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Walking experience affects locomotor exploration in infants born prematurely: a comparative cross-sectional study

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Abstract

Background This study aimed to investigate the impact of premature birth on the locomotor exploration of infants with up to six months of independent walking experience.

Methods Participated in this study, 16 preterm infants (PT) (32.5 ± 3.59 weeks gestational age) with low birth weight (1.91 ± 0.66 kg) and low- and lower middle income (75%); and 15 full-term infants (FT) (38.93 ± 0.94 weeks gestational age) with normal birth weight (≥ 2.5 kg) and middle- or upper middle income (73.3%). Both groups had similar walking experience and motor development stages and they did not present any physical or mental impairments. Non-object-oriented natural locomotor exploration was measured by recording 20 min in a multidisciplinary laboratory room. Five toys were spread around the room to stimulate upright locomotion, without interaction from the caregiver. Real-time analyses of spontaneous locomotion were coded offline using Datavyu software.

Results PT and FT infants showed similar locomotor exploration, spending most of their time in standing locomotion (PT: 24.93%, FT: 35.46%) and exhibiting similar locomotor behaviors (i.e. average PT: 623 steps and 2 falls, FT: 995 steps and 3.27 falls). Spearman correlation across all infants showed that greater walking experience (measured in months) was moderately associated with more time in standing locomotion ($r = 0.546$, $p = 0.001$), a greater number of bouts ($r = 0.543$, $p = 0.003$), and less time in a sitting position ($r = -0.636$, $p = 0.00$). Linear regression showed that for infants in the FT group, there was a positive trend between walking experience and time spent in standing locomotion, number of bouts, and number of total steps. The greater the walking experience, the greater the locomotor exploration for FT infants. However, such a relation was not observed in the PT group .

Conclusions Walking experience can predict developmental changes in the exploratory locomotor behavior of FT infants, but not in PT infants, who exhibit different developmental trends compared to their peers. Opportunities gained with the increase in independent walking experience in the first six months of age do not seem to minimize the subtle impacts associated with being born prematurely on locomotor exploration, which reinforces the necessity for monitoring these infants in early intervention programs, even without motor or mental impairments.

Keywords Infant. premature. walking. locomotor. exploration. playtime

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Background

Prematurity, defined as birth before completing 37 weeks of gestational age (GA), is a significant global public health issue, affecting an estimated 13.4 million infants annually [1]. Due to incomplete intrauterine development, these infants usually present neuropsychomotor impairments, which, in turn, impact an unequal progression of their growth and development. Preterm (PT) infants' development is influenced by multiple factors including not only GA but also their neonatal profile (e.g. low birth weight), family income, and parental practices [2, 3].

Studies have shown that the lower the GA, the later the acquisition of independent walking. For instance, late PT infants walk independently at ~13.72 months, very PT at ~14.44 months, and full-term (GA ≥ 37 weeks) at ~12.24 months [4]. This delay in the acquisition of walking reflects more than just a motor delay – it highlights the centrality of motor development in shaping broader developmental trajectories. Motor development is not merely a domain of movement but a foundation for broader psychological growth.

As pointed out by Adolph and Hoch [5], motor skill acquisition is embodied, embedded, enculturated, and enabling—each new skill expands the infant's capacity to explore, learn, and adapt. Accordingly, reduced opportunities for self-initiated movement (i.e. infant exploration) can constrain not only motor learning but also the acquisition of cognitive and perceptual skills that may have future impacts on cascades of development. As a result of acquiring independent walking later, PT infants may be at increased risk of subsequent motor impairments in childhood [6] which, could lead to delays across multiple developmental domains; also, study [7] reported that PT infants from low-income families exhibit poor motor skills at 8 and 12 months, as well as a higher risk for cognitive and language impairments at 3 years of age.

Beyond the neuropsychomotor impairment linked to premature birth, PT infants also present less efficient exploratory behaviors in different body positions compared to their FT peers. For instance, at 6 months of age, extremely PT infants (GA ≤ 28 weeks) spend more time visually engaging with objects than actually manipulating and playing with the toys while lying on their backs [8]. Moreover, another study showed that extremely and very PT infants (GA ≤ 30 weeks) had less efficient postural control, fewer episodes of environmental exploration, and less variability in different body positions such as supine and sitting positions in the first 2 years of life [9].

