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Research article

Risk of using smartphones while walking for digital natives in realistic environments: Effects of cognitive–motor interference

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ABSTRACT

The effect of using smartphones while walking on the cognitive and physical abilities of the "digital native" generation, i.e., individuals who have grown up in a digital media–centric environment, remains poorly understood. This study evaluated the effects of cognitive–motor interference on the use of smartphones while walking in children and young adults. The study involved 50 individuals from the digital age generation, including 24 children and 26 young adults. The study encompassed three experimental conditions, in which participants were instructed to traverse a distance of 60 m. The initial condition functioned as a control, wherein the participants walked without supplementary stimuli. In the second condition, the participants were provided with explicit instructions to grasp the smartphone device and position it in front of their chest by using both hands. This manipulation introduced a postural component into the experimental setup. The third condition required participants to be ambulatory while concurrently engaging in a cognitive task, namely, participating in a game that necessitated focused attention. Gait parameters were obtained by using inertial measurement unit sensors. Subsequently, the acquired gait characteristics were converted into dual-task costs (DTC). In the cognitive condition, children exhibited significantly greater DTC values for gait speed (76%), stride length (79%), stride time (102%), and stride length coefficient of variation (CV) than the young adults ($p < 0.025$). Moreover, as shown by the increased CV, a significant association exists between poor performance in smartphone games among children and increased variability in stride length. In children, the DTC of stride time CV decreased as smartphone game scores increased ($R^2 = 16.5\%$), and the DTC of stride length CV decreased more markedly as smartphone game scores increased ($R^2 = 28.2\%$). In conclusion, children are at a higher risk of pedestrian accidents when using smartphones while walking compared to young adults.

1. Introduction

Smartphone use has become ubiquitous in contemporary society, with individuals frequently engaging with their smartphones while in transit [1,2]. The generation commonly referred to as "digital natives," are individuals raised in an atmosphere saturated with digital media and exhibit a significant reliance on smartphones in their daily routines. They frequently use smartphones even while traversing pedestrian pathways or crosswalks [3,4]. Recently, safety incidents resulting from the use of smartphones by children and

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List of abbreviations

CMI	cognitive–motor interference
DTC	dual-task costs
CV	coefficient of variation
IMU	inertial measurement unit

young people while engaged in pedestrian activities have notably increased [5,6]. Compared with other age cohorts, individuals under the age of 35 years make more emergency calls owing to mishaps resulting from smartphone use while walking. The annual incidence of hospital admissions for young individuals has shown a consistent upward trend [7,8]. Furthermore, statistical data revealed that a significant proportion (80%) of accidents occurred within traffic facilities [8]. Specifically, younger pedestrians have an increased incidence of accidents [5]. Therefore, safety mishaps frequently occur because of distractions associated with the cognitive processes of pedestrians [9–12].

The act of using a smartphone while walking is often regarded as a form of multitasking [13–16]. Multitasking involves the simultaneous utilization of cognitive and physical resources [17]. The completion of multiple tasks leads to cognitive–motor interference (CMI) because this type of activity requires cognition and locomotion to compete for or share central resources [18–21]. CMI refers to the phenomenon in which the execution of cognitive and motor activities concurrently leads to a decrease in performance in either or both tasks compared with when these tasks are performed individually (referred to as single-task performance) [22–24]. Specifically, CMI will probably result in increased instability in the gait of children with deficient cognitive–motor functions as they progress in their development [25–27].

There are discernible disparities in physical functioning between children under the age of 10 years and young adults, and these differences cannot be solely attributed to variations in body size. Typically, a positive correlation exists between the magnitude of the performance average and variability level. Nevertheless, when assessing a child's physical function, a significant disparity exists in the variability of movements indicated by the standard deviation or coefficient of variation (CV) despite the relatively high average performance level. This has been empirically demonstrated in a range of tasks, including isometric force control [28] and walking [29]. After accounting for height, weight, and walking speed, no discernible disparity in the average gait characteristics was found in boys aged approximately 9 years compared with young adults. However, an increase in gait variability was notable, as indicated by the CV [29]. This observation demonstrates that the differences in the gait of children and adults cannot be attributed only to variations in body size and could also stem from disparities in internal neuromodulatory mechanisms [30]. Consequently, drawing from prior research findings, the control mechanisms of children will exhibit distinct characteristics when engaging in dual-task activities during ambulation compared with those of young adults.

The use of smartphones while walking is a complex task that simultaneously requires cognitive focus and visual–motor coordination [16,31,32]. Multiple task factors are responsible for the instability in locomotion. For example, smartphone use while walking, texting, and gaming causes considerable cognitive interference, thus resulting in decreased gait velocity (41%); increased step time (24%); decreased step length (28%); and decreased walking performance, such as cadence (18%) [1,18]. In addition, the characteristics of smartphone use while walking, namely, fixed arms without swinging, lowered head, and not looking directly ahead, reduces the kinematic locomotion variables (the percentage of increase) and the natural coordination between segments, thus decreasing the angle of the ankle joint (13%) and the range of mediolateral position (25%) [33,34]. CMI, which is caused by the simultaneous demand for cognitive and motor performance while walking, causes gait instability; therefore, it is essential to quantify CMI to comprehend the mechanism of smartphone-induced gait instability. DTC is a simple and practical method for quantifying CMI involvement in locomotion [35–38] and the degree to which dual-tasking reduces motor performance [39]. DTC enables the objective evaluation of the CMI of locomotion regarding smartphone use among young adults and children.

A recent study documented that the use of smartphones among young adults has a discernible effect on their walking performance compared with abstinence from smartphone use [4]. However, the extent to which this interference affected dual-task performance in children engaged in smartphone use while walking was not examined. Objective quantification was not feasible, and the degree to which cognitive or physical interruption during this period affects the difficulty of walking in children compared with relatively young adults is unclear. Furthermore, the findings of investigations on the effect of dual tasks on children's walking behavior have primarily relied on extrapolations from laboratory data. Consequently, disparities exist between these simulated conditions and real-life walking scenarios, thus potentially impeding a comprehensive understanding of the underlying mechanisms governing children's performance in dual-task situations. Hence, this study aimed to ascertain the comparative effect of CMI on children and young adults who are engaged in smartphone use while walking in real-world settings compared with controlled laboratory environments. An earlier study demonstrated significant increases in children's DTC for gait speed, step length, and cadence during dual-task conditions, such as the complex task of moving a cup with a pitcher or Tray [26]. These increases were observed across all age groups, reflecting the disparities in motor development between children and young adults. Therefore, we hypothesized that the impact of CMI on smartphone use while walking would result in a higher DTC of the average gait parameters and variability in children than in young adults. Specifically, children with increased levels of cognitive interference are expected to exhibit increased DTC for stride length and time, which are key spatiotemporal parameters of gait characteristics.

