BJMB
Brazilian Journal of Motor Behavior

Research Articles

Inter-joint coordination changes during walking in typically developing children: the vector coding analysis

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https://doi.org/10.20338/bjmb.v18i1.417

HIGHLIGHTS

- We applied vector coding analysis to study gait in typically developing children
- The in-phase coordination mode increased in the late stance phase
- Anti-phase coordination duration varied by subphase and age, with younger kids longer in late stance
- 5-8-year-olds used serial coordination, while 9-10-year-olds had a mixed strategy late stance

ABBREVIATIONS

A	Ankle
ANOVA	analysis of variance
COMOS	Coordination mode sequence
CRP	Continuous relative phase
CV	Coefficient of variability
f	Frontal
H	Hip
K	Knee
s	Sagital
t	Tranverse
ϕ	Coupling angle
α	One joint angle
β	Another joint angle

PUBLICATION DATA
Received 12 02 2023
Accepted 17 07 2024
Published 06 09 2024

BACKGROUND: Coordination is the key to developing biomechanical gait patterns.
AIM: To describe the coordination modes during walking in 5-to-10-years-old typically developing children using the vector coding analysis.
METHOD: 11 boys and 17 girls were divided into three groups according to their ages. Joints of the right lower limb kinematics were analyzed during walking. The coupling angle was calculated using vector coding analysis to describe the inter-joint coordination by the coordination modes.
RESULTS: Results indicated significant differences in coordination modes based on the stance subphase and age group. The in-phase mode duration increased in the late stance, while the anti-phase mode varied more across subphases and groups. Proximal and distal modes also showed differences, with variability and predominant coordination strategies analyzed across groups.
CONCLUSION: Changes in inter-joint coordination were mostly related to the mid-stance phase. Its variability decreased as children were older. Motor development seems to move towards an optimal for walking, suggesting older children control more than one joint at the same time using parallel coordination.

KEYWORDS: Gait | Children | Inter-joint coordination | Kinematics

INTRODUCTION

The bipedal stance of legs is a hallmark of the Homo species [1]. While standing and walking, children not only explore the environment with greater visual field but also manipulate objects more effectively [2,3]. Gait development is a significant motor achievement in childhood. Typically developed children achieve postural and motor milestones such as sitting, crawling, standing, and walking. Children start to walk around 13 to 15 months old with an irregular and unstable pattern [4–7]. At the second year of life, children present a consistent heel strike walking pattern and walk with a similar vertical ground reaction force pattern to an adult [8]. Sala and Cohen [9] proposed three markers/milestones for independent locomotion in children: 1) a consistent heel strike pattern, around 2.5 years old; 2) transition from a wide base of support to a narrower one, around 2 years old; and 3) upper limbs held in high guard position to reciprocal arm swing, around 3.5 years old. In terms of coordination, Hu [10] suggested 3- years old-children have already mastered the basic principles of walking, coordinating the knees and ankles joints.

Gait milestones are based on specific postural, motor, or biomechanical parameters, but none of these milestones are independent [11]. Coordination is the key to mastering the environmental and biomechanical constraints to develop the biomechanical gait patterns. A typical gait-related milestone is the stable single leg stance and leg swing control [5]. Which are the coordination milestones in childhood gait? Hu [10] described the continuous relative phase (CRP) and phase portrait of the knee and ankle joints in 3-6- years old typically developing children, and they have found that these joints are coordinate in similar patterns during five key events in the gait cycle (heel contact, footflat, heel off, toe off, and mid swing). Besides describing how two elements are coordinated, such as the CRP, the vector coding analysis can encode the coordination of a joint pair into coordination modes (in-phase, antiphase, proximal and distal phases). Gait variability emerges from the multiple degrees of freedom of our motor system to support different control strategies [12,13], using different movement time and magnitude combinations [14]. Measuring variability prevents us from losing valuable information about the movement's execution. There is no information about the gait coordination modes in typically developing children. How do coordination modes change in childhood?