Although studying non-object-oriented locomotor exploration (i.e. spontaneous activity) is important for infants' development, this area has been underexplored in PT infants without physical or mental impairments. One reason may be the subtlety of behavioral differences when compared to their FT peers, which makes the role of experience more difficult to observe. Locomotor exploration involves self-initiated movement through space that is often not directed at specific objects or destinations [10, 11]. Instead, these movements appear to function as a means of generating sensorimotor experiences about the body and the environment, even in the absence of external goals.

Evidence on spontaneous activity in PT infants is still relatively scarce, and only two classical studies have addressed this topic. The study by Hempel [12] examined how different groups of infants and children (mean age = 1.5 years, range = ± 4 years) explored an open space to play freely. This study focused on observing motor functions such as grasping, sitting, crawling, standing, and walking in infants and children who were at high risk of birth complications, such as premature birth. The authors found that infants and children in the PT group had a smaller range of movement in different body positions compared to their FT peers. Similarly, the study by Groot, Groot, and Hopkins [13] found that PT infants had poor locomotor and coordination patterns during exploratory activities 14 days after acquiring independent walking, as measured by a scale of locomotor movement patterns.

It is known that infants who learn to walk independently and engage early in locomotor exploration tend to become more independent in their developmental process [14]. Behaviorally, as they gain more walking experience, they tend to take more steps, cover greater distances, and experience fewer falls. This indicates that infants accumulate massive amounts of time-distributed, variable practice [14]. Therefore, walking ability improves with experience over time. In this sense, independent walking becomes more fluent, automatic, smooth, and consistent under different conditions and environments [15].

But what about PT infants? How do they explore their environment through walking ? Based on the challenges faced in achieving motor milestones, particularly independent walking during the first two years of life, we hypothesize that infants who were born preterm lack an effective means of exploring their surroundings through locomotion in comparison to infants who were born FT. Different biological and environmental factors might be linked to numerous developmental paths of initial locomotor exploration. Therefore, the primary aim of this study was to examine the locomotor exploration of PT infants and compare it with FT infants who had the same independent walking experience. Our secondary aim was to investigate how characteristics of infant growth and development (e.g. infant profile, anthropometric measurements, and independent walking experience) might impact locomotor exploration.

Methods and materials

Study design and participants

We carried out a comparative cross-sectional study between February and September 2023. Sixteen PT infants (GA = 32.5 ± 3.59 weeks) with 2.53 months (± 1.50) of independent walking experience, and low birthweight (1.91 ± 0.66 kg), and fifteen full-term (FT) healthy infants (GA = 38.93 ± 0.94 weeks) with 2.47 months (± 1.63) of independent walking experience, and birthweight ≥ 2.5 kg participated in this study after their parents or guardians gave written informed consent. Both groups were at similar stages of motor development and had the same average time of independent walking experience. Families were invited to participate through contact with multidisciplinary rehabilitation clinics and through social media. All infants were predominantly white, lower-middle class, and living in the same geographical area (residents of Bauru city in the Midwest of São Paulo state, Brazil). In addition, PT infants occasionally participated in an early intervention program with a multidisciplinary team. More information about demographic data and infant profile descriptions of all participants is shown in Table 1. As inclusion criteria, infants should be able to stand upright independently for at least 10 seconds, take at least three steps without support, and be no more than 24 months old. As exclusion criteria, the infants should not present physical or mental impairments that would affect the performance of the experimental procedures, including significant visual or motor impairments, and a history of severe neonatal illness with recent prolonged hospitalization. This study was approved by the local Ethics Committee (CODE: 60800622.0.0000.5398).