2. Materials and methods

2.1. Participants

A cohort of 50 individuals from the digital native generation was selected as volunteers for this study. A total of 24 children and 26 young adults who actively participated in the experimental procedures were recruited and included in this study. Participants were selected from two local elementary schools to represent the group of children, whereas university students were included in the group of young adults. Both the children and young adults owned smartphones. According to their responses, their primary use of smartphones includes web browsing, text messaging, and gaming. Table 1 displays the participant-specific data.

None of the participants exhibited signs of mental or physical illness, and they all had an unrestricted ability to walk independently. The participants provided informed consent prior to participation in the experiment in accordance with the ethical guidelines outlined in the Declaration of Helsinki. Participant attrition was not observed during the experimental process, and no adverse effects were reported by any of the participants even until the conclusion of the experiment. Consent forms were obtained from both, parents (legal representatives) and participants in the 9-year-old age group, whereas young adults provided their own consent for participation in the experiment. The present study was approved by the Bioethics Committee (IRB-2018-09-003-004).

2.2. Experimental procedures

The study employed a 7D inertial measurement unit (IMU) sensor (Physilog5®, GaitUp™, Lausanne, Switzerland) to evaluate the gait parameters. The IMU sensor consisted of a 3D accelerometer, 3D gyroscope, and 1D barometer. The initial configuration of the sensors was an accelerometer at 256 Hz, a gyroscope at 256 Hz, and a barometer at 64 Hz. Studies [40–42] have established the validity and reliability of the measurements of IMU sensors. In a previous study, the concurrent validity between the Physilog5® sensor and GAITRite was highly consistent for stride length (concordance correlation coefficient [CCC] = 0.975), stride velocity (CCC = 0.979), and stride time (CCC >0.996) [43]. IMUs have been proposed as a valuable tool for assessing children with ambulatory impairments in real-world settings [43,44]. The alignment and calibration of IMU sensors prior to measurement are not necessary because the Physilog® algorithm is capable of immediately estimating their values while walking [45]. Two IMU sensors were securely affixed to the dorsal surface of the foot of each participant. Raw data obtained from the IMU sensors affixed to each foot were collected and saved on memory cards. The data were then processed using GaitUp™ analysis package software installed on a desktop computer. Three initial steps were excluded from data analysis.

Before the experiment, the participants received a comprehensive explanation from the researcher and were guided by the experimental protocol. The participants performed sufficient preliminary practice within 10 min to familiarize themselves with the experimental environment and wear the equipment. Afterwards, they rested for approximately 5 min and participated in a walking experiment. The walking experiment was conducted in an authentic outdoor setting on a linear pathway (Fig. 1) rather than in a controlled laboratory environment. During the experiment, the participants were instructed to walk in a straight corridor while wearing the IMU sensors on both feet. Participants wearing the IMUs sensors walked under three randomly assigned conditions. In the

Table 1
Demographic, smartphone, and gait variables of children and young adults.

	Children (n = 24)	Young adults (n = 26)	P-value
Demographic information			
Age (years)	9.41 (0.21)	22.76 (2.08)	<0.01
Height (cm)	139.39 (5.96)	170.68 (9.85)	<0.01
Weight (kg)	37.11 (7.94)	68.77 (13.54)	<0.01
Gender (female/male)	12/12	14/12	NS
Smartphone usage information			
Smartphone use (yes/no)	24/0	26/0	NS
Smartphone usage period (month)	24.04 (13.96)	119.81 (21.07)	<0.01
Smartphone usage time (minute)	101.25 (76.06)	376.69 (167.62)	<0.01
Smartphone accident (yes/no)	0/24	0/26	NS
Smartphone game (score)	266.67 (135.01)	571.73 (372.47)	<0.01
Average gait parameters			
Gait speed (m/s)	1.25 (0.13)	1.33 (0.16)	0.04
Stride length (m)	1.18 (0.09)	1.38 (0.15)	<0.01
Stride time (s)	0.96 (0.06)	1.04 (0.05)	<0.01
Stance phase (%)	60.96 (1.68)	61.16 (1.57)	NS
Swing phase (%)	39.03 (1.68)	38.83 (1.57)	NS
Double support phase (%)	21.73 (3.12)	22.36 (3.17)	NS
Gait variability			
Stride length CV (%)	4.04 (1.06)	2.73 (0.49)	<0.01
Stride time CV (%)	3.73 (1.04)	2.13 (0.69)	<0.01
Stance phase CV (%)	2.54 (0.83)	1.77 (1.10)	0.01
Swing phase CV (%)	3.99 (1.32)	2.78 (1.71)	0.01
Double support phase CV (%)	11.19 (3.89)	8.15 (4.16)	0.01

Data are presented as mean (SD). SD: standard deviation; CV: coefficient of variation; NS: not significant.