Despite the comparisons between typically developing and impaired children [15,16] or between adults and children [17] show how gait patterns change from childhood to adulthood, or due to any health condition, little is known about gait coordination changes along the childhood. This study aims to describe the coordination modes during walking in 5-to-10-years-old typically developing children using the vector coding analysis. We will compare the coordination modes, and coordination variability during walking along groups (5-6 years old, 7-8 years old, and 9-10 years old) in different gait phases.

Compared with healthy controls, people with cerebellar ataxia present larger stance phase and double support phase [18]. Therefore, as development arrow might overcome the incoordination states to coordinate states, our hypothesis is the coordination variability will be different between single and double support phases across groups. We expect that older children will decrease the coordination variability during the single support phase.

METHODS

This is a cross-sectional, observational study with a convenience sample, based on snowball sampling strategy. Folders were displayed at the University bulletin inviting parents to bring their children to attend this study. All children and their parents signed a consent term (ethical committee registration number 006/2009) agreeing to join in this study.

Participants

Twenty-eight children (11 boys and 17 girls) aged 5 to 10 years old were divided into three groups (5-6 years old, 7-8 years old, and 9-10 years old) according to their ages (table 1). The inclusion criteria were aging between 5 to 10 years old, no lower limb orthopedic or neurologic injury, disease or impairment during the evaluation sessions, and the signed consent term. The exclusion criterion was children who could not understand the instructions to walk during the motion capture session. One-way analyses of variance (ANOVA) showed the older children was heavier and taller ($p<0.05$) than younger ones, but their body mass index was similar across groups ($p>0.05$).

Table 1. Participants' characteristics.

Variable	5-6 years old	7-8 years old	9-10 years old	p
Age (years)	5.2(0.6)	7.8(0.5)	9.6(0.5)	<0.001
Body mass (kg)	22.7(5.1)	28.0(7.9)	31.3(5.4)	0.015
Body height (cm)	116.3(5.8)	125.1(10.2)	139.9(9.3)	<0.001
Body mass index (kg/m^2)	16.6(2.1)	17.5(2.5)	15.9(1.6)	0.25

Instruments

Gait kinematics was recorded with a motion capture system (4 digital cameras, Peak Motus system, Peak Performance, Inc., 60 Hz sampling frequency) and the ground reaction force during the stance phase was recorded with two force platforms (ORC-6 model, Advanced Mechanical Technology, USA, 600 Hz sampling frequency). Body marks location followed the *Helen Hayes Marker set* protocol [19], This protocol allowed us to measure the hip, knee, and ankle joints in the frontal, transverse, and sagittal planes during the walking, these markers were placed on anatomical landmarks along the body (Head: Vertex; Neck: Spinous process of C7; Shoulders: Acromion processes; Upper arms: Lateral epicondyles; Forearms: Medial epicondyles; Wrists: Styloid processes of the radius and ulna; Hips: Anterior superior iliac spines; Thighs: Lateral and medial femoral epicondyles; Knees: Lateral and medial malleoli; Ankles: Calcaneus). The vertical ground reaction force signal was used to find the foot contact and toe off. Since some children had short strides, they could step twice in the same force plate during the task. Thus, using the ground reaction forces to define the single and double support was not possible, and for the analysis, the support phase was divided into three equal windows.

Protocol

The task was walking forward at self-selected speed in a straight pathway for 10 m. Participants should walk using the motion tracking markers glued on their bodies. To make children get used to such conditions, they could walk freely at the motion capture facility until they were comfortable with such setup. Participants were instructed to walk forward along the pathway and step over the force plates. Participants walked barefoot and freely on a 10-m-long sidewalk with two force platforms installed right in the middle of it to get used to the position of these plates. The participants crossed this sidewalk walking at a constant self-selected horizontal speed five times.