Table 1 Mean values and standard deviations (± SD) of demographic data and infant profile description from preterm (PT) and full-term (FT) infants

Variables	Categories/units	PT (*N* = 16)	FT (*N* = 15)
Sex	Boys	*N* = 9	*N* = 7
	Girls	*N* = 7	*N* = 8
Gestational age	Weeks	32.5 ± 3.59	38.93 ± 0.94
#Chronological age	Months	17.94 (± 3.37)	16.03 (± 3.06)
Corrected age		16.12 (± 3.43)	-
*Age of onset walking		15.41 (± 1.50)	13.57 (± 2.20)
Independent walking experience		2.53 (± 1.50)	2.47 (±1.63)
Current weight	Kilogram	9.79 (± 1.81)	10.00 (± 1.59)
Current Height	Meters	0.77 (± 0.05)	0.77 (± 0.04)
Birth weight	Kilogram	1.91 (± 0.66)	3.30 (± 1.59)
Adequacy of birth weight to gestational age	Small for GA	37.5% (6)	6.67% (1)
	Suitable for GA	62.5% (10)	86.67% (13)
	Large for GA	0% (0)	6.67% (1)
*Length of stay in hospital after birth	Days (*n* = 29)	30.33 (± 21.14)	2.33 (± 1.35)
Income	Upper middle class	0% (0)	20% (3)
	Middle class	25% (4)	53.33% (8)
	Lower middle class	25% (4)	26.67% (4)
	Low-income class	50% (8)	0% (0)
Race	White	68.75% (11)	100% (15)
	Brown	31.25% (5)	0% (0)
Multidisciplinary team	Yes	56.25% (9)	26.67% (4)
	No	43.75% (7)	73.33% (11)

Symbol # = trend of statistical difference ($p = 0.058$). Symbol * = statistically significant difference ($p < 0.05$). Chronological age ($F_{1,19} = 4.092$, $p = 0.058$), age of onset walking ($F_{1,39} = 3.74$, $p < 0.03$), independent walking experience $F_{1,30} = 0.013$, $p > 0.05$), current weight ($U = 95.5$, $p > 0.05$), current height ($F_{1,30} = 0.0001$, $p > 0.05$), birth weight ($U = 5$, $p > 0.05$), Length of stay in hospital after birth ($n = 29$ data available, $U = 184.5$, $p < 0.0001$). Adequacy of birth weight to gestational age was referenced from INTERGROWTH-21st (https://intergrowth21.tghn.org/), family income (upper middle class – between R$10,450.01 and R$20,900; middle class – more than R$4,180 to R$10,450; lower middle class – between R$2,090.01 and R$4,180; and low income – up to R$2,090). The "multidisciplinary team" variable indicates the percentage of infants received support from early childhood professionals (e.g., physiotherapy, occupational therapy, psychomotricity, speech therapy, or psychotherapy). Specifically, PT children primarily accessed these services for follow-up care due to their increased neuropsychomotor risk, especially, in lower socioeconomic contexts. Conversely, some FT infants participate in structured motor activities, mainly for health promotion and developmental stimulation. Source: the authors.

Experimental procedures

Parents or caregivers of the infants answered an electronic form with questions focused on the infant's health conditions and family history, the current state of infant growth and development, participation in daily activities, and socioeconomic profile. The questionnaire was structured from the International Classification of Functioning, Disability, and Health (ICF model). In-person, the infants participated in a 20-minute session of non-object-oriented natural locomotor exploration. The multidisciplinary laboratory room (five meters x three meters) had cold-colored walls, no illustrations, and the floor was partially covered with rigid foam tatami mats. Five toys were spread around the room to stimulate upright locomotion: a doll car, a racing car, a spinning wheel, a large ball, and a bucket with several small balls (Fig. 1). The experimental situation was based on the study by Hoch and colleagues [10], who showed that moving around with toys in a lab room encourages infants to move away from their caregivers and explore new areas. The caregiver remained seated in a chair at the end of the room and was instructed not to interact with the infant, except in special situations, for example, if the infant started crying or demonstrated excessive fussiness. Infants' movements were recorded from different angles to facilitate the coding and analysis of their behavioral patterns. Two portable cameras (GoPro Hero 3 model) were positioned on the ceiling and the side of the room, providing different perspectives. In addition, an experimenter was present in the experimental room carrying a Handycam

