, E., Ersoz, D. D., Kiper, N., & Ozcelik U. (2019). Developmental and behavioral problem in pre-school-aged primery ciliary dyskinesia patients. *European Journal of Pediatrics*, 178, 995-1003. https://doi.org/10.1007/s00431-019-03382-z

Bakker, L. B. M., Nandi T., Lamoth C. J.C., & Hortobagyi T. (2021). Task specificity and neural adaptations after balance learning in young adults. *Human Movement Science*, 78, No. 102833. https://doi.org/10.1016/j.humov.2021.102833

Bayram, M. B., Siemionow, V., Yue, & G. H. (2015). Weakening of Corticomuscular Signal Coupling During Voluntary Motor Action in Aging. *The Journals of Gerontology: Series A*, 70 (8), 1037-1043. https://doi.org/10.1093/gerona/glv014

Beck, M. M., Spedden, M.E., & Lundbye-Jensen, J. (2021). Reorganization of functional and directed corticomuscular connectivity during precision grip from childhood to adulthood. *Scientific Reports*, 11, No. 22870. https://doi.org/10.1038/s41598-021-01903-1

Chakarov, V., Naranjo, J. R., Schulte-Monting, J., Omlor, J.W., Huethe, F., & Kristeva, R. (2009). Beta Range EEG-EMG Coherence with Isometric Compensation for Increasing Modulated Low-Level Forces. *Journal of Neurophysiology*, 102 (2), 1115-1120. https://doi.org/10.1152/jn.91095.2008

Chen, Z., Ishii, Y., & Watanabe, K. (2010). A Biomechanical study on the range of motion of standing long jump in elementary school children. *Japan Society of Human Growth and Development*, 48, 1-7. https://doi.org/10.5332/hatsuhatsu.2010.48_1

Chin, Y., & Ikeda, N. (2014). A study on the learning instruction of the long jump in the third and fourth grades of elementary school children -Through a comparison of the class result of the third grades and fourth grades-. *Japan Journal for the Pedagogy of Physical Education*, 30 (1), 17-32. Japanese. https://doi.org/10.11243/jsppe.30.1_17

Committee for the Development of Guidelines for Childhood physical activity. (2012). *Childhood Physical Activity Guidelines Guidebook.* Tokyo: Ministry of Education, Culture, Sports, Science and Technology.

Conway, B. A., Halliday, D. M., Farmer S.F., Shahani, U., Maas, P., Weir, A. I., & Rosenberg, J. R. (1995) Synchronization between motor cortex and spinal motoneuronal pool during the performance of a maintained motor task in man. *The Journal of physiology*, 489 (3), 917-924. https://doi.org/10.1113%2Fjphysiol.1995.sp021104

Farmer, S. F., Bremner, F. D., Halliday, D. M., Rosenberg, J. R., & Stephens, J. A. (1993). The frequency content of common synaptic inputs to motoneurones studied during voluntary isometric contraction in man. *The Journal of Physiology*, 470 (1), 127-155. https://doi.org/10.1113/jphysiol.1993.sp019851

Gallahue, D. L. (1999). *Physical Education in Childhood*: Sugihara T. Tokyo.

Graziadio, S., Basu, A., Tomasevic, L., Zappasodi, F., Tecchio, F., Eyre J. A. (2010). Developmental Tuning and Decay in Senescence of Oscillations Linking the Corticospinal System. *Journal of Neuroscience*, 30 (10), 3663-3674. https://doi.org/10.1523/JNEUROSCI.5621-09.2010

Grosse, P., Cassidy M. J., & Brown, P. (2002). EEG–EMG, MEG–EMG and EMG–EMG frequency analysis: physiological principles and clinical applications. *Clinical Neurophysiology*, 113, 1523–1531. https://doi.org/10.1016/s1388-2457(02)00223-7

Halliday, D. M., Rosenberg, J. R., Amjad, A. M., Breeze, P, Conway, & B. A., Farmer, S. F. (1995). A framework for the analysis of mixed time series/point process data – theory and application to the study of physiological tremor, single motor unit discharges and electromyograms. *Progress Biophysics Molecular Biology*, 64 (2-3), 237-278. https://doi.org/10.1016/s0079-6107(96)00009-0