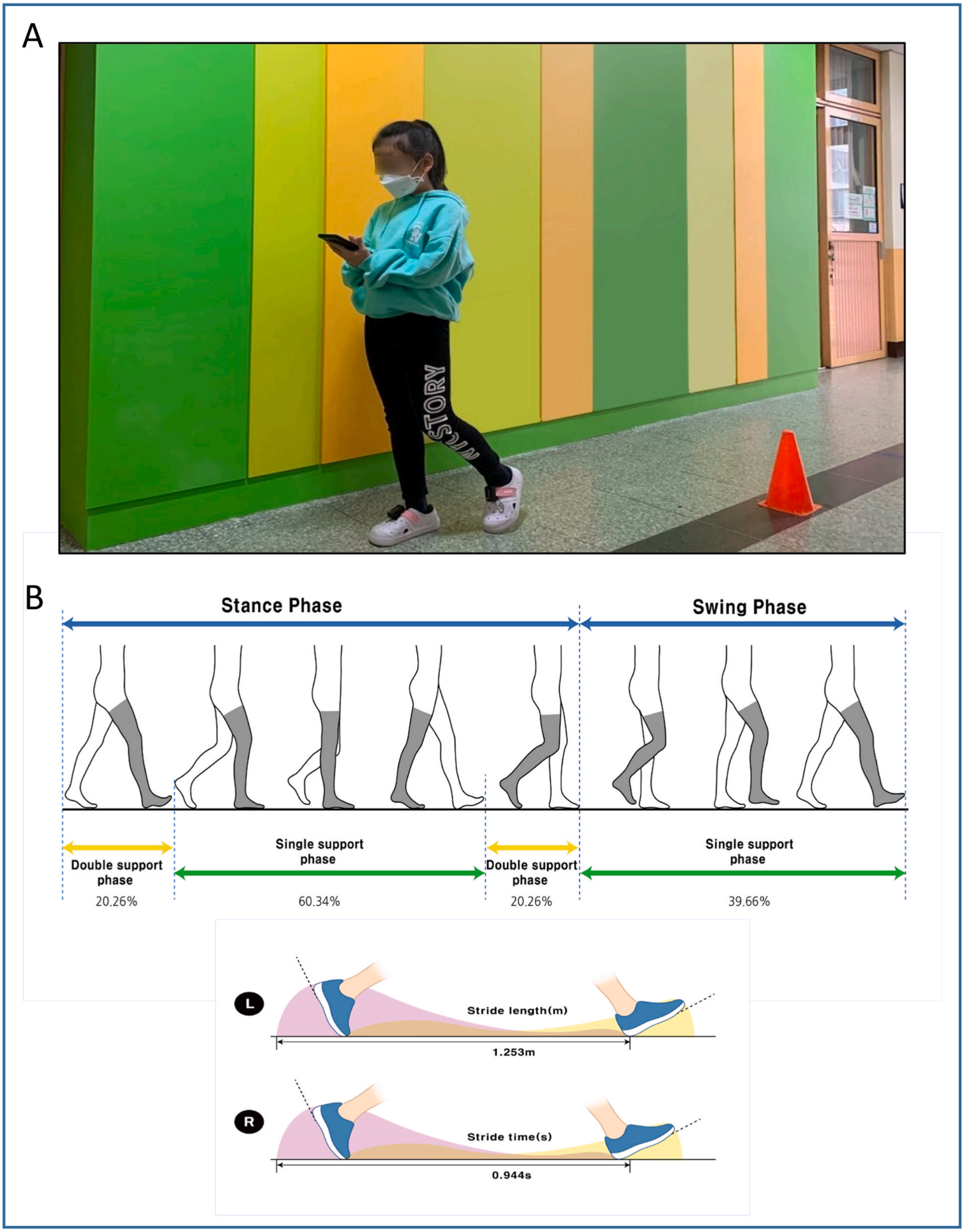

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Fig. 1. (A) An example of a walking protocol while a child is using a smartphone. There are three walking protocols: (1) normal walking without a smartphone, (2) walking while holding a smartphone with both hands (postural condition), and (3) walking while playing a smartphone game (cognitive condition). At this time, relative posture and cognitive walking DTC compared with normal walking were calculated. For each trial, gait parameters were collected from the inertial measurement unit sensors in the 60 m realistic environment. (B) Example of gait parameters and average values calculated from an IMU sensor in a child.

first protocol, the participants engaged in a 60 m walk under normal settings, which served as the baseline measurement. In the second protocol, the participant assumed a postural position by holding the smartphone with both hands in front of the chest and then walking for 60 m (postural condition). First, the participants' smartphone posture conditions were controlled as follows: They were instructed to hold the smartphone with both hands and form a smartphone perpendicular to the solar plexus of the chest. In particular, we requested that both elbows be in close contact with the area under the side armpits so that the chest and smartphone were perpendicular. At this time, the vertical distance between the chest and smartphone may vary depending on the participant's arm length, but all participants could be controlled in a comfortable position while using the smartphone. In the third protocol, the participant proceeded to grasp the smartphone firmly with both hands and walked for 60 m while engaging in a game that demanded cognitive attention (cognitive condition). Emerging evidence has indicated that smartphone games play a significant role in the occurrence of accidents and injuries among younger individuals immersed in distracted walking. These games impose a considerable amount of cognitive interference, surpassing that induced by less complex activities such as Internet browsing and sending text messages [46–49]. The selection of gaming as our focus was based on its higher level of cognitive interference compared to less complex activities such as web browsing and texting, as well as its quantifiable nature. Specifically, the 'Tetris' game was chosen because of its accessibility across different age groups and its ability to accurately measure scores related to time limitations and cognitive interference. A previous study with similar objectives used the same Tetris game [48]. The smartphone game in question was the Tetris game developed by N3TWORK Inc. (California, United States) and involved the accumulation of points. The participants were given explicit instructions to concentrate on the game while walking and to strive to achieve the highest potential score. The mean scores achieved by children and young adults in the game were 266.67 ± 135.01 and 571.73 ± 372.47, respectively. The smartphone used in this study was a Samsung Galaxy S10 5G (Samsung, Seoul, South Korea). It is characterized by its compact size, with dimensions of $162.2 \times 77.1 \times 7.8$ mm and weight of 208 g. The experiment took approximately 1 h and 20 min per participant, and a sufficient rest period of 10 min was provided for each experimental condition. The rest time was adjusted to 5–15 min depending on the participant's condition. Finally, no participants complained of side effects during the experiment, and no side effects were recorded after the study ended.

2.3. Gait parameters and smartphone usage information

Gait parameters calculated from the IMU sensor are defined in the text below.

Gait speed (m/s): Mean speed of forward walking calculated in m/s

Stride length (m): Represents the distance between two consecutive footprints on the ground spanning from the heel of one foot to the heel of the same foot in a single cycle.

Stride time (s): The time required to complete a full cycle.

Stance phase (%): The phase of the cycle in which part of the foot contacts the ground. Typically, the normal stance phase accounts for approximately 60% of the total duration of the gait cycle.

Swing phase (%): The phase of the cycle in which the foot is airborne and does not contact the ground. Typically, the normal swing phase accounts for approximately 40% of the overall duration of a gait cycle.

Double support phase (%): Occurs when both feet contact the ground during the cycle phase

We collected information on smartphone use from the participants through interviews and questionnaires. The following information was collected.