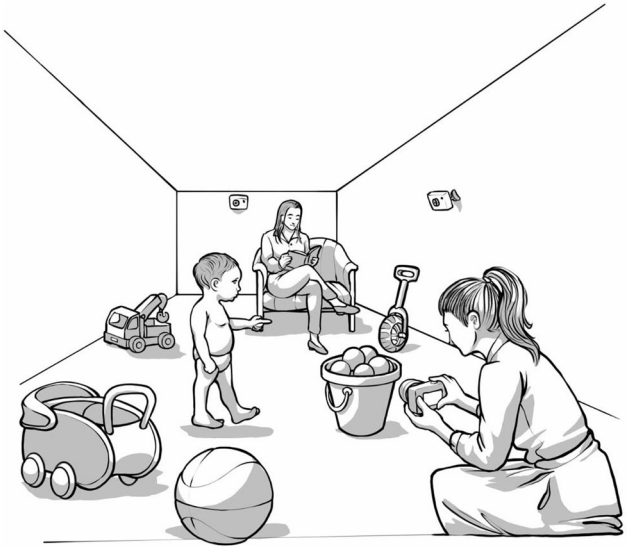

Fig. 1 Experimental situation in the multidisciplinary laboratory room with an infant performing a natural, non-object-oriented locomotor exploration. To initiate the environmental exploration, the infant had to be calm and exhibit typical behavior, so that any irritability would not interfere with the exploration. Additionally, parents were advised to bring their infants when they were not sleepy, hungry, tired, or ill (e.g., with a flu or cold)

(Sony HDR-PJ670 model) but did not interact with the infant.

The locomotor exploration video was coded offline by an experimenter, a specialist in human movement, using the Datavyu software (https://datavyu.org/). This tool is widely used for the analysis of infant behavior. The software enabled the identification and labeling of different types of motor behaviors such as: spending time in different positions such as crawling, sitting, lying down, and standing locomotion. Besides, it is possible to analyze whether the infant was close to the caregiver or received any caregiver intervention during the session, the number of bouts, steps, average steps per bouts, imbalances, and falls. The duration of each behavior was expressed in percentage (%), which consists of calculating the duration of the activity (dependent variable), multiplied by 100, divided by the number of seconds in the session (i.e., 1200 s = 20 min).

We defined time in locomotion as the period between pauses and rests of at least 500 milliseconds (ms), regardless of the amount of support [10, 15]. The initiation of each time in locomotion was determined by the frame in which the infant lifted their foot or knee off the ground. After moving, the displacement was recorded until the period in which the infant stopped using the support of the foot or knee to move around. Additionally, we recorded the periods in which the infants were in sitting or lying down positions; however, we did not specifically describe the movement patterns during these periods.

The time spent in the caregiver's arms was computed when the infant leaned against or asked to be held by the responsible person (mother/father). Adult interventions were computed when the caregiver got up from the chair and intervened in the experimental situation, for example, calming the infant after a fall, or adjusting a toy after the infant had used excessive force.

A bout was considered when the foot initially moved in any direction; the end of a bout was computed when both feet remained on the ground for longer than the typical period of "double support" for walkers [15]. If an infant did not stop when viewed at full speed, bouts were not separated even if the pause exceeded 500 ms. A step was considered any upward, downward, or lateral movement of a foot, which aimed to change the infant's direction in the laboratory room, regardless of the length of that step. Imbalances were characterized by situations in which infants lost their balance and did not result in falls, which, in turn, were defined as the event when part of an infant's body or hands touched the floor.

In this study, "locomotor exploration" refers to the overall self-initiated movement of infants through space, regardless of specific goals or object interaction. "Locomotor behaviors" are the specific quantifiable measures used to describe this exploration, such as the number of bouts and the total number of steps taken. To examine differences between PT and FT groups in locomotor exploration, one-way analyses of variance (ANOVAs) and Mann-Whitney tests were performed. The dependent variables for locomotor exploration were: time in standing locomotion, crawling, sitting, and lying down, infant close to the caregiver, caregiver intervention, and number of bouts, steps, average steps per bouts, imbalances, and falls. Post hoc tests with Bonferroni corrections were performed when necessary. Spearman's rho correlation was used to examine the association between infants' profile and locomotor exploration variables. The infant profile variables were: Independent walking onset (age of acquisition of independent walking, in months), body weight (current body weight, in kilograms), height (current height, in meters), walking experience (calculated from the age of independent walking onset, in months), birth weight (in grams), length of stay in hospital after birth (in days), APGAR score 1 min, and APGAR score 5 min. To describe the relationship between significant correlations, simple linear regressions were computed. The level of significance for all analyses was maintained at 0.05, and the software used was the Statistical Package for the Social Sciences (IBM SPSS Statistics, 21.0) and GraphPad Prism 8).