Harigai, M., & Kondoh, T. (2017). A study on derivation of criteria for observational evaluation of horizontal bar movement: focusing on the basic movement for first to fourth grade elementary school children. *Japan Journal for the Pedagogy of Physical Education*, 33 (2), 19-34. Japanese. https://doi.org/10.11243/jsppe.33.2_19

Jaiser, S. R., Baker, M. R., Baker, S. N. (2016). Intermuscular Coherence in Normal Adults: Variability and Changes with Age. *Plos One*, 11 (2), No. e014029. https://doi.org/10.1371/journal.pone.0149029

Johnson, A. N., & Shinohara, M. (2012). Corticomuscular coherence with and without additional task in the elderly. *Journal of Applied Physiology*, 112 (6), 970-981. https://doi.org/10.1152/japplphysiol.01079.2011

Kamp, D., Krause, V., Butz, M., Schnitzler, A., & Pollok, B. (2013). Changes of cortico-muscular coherence: an early marker of healthy aging?. *Age*, 35, 49-58. https://doi.org/10.1007/s11357-011-9329-y

Kawashima, K., Funabiki, Y., Ogawa, S., Hayashi, H., Soh, Z., Furui, A., Sato, A., Shiwa, T., Hiroki, M., Shimatani, K., Mgami, H., Konishi, Y., & Tsuji, T. (2020). Video-based evaluation of infant crawling toward quantitative assessment of motor development. *Scientific reports*, 10, No. 11266. https://doi.org/10.1038/s41598-020-67855-0

Kenville, R., Maudrich, T., Vidaurre, C., Maudrich, D., Villringer, A., Nikulin, V. V., & Ragert, P. (2020a) Corticomuscular interactions during different movement periods in a multi-joint compound movement. *Scientific Report*, 10, No. 5021. https://doi.org/10.1038/s41598-020-61909-z

Kenville, R., Maudrich, T., Vidaurre, C., Maudrich, D., Villringer, A., Ragert, P., & Nikulin, V. V. (2020b) Intermuscular coherence between homologous muscles during dynamic and static movement periods of bipedal squatting. *Journal of Neurophysiology*, 124 (4), 1045-1055. https://doi.org/10.1152/jn.00231.2020

Kitajo, K., Yamamoto, Y., Miyashita, M. (1998). Developmental process of the human motor nervous system. *BME*, 12 (7), 40-48. Japanese. https://doi.org/10.11239/jsmbe1987.12.7_40

Larsen, L. H., Jensen, T, Christensen, M. S., Lundbye-Jensen, J., Langberg, H., & Nielsen, J. B. (2016). Changes in corticospinal drive to spinal motoneurones following tablet-based practice of manual dexterity. *Physiological Reports*, 4 (2), No. e12684. https://doi.org/10.14814/phy2.12684

Lee, S. W., Landers, K., & Harris-Love, M. L. (2014). Activation and intermuscular coherence of distal arm muscles during proximal muscle contraction. *Experimental Brain Research*, 232 (3), 739-752. https://doi.org/10.1007/s00221-013-3784-x

Lee, M. Y., Wang, R. Y., Hsu, S. S., Yang, W. W., Chen, S. S., & Yang, Y. R. (2020). Muscle activation and intermuscular coherence during forward and backward pedaling. *Chinese Journal of Physiology*, 63(2), 85-89. doi: 10.4103/CJP.CJP_82_19

Lundbye-Jensen, J., & Nielsen, J. B. (2008). Central nervous adaptations following 1 wk of wrist and hand immobilization. *Journal of Applied Physiology*, 105(1), 139-151. https://doi.org/10.1152/japplphysiol.00687.2007

Ministry of Education, Culture, Sports, Science and Technology. (2022). Report on the Fiscal Year 2022 Physical Fitness and Exercise Capacity Survey. Japanese. https://www.mext.go.jp/sports/b_menu/toukei/chousa04/tairyoku/kekka/k_detail/1409822.htm

Mizuta, N., Hasui, N., Nakatani, T., Takamura, Y., Fujii, S., Tsutsumi, M., Taguchi, J., & Morioka, S. (2020). Walking characteristics including mild motor paralysis and slow walking speed in post-stroke patients. *Scientific Report*, 10, No. 11819. https://doi.org/10.1038/s41598-020-68905-3