Smartphone use (yes/no): Refers to whether the participant possesses a smartphone under their personal name.

Smartphone usage period (months): Refers to the period since purchasing a smartphone.

Smartphone usage time (min): Refers to the average number of minutes spent on smartphones per day over the past three months.

Smartphone accidents (yes/no): Refers to whether there have been any accidents while walking or moving while using a smartphone in daily life in the past year.

Smartphone game (score): Refers to the score of Tetris, a classic puzzle video game, on the smartphone software. The main feature of the game is the manipulation of falling block pieces to complete a horizontal line. When the completed horizontal lines disappear, the player receives a high score. As the game progresses, the blocks fall faster, requiring quick judgment and reaction.

2.4. Data analysis

The data obtained from the walking analysis were divided into average gait characteristics to assess performance and gait variability and to quantify the extent of movement variability [50]. The average gait parameters were calculated as mean values, and gait variability was determined as follows [51]:

$$CV\ (\%) = \left(\frac{Standard\ deviation}{Mean}\right) * 100$$

The computed average gait parameters and variability encompassed spatiotemporal gait characteristics, such as gait speed, stride length, stride time, stance phase, swing phase, and double support phase. The aforementioned variables were computed using the DTC method, which includes the average gait characteristics and corresponding variability, as outlined below.

The calculation of the DTC for average gait parameters and variability involved computing the discrepancy between single-task performance (normal walking) and dual-task performance (both postural and cognitive walking). This discrepancy was then divided by single-task performance and was multiplied by 100. The equations are as follows.

First, the average gait parameters, including the stride time, stance phase, and double support phase, were determined using the equation provided by reference [18]. The DTC of the average gait parameters was determined on the basis of the following equation [18]:

$$DTC\ of\ average\ gait\ parameters = \frac{dual\ task\ value - single\ task\ value}{single\ task\ value} * 100.$$

Second, the DTC coefficients for the average gait parameters, including gait speed, stride length, and swing phase, were calculated on the basis of the equation provided in reference [18]:

$$DTC\ of\ average\ gait\ parameters = \frac{single\ task\ value - dual\ task\ value}{single\ task\ value} * 100.$$

Third, the calculation of DTC for gait variability parameters, including stride length CV, stride duration CV, stance phase CV, swing phase CV, and double support phase CV, was performed using the following formula:

$$DTC\ of\ gait\ variability = \frac{dual\ task\ value - single\ task\ value}{single\ task\ value} * 100.$$

A decrease in motor function is indicated by a positive DTC of the average gait metrics and variability.

2.5. Statistical analysis

The Shapiro–Wilk test was used to assess the normality of the dataset [52]. The current study compared demographic information, smartphone information, average gait parameters, and gait variability between children and young adults. This comparison was performed using statistical tests, such as the independent sample *t*-test and the Mann–Whitney test. This study manipulated two independent variables: group (children and young adults) and task circumstances (postural and cognitive conditions). The dependent variable of interest was the DTC observed in gait characteristics, including the average gait parameters and gait variability. This study also examined the influence of the CMI on the behavior of children and young adults regarding smartphone use while walking. The statistical analysis used to determine the significance level was a two-way repeated-measures analysis of variance (ANOVA), with one factor between groups and one factor within groups. The results confirmed the effect of the CMI on walking while using smartphones at a significance level of 0.05. The interaction effect between groups was subjected to post hoc testing, which involved multiple comparisons with Bonferroni correction. The level of significance was recalibrated to 0.025 by dividing 0.05 by 2. We hypothesized that the interaction effect would show higher DTC values of DTC the average gait parameters and variability in children than in young adults. The association between the DTC measurements of the gait metrics and game scores in the cognitive condition was transformed into Z-values to normalize the data. Subsequently, the data were subjected to basic linear regression analysis. We hypothesized that, as cognitive interference increases, children's DTC of average gait parameters and variability will increase linearly. Statistical analysis was performed using SPSS Statistics for Windows 23.0 (IBM Corporation, Armonk, NY, USA). The sample size for the two-way repeated-measures ANOVA was determined using G*Power 3.1.9.4 (Heinrich Heine Düsseldorf University, Düsseldorf, Germany) [53]. The estimated sample size required for the study was 46 individuals, which was based on an effect size (f) of 0.5, a significance level (α) of 0.05, and a power (1–β) of 90%. The partial eta-squared (η_p^2) was used to calculate the effect size for the two-way repeated-measures ANOVA. Cohen's d was used to ascertain the magnitude of the effect of the interaction. According to Cohen [54], the values of d (0.2, 0.5, and 0.8) are associated with effect sizes categorized as small, medium, and large, respectively. The effect size in simple linear regressions was determined using the product-moment correlation coefficient. According to Cohen's classification, correlation coefficients of 0.1, 0.3, and 0.5 represent small, medium, and high effect sizes, respectively [55].

3. Results

3.1. Demographic, smartphone, and gait variables in children and young adults

Table 1 displays the disparities in the demographic, smartphone, and gait variables between individuals belonging to the children and young adult groups. According to demographic data, children exhibited significantly lower values for age, height, and weight than young adults ($p < 0.05$). According to our findings, young adults exhibited higher levels of smartphone use period (month), smartphone use time (minutes), and smartphone game scores than children ($p < 0.05$). In terms of average gait parameters, children exhibited lower gait speed, stride length, and stride duration than young adults ($p < 0.05$). Additionally, children had larger gait variability across all parameters than young adults ($p < 0.05$).

3.2. DTC difference in average gait parameters for walking while using smartphones in children and young adults

These findings are shown in Table 2. The analysis revealed a significant interaction effect ($p < 0.05$) for all dependent variables related to average gait characteristics. According to the findings of a post hoc analysis of the interaction effect (see Fig. 2), the DTC of gait speed exhibited a statistically significant increase in children compared with young adults under cognitive conditions ($p = 0.001$, $d = 1.072$). Furthermore, the DTC of stride length exhibited a statistically significant increase in children compared with young adults under cognitive conditions ($p = 0.001$, $d = 1.260$). Furthermore, the DTC of stride time was considerably greater in children than in young adults in the cognitive condition ($p = 0.009$, $d = 0.784$). Statistically significant disparities were not observed in the DTC of the stance, swing, and double support phases between children and young adults in the cognitive condition. Furthermore, there were no statistically significant disparities in any DTC measurement of average gait characteristics between children and young adults under the postural condition. This condition involved walking while maintaining the same cognitive state and posture but without actively engaging in the game.