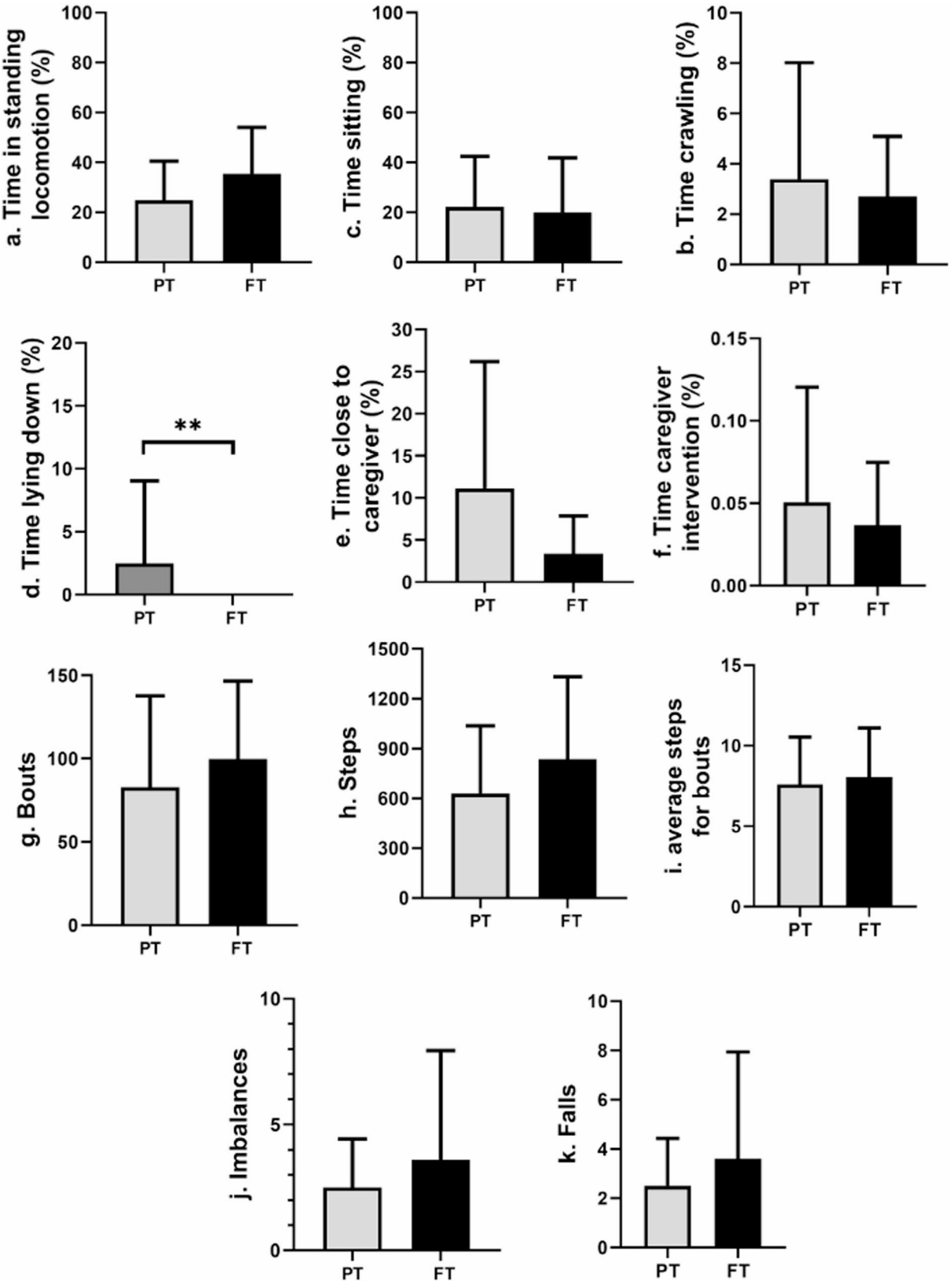

Fig. 2 (See legend on next page.)

(See figure on previous page.)