Data processing

Only the right lower limb (hip H, knee K, and ankle A) joint kinematics at the frontal f, transverse t and sagittal s planes during the stance phase were analyzed. These nine joint angles time series were filtered (low-pass second order Butterworth filter, 20 Hz cutoff frequency) and time-normalized (0-100%, 2% progression). For each trial, the coupling angle ϕ was calculated using the vector coding approach [11], where α is one joint angle and β is another joint angle. This coupling angle ϕ was calculated for all possible joint angles' pairs; but not all of them were considered for analysis (the auto-joint pairs, any coupling angle within the same joint) were discarded for analysis. To avoid two pairs with the same joint angles, the abscissa coordinate was always the proximal joint and the ordinate coordinate was always the distal joint. Thus, for the analysis all coupling angles with the distal joint as the abscissa and the proximal joint as the ordinate were also discarded. These are the evaluated joint angle pairs: hip and knee [9 pairs (K_t-H_t, K_t-H_f, K_t-H_s, K_f-H_t, K_f-H_f, K_f-H_s, K_s-H_t, K_s-H_f, K_s-H_s)]; hip and ankle [9 pairs, (A_t-H_t, A_t-H_f, A_t-H_s, A_f-H_t, A_f-H_f, A_f-H_s, A_s-H_t, A_s-H_f, A_s-H_s)]; and knee and ankle [9 pairs (A_t-K_t, A_t-K_f, A_t-K_s, A_f-K_t, A_f-K_f, A_f-K_s, A_s-K_t, A_s-K_f, A_s-K_s)]. For these 27 joint pairs, the vector coding approach was applied, leading to 27 coupling angles.

The coupling angle ϕ relative to the right horizontal is calculated from the vector defined by the position of the pairs (α_i, β_i) and (α_i+1, β_i+1) (Figure 1 and equation 1). The coupling angle ϕ defines four coordination modes: 1) in-phase, $22.5° < \phi < 67.5°$ and $202.5° < \phi < 247.5°$; 2) anti-phase, $112.5° < \phi < 157.5°$ and $292.5° < \phi < 337.5°$; 3) phase α, $337.5° < \phi < 22.5°$ and $157.5° < \phi < 202.5°$; and 4) phase β, $67.5° < \phi < 112.5°$ and $247.5° < \phi < 292.5°$. We can then classify any coupling angle as a coordination mode.

$$\phi = \tan^{-1}\left(\frac{\beta_{i+1} - \beta_i}{\alpha_{i+1} - \alpha_i}\right) \qquad \text{Equation 1}$$

The coupling angle series was discretized into those four coordination modes. This transformation turns the coupling angle time series into the coordination mode sequence (COMOS). Then, COMOS has only four levels (in-phase, anti-phase, proximal phase, and distal phase). For convenience, all COMOS were the same length (51 coordinate modes because gait support phase was normalized and resampled every 2%). The COMOS was separated into the early stance (0-32% stance phase), middle stance (34-64% stance phase), and late stance (66-100% stance phase) phases. For each stance subphase, it was accounted how long the four coordination modes have lasted. In the early and late stance phases, the double support occurs, while during the middle stance we have the single support.

The coordination modes can be separated into two classes, parallel and serial. In parallel coordination, both joints are moving simultaneously (in-phase and anti-phase coordination modes); while, in serial coordination, just one joint is moving (proximal or distal modes) while the other is still.

Statistical Analyses

All 27 coordination pairs were grouped for statistical analyses. The duration of each coordination mode last was compared among the stance subphases (early, middle, and late phases) and groups (5-6 years old, 7-8 years old, and 9-10 years old) using a two-way analysis of variance (ANOVA). This analysis will evaluate our hypothesis and will show whether the coordination modes are different across stance subphases. The duration of parallel (in-phase and antiphase coordination modes) and serial (proximal and distal coordination modes) were summed and compared among the stance phases and groups using another two-way ANOVA. The variability of coordination modes duration in every stance phase was calculated using the coefficient of variability (CV), where the CV is the standard deviation divided by the mean. All CV was grouped for a two-way ANOVA for groups and stance subphases. Tukey HSD test was applied as a post hoc test when necessary. For all comparisons, we set $p < 0.05$.