3.3. DTC difference in gait variability for walking while using smartphones in children and young adults

These findings are displayed in Table 2. A statistically significant effect was observed on the DTC measures of stride length, stride time, stance phase CV, and swing phase CV ($p < 0.05$). A statistically significant interaction effect was observed only in the DTC of stride length CV ($p < 0.05$). A post hoc test of the interaction effect (Fig. 2) revealed that there was a significant difference in the DTC of stride length CV between children and young adults in the cognitive condition ($p = 0.001$, $d = 1.293$). Furthermore, the CV for stride length in the dynamic task condition was considerably greater in children than in young adults ($p = 0.003$, $d = 0.954$). By contrast, the differences in the DTC of stride duration, stance, swing phase, and double support phase CV between children and young adults in the cognitive and postural conditions were not statistically significant ($p > 0.05$). Fig. 3 presents an overview of the findings obtained from this investigation.

3.4. Association between smartphone game scores and DTC of average gait parameters and gait variability in cognitive conditions

These findings are shown in Fig. 4. A significant correlation ($R^2 = 0.282$, $r = 0.571$) was observed between lower smartphone game scores in children and the higher DTC of stride length CV. Moreover, a significant correlation ($R^2 = 0.165$, $r = 0.483$) was observed between the decrease in smartphone game scores among children and the increase in the CV of stride time during dual-task conditions. Conversely, among young adults, there were no statistically significant correlations between smartphone game scores and DTC values for stride length and stride time CV.

Table 2
Results of the two-way repeated-measures ANOVA for the postural and cognitive DTCs of the average gait parameters and gait variability in children and young adults.

	Children (n = 24)		Young adults (n = 26)		Group effect	Condition effect	Interaction effect	
	Postural	Cognitive	Postural	Cognitive				
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	P-value	P-value	P-value	η_p^2
DTC of average gait parameters								
DTC of gait speed (%)	−2.51 (9.48)	24.36 (11.30)	1.87 (5.63)	13.83 (8.34)	0.14	<0.01	<0.01	0.36
DTC of stride length (%)	−1.49 (5.20)	17.35 (7.26)	1.41 (3.55)	9.65 (4.96)	0.04	<0.01	<0.01	0.38
DTC of stride time (%)	−0.27 (6.64)	10.78 (8.55)	0.74 (2.79)	5.33 (5.36)	0.15	<0.01	<0.01	0.24
DTC of stance phase (%)	−0.54 (2.18)	2.62 (3.19)	0.40 (1.69)	2.00 (2.26)	0.79	<0.01	0.01	0.11
DTC of swing phase (%)	−0.98 (3.51)	3.98 (4.89)	0.56 (2.75)	3.12 (3.53)	0.70	<0.01	0.02	0.10
DTC of double support phase (%)	−2.20 (11.70)	15.25 (14.56)	3.27 (9.96)	11.93 (11.48)	0.71	<0.01	0.01	0.11
DTC of gait variability								
DTC of stride length CV (%)	17.57 (33.54)	49.99 (52.93)	−6.90 (17.74)	0.98 (22.88)	<0.01	<0.01	0.02	0.09
DTC of stride time CV (%)	8.95 (44.53)	52.52 (50.72)	0.77 (21.57)	26.12 (47.20)	0.09	<0.01	0.15	0.04
DTC of stance phase CV (%)	9.64 (36.32)	40.95 (36.63)	−1.52 (31.88)	24.80 (37.13)	0.12	<0.01	0.62	0.01
DTC of swing phase CV (%)	7.89 (34.23)	50.46 (37.69)	−0.65 (31.97)	31.74 (40.07)	0.12	<0.01	0.35	0.01
DTC of double support phase CV (%)	10.96 (41.58)	15.82 (43.70)	3.78 (47.45)	4.33 (41.51)	0.40	0.61	0.69	0.01

Data are presented as mean (SD). SD: standard deviation; CV: coefficient of variation; DTC: dual-task cost.