Mohr, M., Nann, M., Tscharner, V., Eskofier, B., Nigg, B. M. (2015). Task-Dependent Intermuscular Motor Unit Synchronization between Medial and Lateral Vastii Muscles during Dynamic and Isometric Squats. *Plos One*, 10 (11), No. e0142048. https://doi.org/10.1371%2Fjournal.pone.0142048

Matsukawa, S., Miyazaki, A. & Okade, Y. (2013). A Focusing on the Smooth Transition from Hurdling to Interval Runs in fifth grade physical education class - Using "One Step Hurdles" -. *Japan Journal for the Pedagogy of Physical Education*, 29 (1), 23-33. Japanese. https://doi.org/10.11243/jsppe.29.1_23

Murai, R., & Ogiwara, T. (2021). An Examination of the Learning Outcomes of "Floor Kickball" Teaching Materials in Elementary School Physical Education Classes: Focusing on Children's Skills of Kicking and Stopping the Ball. *Japan Journal for the Pedagogy of Physical Education*, 37 (1), 17-33. Japanese. https://doi.org/10.11243/jsppe.37.1_17

Murnaghan, C. D., Squair, J. W., Chua, R., Inglis T., & Carpenter M. G. (2014). Cortical contributions to control of posture during unrestricted and restricted stance. *Journal of Neurophysiology*, 111 (9), 1920-1926. https://doi.org/10.1152/jn.00853.2012

Nakamura, K., Takenaga, R., Kawaji, M., Kawazoe, K., Shinohara, T., Yamamoto, T., Yamagata, Z., & Miyamaru, M. (2011). Development of fundamental motor pattern using the observational evaluation method in young children. *Japan Society of Human Growth and Development*, 51, 1−18. Japanese. https://doi.org/10.5332/hatsuhatsu.2011.51_1

Nanasawa, A., & Honda, T. (2014). A Study on the Effects of Physical Education Learning with Emphasis on Movement Rhythm -Effects of physical Education with Emphasis on creating a variety of movement-. *Japan Journal for the Pedagogy of Physical Education*, 30 (2), 1-11. Japanese. https://doi.org/10.11243/jsppe.30.2_1

Nguyen, H. B., Lee, S. W., Harris-Love, M. L., & Lum, P. S. (2017). Neural coupling between homologous muscles during bimanual tasks: effects of visual and somatosensory feedback, *Journal of Neurophysiology*. 117 (2), 655-664. https://doi.org/10.1152/jn.00269.2016

Norton, J. A., & Gorassini, M. A. (2006). Changes in Cortically Related Intermuscular Coherence Accompanying Improvements in Locomotor Skills in Incomplete Spinal Cord Injury. *Journal of Neurophysiology*, 95 (4), 2580-2589. https://doi.org/10.1152/jn.01289.2005

Oya, C., Keisuke, T., Muramatsu, E. (2015). Features of longitudinal changes in body fat distribution in Japanese children. *The bulletion of aichi university of education health and physical education* , 39, 7-15. Japanese. https://doi.org/10.11243/jsppe.33.2_1

Ritterband-Rosenbaum, A., Herskind, A., Li, X., Willerslev-Olsen, M., Olsen, M. D., Farmer, S. F., & Nielsen, J. B. (2016). A critical period of corticomuscular and EMG–EMG coherence detection in healthy infants aged 9–25 weeks. *The Journal of Physiology*, 595 (8), 2699-2713. https://doi.org/10.1113/jp273090

Roeder, L., Boonstra, T. W., Smith, S. S., & Kerr, G. K. (2018). Dynamics of corticospinal motor control during overground and treadmill walking in humans, *Journal of Neurophysiology*. 120(3), 1017-1031. https://doi.org/10.1152/jn.00613.2017

Roeder, L., Boonstra, T. W., & Kerr, G. K. (2020). Corticomuscular control of walking in older people and people with Parkinson’s disease. *Scientific Reports*, 10, No. 2980. https://doi.org/10.1038/s41598-020-59810-w

Safri, N. M., Murayama, N., Hayashi, Y., Igasaki, T. (2007). Effects of concurrent visual tasks on cortico-muscular synchronization in humans. *Brain Research*, 1155 (25), 81-92. https://doi.org/10.1016/j.brainres.2007.04.052

Sato, S., & Choi, J. T. (2019). Increased intramuscular coherence is associated with temporal gait symmetry during split-belt locomotor adaptation. *Journal of Neurophysiology*, 122 (3), 1097-1109. https://doi.org/10.1152/jn.00865.2018

Scammon, R.E. (1927). The first seriatim study of human growth. *American Journal of Physical Anthropology*, vol.10 (3) 329-336.