The coordination class predominance during each stance subphase was defined as the mode, but only if such a mode was >55%. If the predominant coordination type duration was ranging between 50 and 54%, instead of serial or parallel coordination strategy, we called as mixed coordination strategy, without a clear coordination type of predominance.

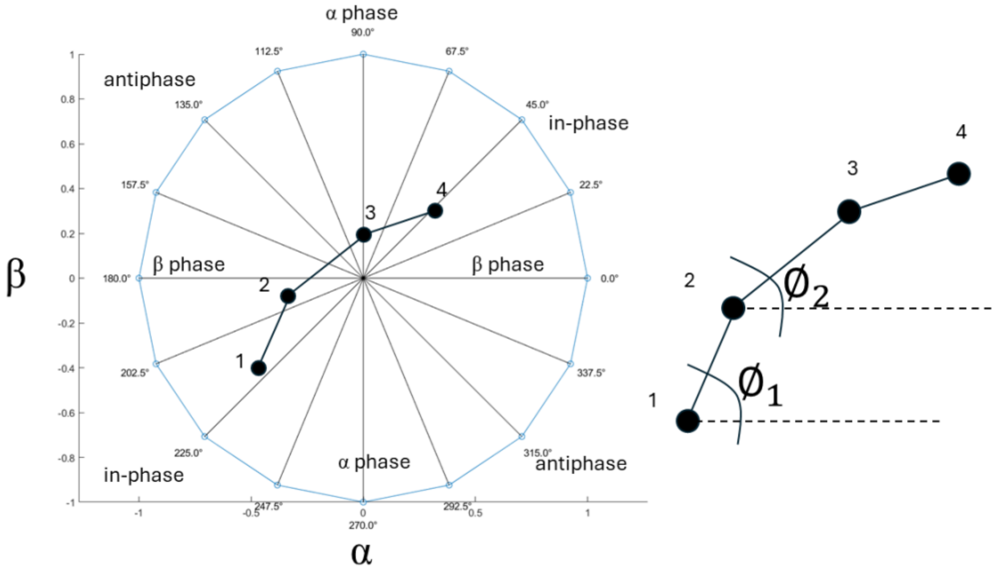

Figure 1. Vector coding analysis. Plotting the variables α and β, the coupling angle Ø1 is defined as the horizontal angle of the vector defined by the points 1 and 2. The blue circle shows the angles for the coordination modes.

RESULTS

Figure 2 shows the average coordination modes duration across groups and stance subphases. How long each coordination mode lasts during each stance subphase, and groups were compared with two-way ANOVA. These ANOVAs indicated how each coordination mode has changed according to factors stance subphase and group. For each coordination mode, a separated two-way ANOVA was performed. The in-phase coordination mode duration was only affected by the stance subphase ($F_{2,83}=33.1$, $p<0.001$ partial $\eta^2=0.46$, power=1.0); and post hoc tests showed the in-phase mode duration was longer at the late stance than the early and middle stances, and it was shorter at the middle stance than the early and late stances. The anti-phase coordination mode duration was affected by the stance subphase ($F_{2,83}=13.4$, $p<0.001$ partial $\eta^2=0.26$, power=0.99) and the interaction between the stance subphases and group ($F_{4,83}=2.7$, $p=0.03$ partial $\eta^2=0.12$, power=0.73). The post hoc tests showed the anti-phase mode duration increased from the early to the late stance, while for the interactions: 1) for 5-6 years old group, this duration was longer at the late stance than the other two stance subphases, and similar between early and middle stance; 2) for 7-8 years old group, this duration was longer at the late stance than early stance, and similar between early and middle stances, and between middle and late stances; 3) for 9-10 years old group, there was no difference among stance subphases; 4) for early and late stances, this duration was similar among groups; and 5) for middle stance, 9-10 years old group presented longer anti-phase mode than 5-6 years old group. The proximal phase coordination mode was affected by stance subphase ($F_{2,83}=76.1$, $p<0.001$ partial $\eta^2=0.67$, power=1.0) and group ($F_{2,83}=4.9$, $p=0.01$ partial $\eta^2=0.11$, power=0.79); and post hoc tests showed the proximal mode duration was similar between early and late stance, and both were longer than the middle stance, and this mode duration was longer for the 9-10 years old group than the 5-6 years old group. The distal phase coordination mode duration was affected by the stance subphase ($F_{2,83}=32.0$, $p<0.001$ partial $\eta^2=0.46$, power=1.0) and group ($F_{2,83}=3.1$, $p=0.04$ partial $\eta^2=0.07$, power=0.58); and post hoc Tukey tests showed this duration was longer at the middle stance than the other two subphases and it was shorter at late stance than the other two, and this duration was longer for 5-6 years old group than 9-10 years old group.