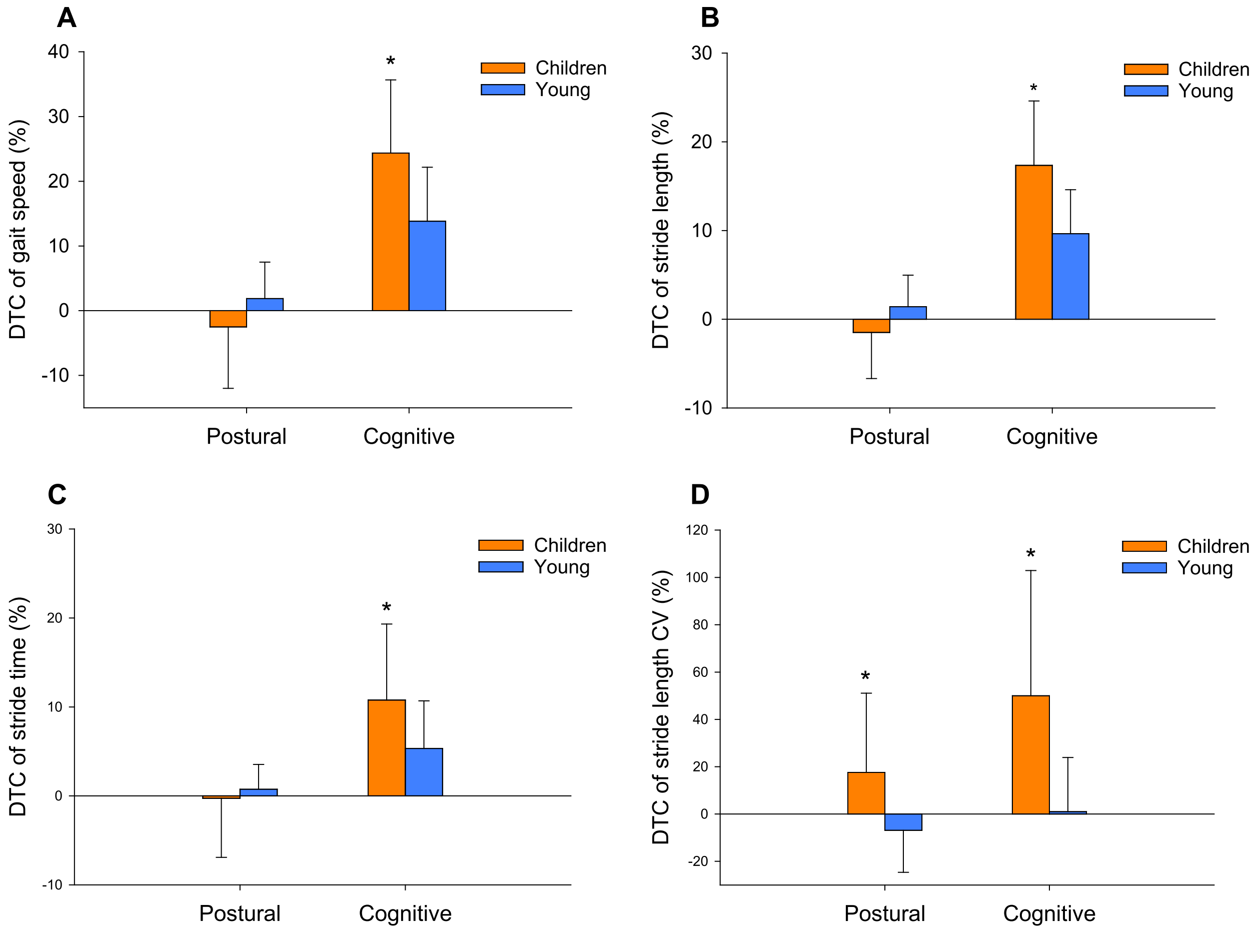

Fig. 2. Post hoc test results for the postural and cognitive DTCs of the average gait parameters and gait variability between children and young adults. "*" indicates a significant difference compared with young adults ($p < 0.025$). The p-value was strictly adjusted to 0.025 by Bonferroni correction.

4. Discussion

This study aimed to ascertain the comparative effect of CMI on smartphone use while walking in children and young adults. We measured the cognitive or physical interference that occurs during walking by using DTC measurements. This study confirmed the correlation between the scores achieved in smartphone games and the cognitive DTC associated with gait metrics. We hypothesized that the influence of CMI on smartphone use while walking would be more pronounced in children than in young adults. Additionally, we expected that children with lower scores in the smartphone game would exhibit higher levels of divided attention while walking, as indicated by the changes in gait characteristics. The primary findings of this investigation are as follows.

First, Children exhibited a decrease in average gait characteristics (6–16%) and an increase in gait variability (27–42%) during walking compared with adults. The stance phase observed throughout the entire gait cycle was approximately 61%, which closely aligns with the established range of 60–62% and denotes a physiologically pleasant gait. This suggests that both the groups were able to achieve a natural gait [56]. The absence of disparities in the characteristics pertaining to the relative proportions of the complete gait cycle such as the stance, swing, and double support phases further substantiated the attainment of a natural gait in both cohorts. Research has indicated that children, particularly those diagnosed with attention-deficit hyperactivity disorder (ADHD), tend to exhibit significant deficits in attention and increased variability in gait patterns [57]. Typically, the prevalence of elevated variability in children's gaits among those with ADHD is notable; however, this variability tends to diminish gradually with age and undergo consistent alterations [58,59]. Children exhibit higher levels of gait variability than adults because of their underdeveloped neuromuscular control. However, as children age and are more exposed to walking, they tend to exhibit reduced gait variability. Consequently, the gait patterns of children exhibit enhanced regularity and stability with age. This phenomenon was previously observed and documented [58]. The current study demonstrated that children have considerable gait variability as a trait that persists during natural walking.

Second, a significant interaction effect was observed between the group variable (children and young adults) and the condition variable (smartphone uses while walking) in relation to the difference in average gait characteristics for DTC. In the context of dual-

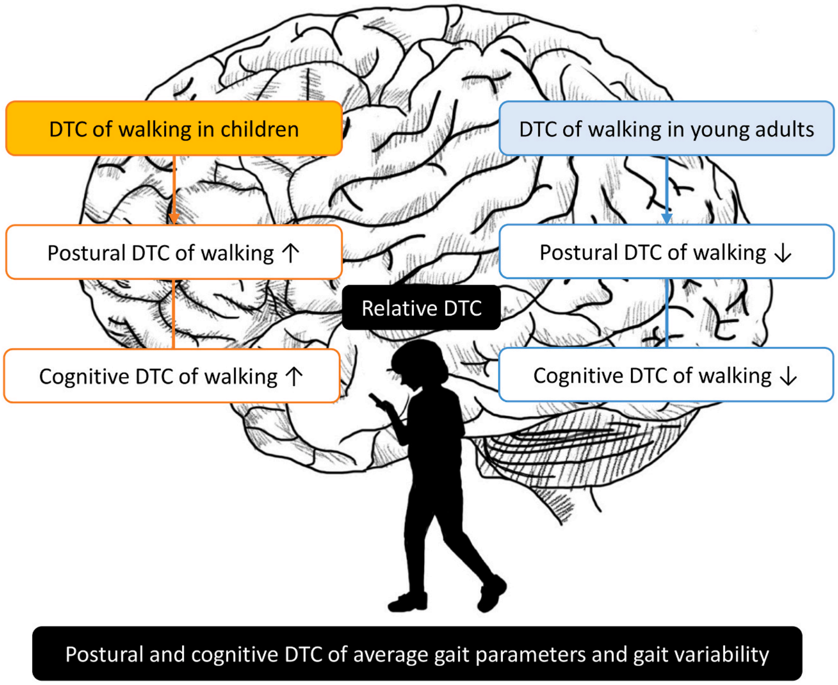

Fig. 3. Relative postural and cognitive DTC of average gait parameters and gait variability in children and young adults. Children had significantly higher postural and cognitive DTC of average gait parameters and gait variability compared to young adults.

task performance, children exhibited considerable increased DTC in many gait parameters, including gait speed (14.9%), stride length (8.24%), stride time (6.46%), stance phase (1.56%), swing phase (2.4%), and double-support phase (8.79%), depending on specific circumstances. This finding demonstrates a notable disparity in the performances of children and adults in dual-task scenarios. The findings of our study indicate the lack of a discernible disparity in DTC between children and adults when performing basic postural tasks while walking. However, a notable distinction in the DTC has been observed in cognitive settings. Caramia, C., C. D'Anna, S. Ranaldi, M. Schmid and S. Conforto [4] showed changes in gait parameters when children walked with a smartphone compared to when they walked without a smartphone. Their results showed that stride length (14.0%) and walking speed (26.8%) decreased in children. However, our findings clearly demonstrate that cognitive interference occurs when children walk while using smartphones and that this effect is greater in children than in young adults. The results of the present study clearly show differences in gait between children and young adults, unlike previous studies, and may provide a basis for a comprehensive understanding of the relationship between children's cognitive interference and gait.