Senda, M. (2007). Urban Architecture as a Child Development Environment, *Trends in the sciences*, 12 (1), 38-40. Japanese. https://doi.org/10.5363/tits.12.1_38

Spedden, M. E., Nielsen, J. B., & Geertsen, S. S. (2018). Oscillatory Corticospinal Activity during Static Contraction of Ankle Muscles Is Reduced in Healthy Old versus Young Adults. *Neural Plasticity*, No. 3432649. https://doi.org/10.1155/2018/3432649

Spedden, M. E., Jensen, P., Terkildsen, C. U., Jensen, N. J., Halliday, D. M., Lundbye-Jensen, J., Nielsen, J. B., & Geertsen, S. S. (2019). The development of functional and directed corticomuscular connectivity during tonic ankle muscle contraction across childhood and adolescence. *NuroImage*, 191 (1), 350-360. https://doi.org/10.1016/j.neuroimage.2019.02.054

Takai, K. (2007). Recent trends in research on physical coordination and integration in children (2nd report). Japanese. *Annual report of the Faculty of Education, Bunkyo University*, 41, 83-94.

Takizawa, Y., & Kondoh, Y. (2017). Research on criteria for observational evaluation of throwing motion: Motion analysis from 1st to 6th grade elementary school students. *Japan Journal for the Pedagogy of Physical Education*, 33 (2), 1-17. Japanese. https://doi.org/10.11243/jsppe.33.2_1

Ushiyama, J., Takahashi, Y., & Ushiba, J. (2010). Muscle dependency of corticomuscular coherence in upp.er and lower limb muscles and training-related alterations in ballet dancers and weightlifters. *Journal of Applied Physiology*, 109 (1), 1086-1095. https://doi.org/10.1152/japplphysiol.00869.2009

Vries, I. E. J., Daffertshofer, A., Stegeman, D. F., & Boonstra, T. W. (2016). Functional connectivity in the neuromuscular system underlying bimanual coordination. *Journal of Neurophysiology*, 116 (6), 2576-2585. https://doi.org/10.1152/jn.00460.2016

Walker, S., Piitulainen, H., Manlangit, T., Avela, J., & Baker, S. N. (2020). Older adults show elevated intermuscular coherence in eyes-open standing but only young adults increase coherence in response to closing the eyes. *Experimental Physiology*, 105 (6), 1000-1011. https://doi.org/10.1113/ep088468

Watanabe, T., Nojima, I., Mima, T., Sugiura, H., & Kirimoto, H. (2020). Magnification of visual feedback modulates corticomuscular and intermuscular coherences differently in young and elderly adults. NeuroImage, 220 (15), No.117089. https://doi.org/10.1016/j.neuroimage.2020.117089

Weersink, J. B., Jong, B. M., Halliday, D. M., & Maurits, N. M. (2021). Intermuscular coherence analysis in older adults reveals that gait-related arm swing drives lower limb muscles via subcortical and cortical pathways. *The Journal of Physiology*, 599 (8), 2283-2298. https://doi.org/10.1113/jp281094

Willerslev-Olsen, M., Petersen, T. H., Farmer, S. F., & Nielsen, J. B. (2015). Gait training facilitates central drive to ankle dorsiflexors in children with cerebral palsy. *Brain*, 138 (3), 589-603. https://doi.org/10.1093/brain/awu399

Yoshimi, E., Nomura, T., & Kida, N. (2021). A study of young children’s coordinated movement – the effects of a rhythmic-play exercise program on physical-expression abillity. *Advances in physical education*, 11, 118-134. https://www.scirp.org/journal/ape

Yokoyama, H., Yoshida, T., Zabjek, K., Chen, R., & Masani K. (2020). Defective corticomuscular connectivity during walking in patients with Parkinson’s disease. *Journal of Neurophysiology*, 124 (5), 1399-1414. https://doi.org/10.1152/jn.00109.2020

Yoshida, T., Masani, K., Zabjek, K., Chen, R., & Popovic, M. (2017). Dynamic cortical participation during bilateral, cyclical ankle movements: effects of aging. *Scientific Reports*, 7, No. 44658. https://doi.org/10.1038/srep44658