Figure 3 depicts the coordination variability divided by groups and stance subphases. The variability of all four coordination modes duration was calculated using the coefficient of variability (CV).

The coordination class predominance was calculated across groups and stance subphases (Figure 4). The most common coordination type was accounted as the mode value. For the 5-6-years old children group, and for all stance subphases, the serial coordination strategy was the predominant. For the 7-8-years old children group, and for all stance subphases, the serial coordination strategy was the predominant. For the 9-10-years old children's groups, the serial coordination strategy was the predominant coordination class for the early and mid-stance subphases, while the mixed coordination strategy was the predominant coordination class for the late stance phase, because none of the coordination classes (parallel or serial) presented duration longer than 55%.

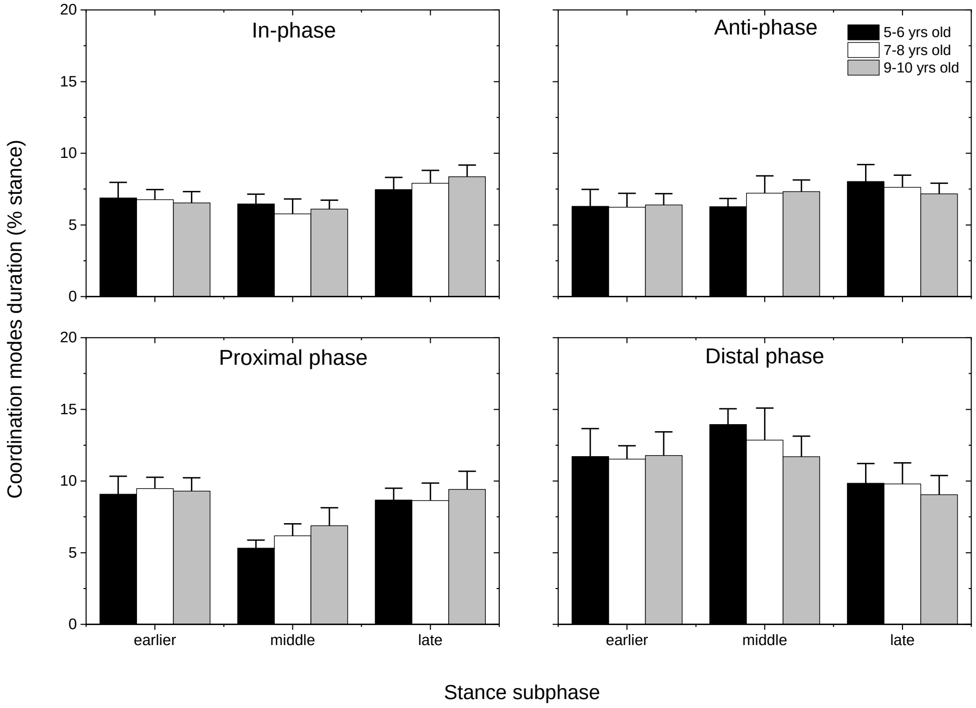

Figure 2. Coordination mode duration (% stance) during stance subphases according to age groups (5-6 years old, 7-8 years old, 9-10 years old) for each coordination mode (in-phase, anti-phase, proximal phase, and distal phase).