Considering the age of the children involved in this study, which was approximately 10 years old, we inferred that the age at which walking performance is less influenced by a cognitive task is estimated to be at least 10 years old and beyond the period of puberty. Research has indicated that even young and healthy individuals exhibit a decrease in both walking and cognitive performance when engaged in a sufficiently challenging cognitive activity [60]. In a study comparing the gait patterns of young adults engaged in a cognitive task of sending a text message while walking, a decrease in both step duration and step length was discovered, but no significant differences in cadence were observed [1]. Furthermore, young adults do not exhibit any alterations in heel contact during the subphases of stance (duration) when engaging in the dual activity of walking and smartphone use [16]. The effect of cognitive tasks associated with internal interference factors appears to have a greater influence on human locomotor performance than on physical demands. This is because the risk associated with smartphone use while walking is not solely attributed to basic physical alterations in posture but rather stems from a multifaceted cognitive process that hampers safe walking. Cherng et al. [61] indicated that the nature of dual tasks (cognitive vs. motor) had an effect on DTC. However, the level of difficulty (easy vs. hard) and the presence of developmental coordination deficits did not have any significant effect on DTC. This finding suggests that the development of cognitive abilities associated with performing dual tasks simultaneously is primarily influenced by age-related maturation. Additionally, Cherng et al. [61] found that the presence or absence of disabilities did not affect dual-task performance; this further highlights the important role of age-related maturity in children's ability to handle dual tasks simultaneously.

Paphawee et al. [1] discovered that the visual and cognitive requirements of performing two tasks simultaneously while walking had a more pronounced effect on gait in older individuals than in younger individuals. However, they also observed that the gross motor demands associated with holding a phone were lower than those associated with walking owing to the lightweight nature of the phone. Pau, M., Corona, F., Pilloni, G., Porta, M., Coghe, G., and Cocco [62] reported that patients with Multiple Sclerosis (MS) decreased walking speed (30.1%) and stride length (6.3%) compared to healthy older adults of the same age when sending text messages on a smartphone while walking. These characteristics could potentially be a result of brain volume reduction and atrophy in

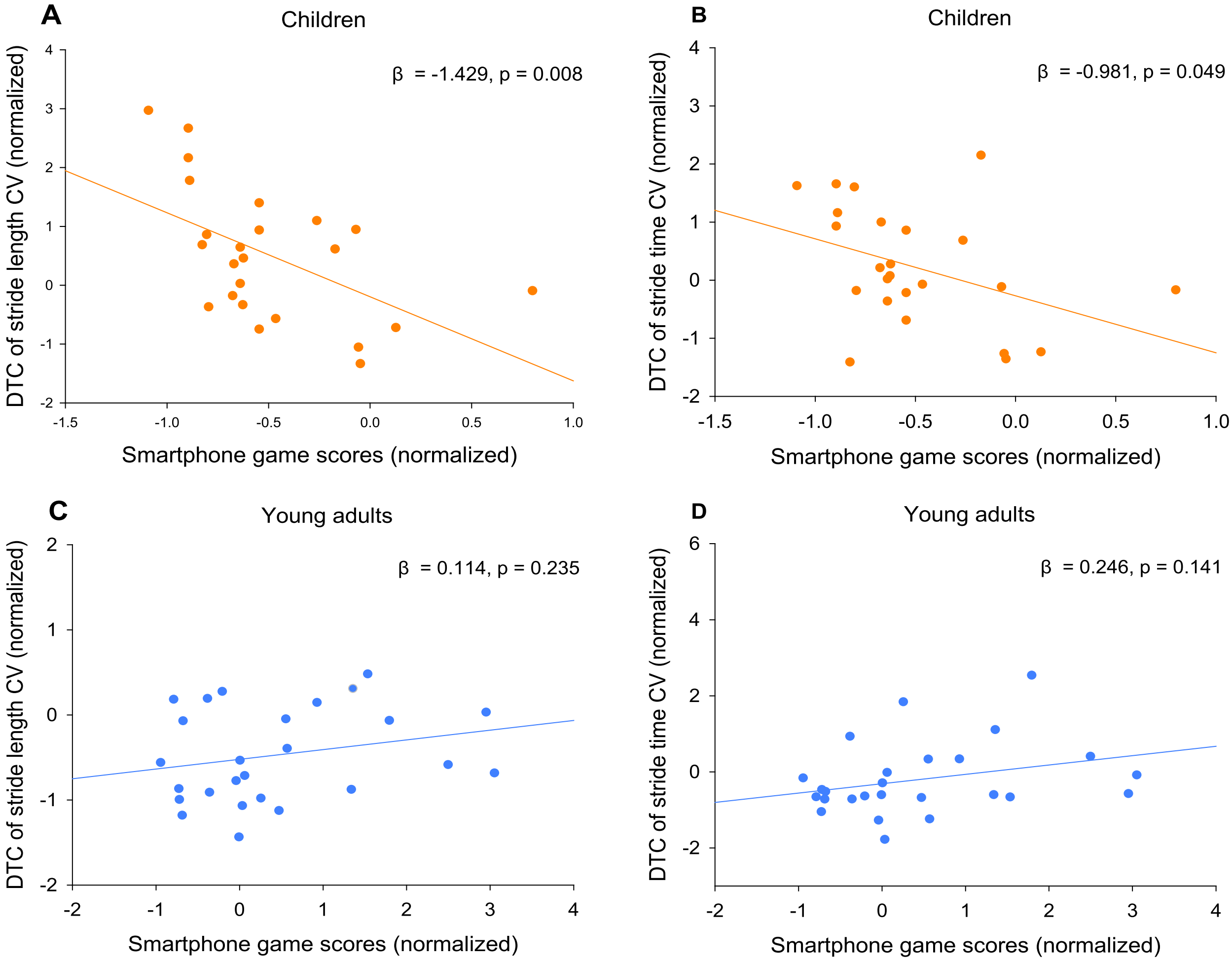

Fig. 4. Association between smartphone game scores and DTC of gait variability in the cognitive condition. Simple regression analysis showed that there was a significant association between these two factors in children ($p < 0.05$) but not in young adults.