Fig. 2 (a – k). No significant differences were found between PT and FT infants in the following variables: (a) time in standing locomotion ($F_{1,30}$ = 2.934, $p > 0.05$), (b) time crawling (U = 105.5, $p > 0.05$), (c) time sitting (U = 123, $p > 0.05$), (e) time close to the caregiver (U = 157, $p > 0.05$), and (f) caregiver intervention time (U = 123, $p > 0.05$). Regarding locomotor behavior, there were no significant group differences in (g) number of bouts (U = 98.5, $p > 0.05$), (h) total number of steps ($F_{1,30}$ = 1.593, $p > 0.05$), (i) average steps per bout (U = 106, $p > 0.05$), (j) imbalances (U = 128, $p > 0.05$), and (k) falls (U = 123.5, $p > 0.05$). A statistically significant difference was found in (d) time in the lying down position (U = 172, $p < 0.04$)

Results

PT and FT infants showed similar locomotor exploration, spending most of their time in standing locomotion and exhibiting similar locomotor behavior. Percentages refer to the proportion of time each posture or activity was observed during the recorded locomotor exploration session (Fig. 2).

In terms of overall time distribution across postures and behaviors, both groups spent the most time in standing locomotion - PT: 24.93% (SD: 15.64%; range: 1.17%–46.42%) and FT: 35.46% (SD: 18.56%; range: 8.67%–66.70%), followed by sitting - PT: 22.20% (SD: 20.24%; range: 0%–60.17%) and FT: 19.93% (SD: 21.88%; range: 0%–70.92%); and crawling - PT: 3.4% (SD: 4.63%; range: 0%–14.33%) and FT: 3% (SD: 2.38%; range: 0%–7.08%). The least amount of time was spent lying down – PT: 2.49%, (SD: 6.5%; range: 0%–26.33%) while FT participants did not exhibit this behavior (0%).

Additionally, PT infants spent slightly more time close to the caregiver - PT: 11% (SD: 15%; range: 0%–51.75%), and FT: 3.36% (SD: 4.5%; range: 0%–13.08%) and received similar levels of caregiver intervention - PT: 5.06% (SD: 7%; range: 0%–23.24%) and FT: 4% (SD: 3.8%; range: 0%–12.83%). Regarding locomotor behavior, PT infants performed an average of 47.56 bouts (SD = 33.98), took 623 steps (SD = 408.77), and averaged 10.18 steps per bout (SD = 3.96). FT infants performed an average of 63.4 bouts (SD = 35.36), took 995 steps (SD = 497.25), and averaged 10.91 steps per bout (SD = 2.81). Imbalances were rare in both groups (PT: 0.5 ± 0.89, FT: 0.3 ± 0.82), as were falls (PT: 2 ± 1.46, FT: 3.27 ± 4.32), indicating that infants across groups were actively engaged with relatively stable motor performance during exploration.

Table 2 shows the results of the Spearman's rho correlation between the infant profile data and the locomotor exploration variables including all participants. An increase in walking experience (measured in months) was moderately associated with increased time spent in standing locomotion ($r = 0.546$, $p < 0.05$), number of bouts ($r = 0.534$, $p < 0.05$), and total steps ($r = 0.521$, $p < 0.05$). Additionally, walking experience was moderately and negatively associated with time spent sitting ($r = -0.636$, $p < 0.05$), indicating that greater walking experience corresponded to less time spent sitting during the session. APGAR scores at 5 min were negatively and moderately associated with the number of bouts ($r = -0.454$, $p = 0.051$) and imbalances ($r = -0.521$, $p < 0.05$).

Table 3 shows the results of the Spearman's rho correlations between the locomotor exploration variables. There was a positive and strong association between the time spent in standing locomotion and the number of bouts ($r = 0.893$, $p < 0.05$), the number of steps ($r = 0.931$, $p < 0.05$), average steps per bout ($r = 0.956$, $p < 0.05$), and imbalances ($r = 0.448$, $p < 0.05$); and a negative and strong association with the time spent in sitting position ($r = -0.779$, $p < 0.05$) during the session. Other significant associations between the locomotor exploration variables are shown in detail in Table 3.