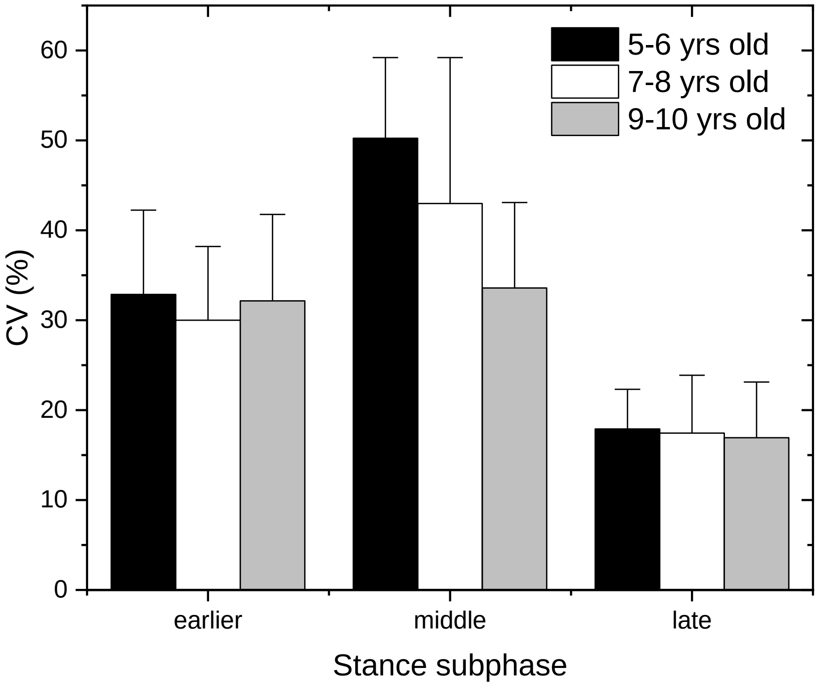

Figure 3. Variability of Coordination mode duration, expressed by the coefficient of variance during stance subphases according to age groups (5-6 years old, 7-8 years old, 9-10 years old).

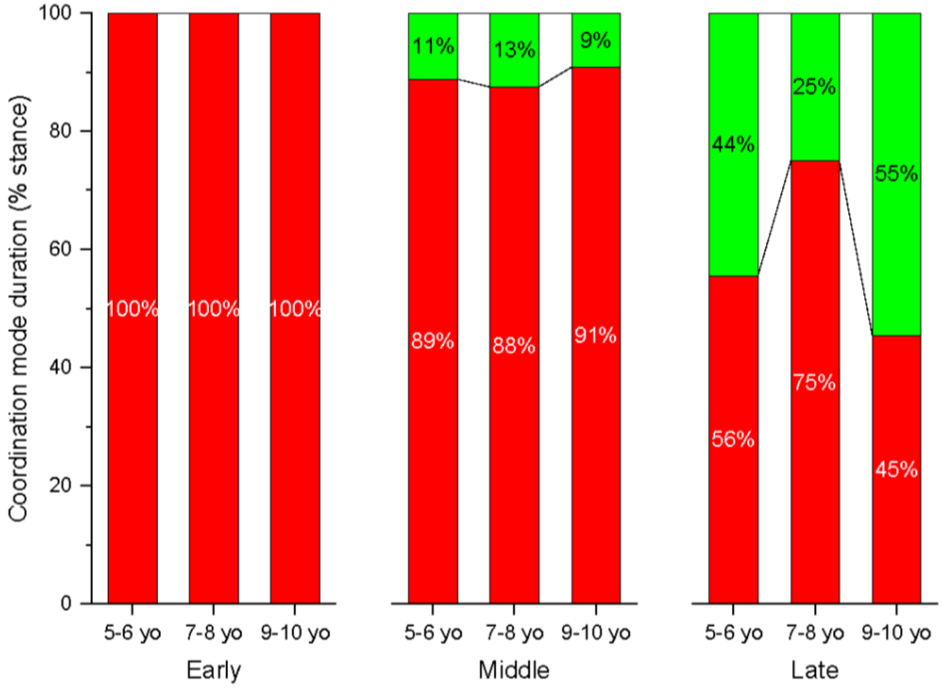

Figure 4. Predominant coordination mode class according to groups and stance subphases. Red corresponds to serial coordination and green corresponds to parallel coordination.