the early stages as observed through magnetic resonance imaging (MRI) [63]. It is suggested that these changes gradually contribute to physical and cognitive dysfunction, thereby providing mechanistic and biomechanical evidence indicating a possible increase in vulnerability to brain injury [64]. These results suggest that symptoms indicating sensory abnormalities or cognitive decline (deterioration of central nervous system function or brain vulnerability) may be associated with potential difficulties in functionally performing the two tasks of daily living [65]. Considering the findings of prior research in conjunction with the current study, it is evident that a disparity exists in the effect of cognitive requirements based on age, as well as an interplay that differently influences walking ability at varying degrees across distinct age cohorts, namely, children, young adults, and older individuals.

Third, there was an interaction effect between the DTC difference of gait variability for smartphone use while walking in children and young adults and the DTC of stride length CV. Gait variability generally refers to irregularities in the central neuromuscular control system, which is responsible for regulating gait and maintaining a consistent gait pattern. This is closely linked to instability and the likelihood of falling. Previous studies have demonstrated that gait variability measures exhibit high sensitivity compared with other gait metrics and that the degree of variability may have a stronger correlation with fall risk than average gait speed, stride length, or stride time [50]. Additionally, the assessment of intraindividual gait speed variability provides additional and differential information regarding gait maturation [58]. In particular, changes in gait speed can provide essential and valid insights into physiological gait development [66,67]. Research has shown that gait variability generally continues to decrease with growth until eight years of age [66]. Considering that the age of the participants in this study was approximately 10 years old, the increase in variability shows that our results are not simply the result of immaturity. The difference from adults in dual tasks can be understood as a lack of adaptability to task characteristics [30,68]. The results of the current study confirmed that the use of smartphones while walking poses a risk to pedestrians because of the differences in physical posture, the dual task of concentrating on the game while walking, and gait variability. This suggests that the possibility of accident risk due to the increase in variability may be higher in children than in young adults.

Fourth, regarding the association between smartphone game scores and the DTC of average gait characteristics and gait variability in cognitive settings, the performance of children was impaired in both gait variability and game scores because of reciprocal interference. The concurrent use of smartphones while walking by children results in decreased smartphone game scores and increased gait variability. Notably, this phenomenon is attributed to the interference between the two tasks rather than the selective allocation of attention during the conflict between walking and smartphone use in children. CMI generally arises when individuals engage in dual-task performance while walking, thus resulting in a decrease in performance in one or both tasks compared with the performance of each task in isolation (single-task performance). This decrease occurs because of the simultaneous execution of cognitive and motor tasks during dual-task performance [22–24]. The extent of performance deterioration varies depending on the specific characteristics of the tasks involved, and instances in which the performance of both tasks is negatively affected are present even when only one task is executed. When young children walk while using smartphones, their performance in both activities decreases. This phenomenon demonstrates the inherent challenges associated with the concurrent performance of cognitive and locomotor tasks, which ultimately impairs the outcomes of both processes. This can be elucidated using the “bottleneck theory” within the framework of cognitive and information processing. During the execution of multitasking or complicated cognitive activities, a central bottleneck phenomenon can arise wherein limited cognitive resources are contested by various tasks or information sources [69]. This phenomenon has the potential to impede cognitive processing speed or substantially diminish the performance of certain activities [70]. Specifically, children experience more noticeable delays or errors in numerous replies when they engage in settings that include both motor responses and cognitive tasks, such as using a cell phone while walking. These fundamental differences may be explained by motor development-related processes. Because of the immature development of children’s cognitive and motor skills, their dual-task performance is often lower than that of young adults [71,72]. For example, from a motor and cognitive development perspective, children’s multitasking abilities, including attention, are still maturing. However, young adults can allocate attentional resources between tasks more efficiently [73,74]. Additionally, from a motor control perspective, children continuously refine their motor and longitudinal skills, making it difficult to coordinate multiple complex tasks [75]. Finally, compared to young adults, children lack more experience and hands-on skills in dual-task situations through everyday activities and formal education [73]. This can reduce the efficiency of various tasks. Hence, the impaired ability of children to perform dual tasks while walking can have a substantial negative effect on their ability to engage in functional mobility.

This study includes inherent and local limitations beyond general constraints. Inherent limitations include: First, this study estimated the effect of using smartphones while walking by using DTC. However, researchers have encountered limitations in collecting direct data on cognitive function. Second, challenges may be associated in the identification of the intricate relationship between human locomotion and smartphone use. To further validate the interaction effects, future research should prioritize the acquisition of a diverse range of experimental equipment and data. Third, future studies should consider larger sample sizes to generate more robust results. Local Limitations include: the participants in this study comprised a group exposed to the digital education system in a developed urban environment. These exposures may have had a direct impact on participants’ development, as well as their cultural and social factors. In other words, making relative comparisons with research results from other regions or cultures may be difficult to prove. Therefore, interpreting and generalizing the results of this study requires full consideration of regional limitations. Finally, we hope that future studies will offer new insights through these inherent and local limitations, and we highlight the need for follow-up studies to examine the risks of using smartphones while walking among individuals of various ages and diseases.

5. Conclusion

This study examined the effect of CMI on walking behavior during smartphone use, with a focus on the differences in influence across age groups. This effect was assessed by objectively evaluating the degree to which dual-task performance was affected. When examining the cognitive DTC related to average gait features and gait variability, children exhibited a higher DTC than young adults. A correlation was observed between lower scores on smartphone games played by children and the higher cognitive DTC associated with gait variability. These findings suggest that within the conflict that arises from performing two tasks simultaneously, there may be mutual interference rather than a focused allocation of attention to a single task. Future research requires substantial evidence to determine whether the mutual interference of the two tasks leads to motor deficits. In summary, the use of smartphones is a source of distraction while walking and may increase the vulnerability of children to potential pedestrian accidents compared with young adults.

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CRediT authorship contribution statement

Yungon Lee: Writing – original draft, Visualization, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Sunghoon Shin:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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