Simple linear regressions were performed to describe the relationship between the infant profile and locomotor exploratory variables for significant correlations in Spearman's tests. The scatter plots in Figs. 3, 4, 5, and 6 illustrate the relationship between walking experience (independent variable) and locomotor exploration variables (dependent variables). Each point represents individual data of PT (gray circle) or full-term (black square) infant groups. The trend lines for each group follow the same colors and sizes. Dashed lines represent ± standard deviations.

Discussion

The present study aimed to examine the locomotor exploration of PT infants during the first six months of independent walking experience and, in addition, we investigated how characteristics of infant growth and development (e.g., infant profile, anthropometric measurements, and walking experience) could affect their locomotor exploration. PT and FT infants showed similar locomotor exploration, spending most of their time in standing locomotion and exhibiting similar locomotor behavior. Although bivariate correlations indicated that, as walking experience increased, there was a corresponding increase in time spent in standing locomotion, number of bouts, number of steps, and a decrease in time spent sitting for all infants, regression analyses revealed that these associations were significant only among FT infants. Notably, FT infants exhibited improvements in locomotor exploratory behavior of up to 36% and 56% in terms of number of bouts and steps, respectively. This relationship, however, was not observed in PT infants, suggesting that walking experience alone may not be sufficient to attenuate the effects of prematurity on locomotor exploration. The following results are discussed in detail below.

Table 2 Spearman's rho correlation results between infant profile and locomotor exploration variables, for all PT and FT participants ($N=31$)

Variables	Standing	Crawling	Sitting	Lying down	Close to caregiver	Caregiver intervention	Bouts	Steps	Average Steps	Imbalances	Falls
Independence walking onset	,028	-,256	-,278	-,022	,115	**-,525**	,111	,005	-,192	,201	**-,401**
p	,883	,165	,130	,907	,539	**,002***	,551	,977	-,300	,279	**,025***
Weight	,116	,085	,037	-,141	0,11	,081	,050	,048	,290	-,083	-,094
p	,535	,650	,842	,449	,954	,663	,790	,796	,114	,657	,615
Height	,267	-,029	-,132	-,073	-,139	-,303	,166	,188	,189	,109	-,213
p	,147	,875	,479	,695	,456	,097	,371	,311	,309	,560	,249
Walking experience	**,546**	-,242	**-,636**	,134	0,85	-,210	**,534**	**,521**	,194	-,173	-,298
p	**,001***	,189	**,000***	,472	,649	,258	**,002***	**,003***	,297	,353	,104
Birth weight	,316	,094	,013	-,288	-,256	,106	,151	,215	,207	-,083	,012
p	,083	,615	,946	,116	,165	,572	,417	,245	,264	,656	,950
Length of stay in hospital after birth ($n=29$)	-,279	,057	,090	,088	,176	-,180	-,200	-,231	-,175	-,106	,030
p	,142	,769	,642	,650	,362	,350	,297	,228	,365	,584	,876
APGAR score 1 min 1 ($n=24$)	,011	,067	,222	-,199	-,351	-,141	-,064	-,086	-,026	-,360	-,208
p	,960	,756	,298	,350	,092	,511	,768	,690	,903	,084	,330
APGAR score 5 min ($n=19$)	-,231	,259	,415	-,099	-,094	,163	**-,454**	-,367	,065	**-,521**	,152
p	,340	,284	,077	,686	,703	,504	**,051**[#]	,122	,793	**,022***	,535

Symbol [#]= trend of statistical difference ($p=0.051$). Symbol [*] = statistically significant difference ($p<0.05$). Source: the authors

Table 3 Spearman's rho correlation results between the locomotor exploration variables for all PT and FT participants ($N=31$)