DISCUSSION

How does the inter-joint coordination modes gait change in typically developing children? We expect older children would show lower coordination variability during single support phase and gait maturity could be expressed in terms of coordination. The mid-stance has presented a higher coordination variability compared with other stance subphases, and such variability decreased for older children. Dynamical gait stability during mid-stance is important because it is a single leg stance situation, when children must manage simultaneously the swing leg dynamics and its weight bearing, and to balance the whole body upon the supporting leg. Under such circumstances, our results suggest gait is oriented to a less coordination mode variability. While serial coordination was predominant for the younger, parallel coordination appeared in older children. In parallel coordination, both joints are moving, increasing the demand for attention and control. Curiously, mid-stance is also the critical phase in the elderly [20]. Older adults usually present decreased coordination variability during this phase [21] and it could indicate how hard balance control is during single support phase.

Coordination modes during load response and propulsion phases were similar among 5-10-years old children. Gait load response changes from 2 to 21 years old [22] were evaluated using different criteria to define support subphases. For gait cycle, mid-stance and mid-swing terms did not have a universal definition [23]. We defined the gait phases in time. The coordination modes sequence was separated into the early stance (0-32% stance phase), middle stance (34-64% stance phase), and late stance (66-100% stance phase) phases. For each stance subphase, it was accounted how long the four coordination modes have lasted. Gibson [23] suggested mid-stance and mid-swing should be located at the midpoints of their cycle phases, as was did in this study. This is important to improve reproducibility and comparison among studies. Typically developing children and children with cerebral palsy were more stable walking at the preferred speed [24].

Coordination variability and gait stability are related. For all groups, the highest coordination variability occurred during the single support phase. Mastering the degrees of freedom is an important milestone in development [25], meaning to control simultaneous degrees of freedom in dynamic equilibrium situations, such as locomotion. Finding the proper coordination mode within joints and lowering the coordination modes variability as children are older suggest these issues are important quests for an optimal solution. Lower coordination variability indicates that few changes were produced in the coordination modes during the action, and it might suggest that 1) the optimal motor solution has already been found, or 2) the system is not able to find an optimal solution, therefore it prefers to show a stereotyped solution. Based on our results, for 5-6 years old children, more variability during the mid-stand phase suggests the use of different coordination approaches to support the body weight during the single support. Thus, lowering the coordination mode variability from 5 to 10 years old might answer the quest for optimal variability [26].

From 5 to 10 years old, the coordination gait variability decreased. The coordination variability, as CV, was calculated for each coordination mode duration. In our results, coordination variability decreased from the youngest group to the oldest group. Ankle joint angle variability decreased from 4-6 to 7-9 years old, and from 7-9 to 15 years old [27]; while 4-years old typically developing children had higher gait stride time variability than 7-years old children, 6-7-years old children were more variable than 11-years old, and 11-14-years old children and young adults had similar gait stride time variability [28]. The coordination mode duration indicates how long a coordination mode occurs during gait. Lower variability in the coordination modes suggests there are less changes in the types of coordination mode along children's development.

Double and single support phases have different coordination variability. Typically developing children showed higher coordination variability at the early stance than for the late stance. Comfortable and fast walking speeds induce different propulsion strategies in younger (6-9 years old) and older (9-13 years old) children [29]. Only fast walking induced changes in propulsion strategy in older children. Our results must be carefully evaluated. Comparing stance subphases, the coordination variability reduced during double support phases compared with the mid-stance; and it was the lowest for the late stance, during propulsion and toe-off. We could expect coordination variability during the double support phases to be similar because right and left lower limbs have similar motion patterns in typically developing children, suggesting a coordination symmetry. Children showed increased symmetry for loading foot parameters during gait as they become older [30], and for spatial-temporal gait measures (stance time, single and double support) [31]; although, gait may not be mature by age 13. Typically developing children have similar lateral stability for both dominant and non-dominant limbs, while children with cerebral palsy, only for the non-dominant limb, were more stable in body weight support compared with typically developing children [32]. As maturity develops, older children walk faster, increasing the single support stance phase and step length4. Less coordination variability during push-off suggests an optimal coordination mode pattern is achieved earlier than for foot strike in childhood.

Coordination modes can be grouped into parallel and serial coordination. The serial coordination is a less complex coordination because just one joint is moving, while for parallel coordination, two joints are moving at the same time. Two joints moving at the same time is an expected movement pattern in gait [19,20]. For all groups, the foot strike and midstance had a serial coordination predominance. For older children, a predominant serial coordination strategy shifts to a mixed coordination at the push off. Therefore, an optimal coordination quest during push off is moving towards the parallel coordination. In serial coordination (proximal or distal coordination modes), just one joint is moving while the other is still; on the other hand, in parallel coordination (in phase and antiphase coordination modes), both joints are moving at the same time. Thus, one-joint motion is less complex than two-joint motion, suggesting parallel coordination might be more complex than serial coordination. The shift from serial coordination to parallel coordination over the years can be explained by motor control maturation, allowing more joints to be controlled at the same time. To overcome an incoordination condition, people with cerebellar ataxia [18] decreases the swing phase and increases the double support phase because during the single support the balance control is unstable [33].

One limitation of this study is not measuring any other motor development milestone to describe the participants. This is an observational study, with a small sample based on a snowball sampling strategy. In our study, variability measures reflect inter-joint coordination changes, not the standard joint motion patterns in time. Another limitation is sample size; and future research should develop larger-scale cross-sectional and longitudinal studies based on these specifications to confirm our proposed coordination milestones.

CONCLUSION

Mastering balance control is crucial to develop the bipedal locomotion in childhood [4,5,14]. During the single support, balance control manages the combination of a static equilibrium condition (by the support leg) and dynamical equilibrium condition (by the swing leg); while during the double support, the balance control has a closed kinetic chain to stabilize the whole body. These completely different balance situations that children need to master to walk independently over any surface and condition. Since development arrow might overcome the incoordination states to coordinate states, we would expect that the coordination variability should be different between single and double support phases across groups. This was true for our results, but the coordination variability decreased during the single support phase, and not for the single support as we were expecting, rejecting our hypothesis.

Changes in inter-joint coordination were mostly related to the mid-stance phase. Its variability decreased as children were older. Results showed a shift from serial coordination to parallel during the mid-stance phase for older children. Our results suggest gait changes could be oriented towards a less coordination mode variability with development. Based on our findings, the clinical gait analysis could hold attention to the coordination modes in different populations to describe how a health condition changes motor coordination. Studies based on larger samples could describe how the coordination variability changes during motor development to evaluate whether our suggestion of coordination milestone is correct. Such findings will significantly improve how educators, healthcare professionals, and parents could track motor development, offering insights into effective strategies for enhancing children’s motor skills. Furthermore, further investigations could explore the factors shaping the gait developmental trajectory, including the influence of physical activity, environmental conditions, and neurological factors. Such inquiries can refine our understanding and inform targeted interventions for promoting optimal motor development in children.

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Citation: Mochizuki L, Pennone J, Ferreira DRMJ, Neiva JFO, Manfio EF . (2024). Inter-joint coordination changes during walking in typically developing children: the vector coding analysis. *Brazilian Journal of Motor Behavior*, 18(1):e417.

Funding: Nothing to declare.
Competing interests: The authors have declared that no competing interests exist.
DOI: https://doi.org/10.20338/bjmb.v18i1.417