Variables	Crawling	Sitting	Lying down	Close to caregiver	Caregiver intervention	Bouts	Steps	Average Steps	Imbalances	Falls
Standing	-,225	**-,779**	-,298	-,269	-,295	**,893**	**,931**	**,956**	**,448**	,053
p	,224	**,000***	,103	,143	,107	**,000***	**,000***	**,000***	**,011***	,777
Crawling		**,408**	,063	,077	,342	-,142	-,131	-,224	-,303	,245
p		**,023***	,738	,680	,060	,447	,481	,227	,097	,185
Sitting			,172	-,116	,284	**-,590**	**-,600**	**-,700**	**-,390**	,158
p			,355	,533	,121	**,000***	**,000***	**,000***	**,030***	,395
Lying down				,191	**,367**	-,206	-,160	-,210	,148	-,069
p				,304	**,042***	,267	,390	,256	,427	,256
Close to caregiver					,189	**-,406**	**-,391**	-,309	-,178	-,243
p					,308	**,023***	**,030***	,091	,338	,188
Caregiver intervention						-,112	-,228	-,274	-,122	,094
p						,548	,218	,136	,513	,614
Bouts							**,942**	**,921**	**,419**	,162
p							**,000***	**,000***	**,019***	,384
Steps								**,967**	**,489**	,162
p								**,000***	**,005***	,384
Average steps									**,533**	,129
p									**,002***	,489
Imbalances										,110
p										,555

Symbol [*] = statistically significant difference ($p<0.05$). Source: the authors

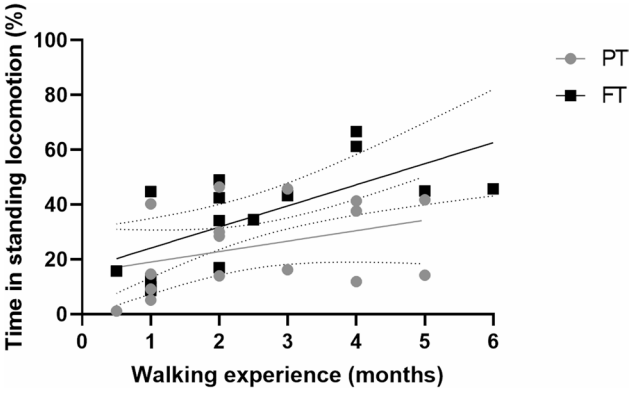

Fig. 3 Linear regression between walking experience and the percentage of time spent in standing locomotion for preterm (PT) (gray circles) and full-term (FT) infants (black squares) in the experimental session
Note: A positive trend is observed for the FT infants' group (black solid and dashed lines) indicating that with increasing walking experience, there is an increase in the percentage of time spent in standing locomotion ($r^2 = 0.457$, $p < 0.005$). Such a relationship was not observed in the PT infants' group (gray solid and dashed lines) ($r^2 = 0.134$, $p > 0.05$). Source: the authors

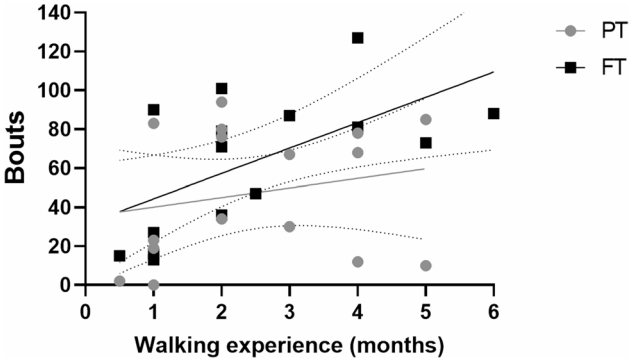

Fig. 5 Linear regression between walking experience and the number of bouts for preterm (PT) (gray circles) and full-term (FT) infants (black squares) during the experimental session
Note: A positive trend is observed for the FT infants' group (black solid and dashed lines) indicating that with increasing walking experience, there is an increase in the number of bouts ($r^2 = 0.361$, $p < 0.02$). Such a relationship was not observed in the PT infants' group (gray solid and dashed lines) ($r^2 = 0.047$, $p > 0.05$). Source: the authors

Infant profiles

PT infants in our sample exhibited delays in the onset of independent walking (chronological age) and had longer hospital stays after birth compared to FT infants. These findings are consistent with the literature, which indicates that motor milestone delays in PT infants are often inversely associated with gestational age and length of hospitalization [4, 16]. Many of the PT infants in this study were enrolled in early intervention programs with multidisciplinary teams during their first year, which may have helped to mitigate some developmental delays and support age-appropriate motor behavior [17]. Additionally, PT infants were more frequently from low- or lower-middle-income families and had lower birth weights [1], characteristics previously linked to an increased risk of developmental delays when compared to FT peers [2, 3, 7]. The APGAR score at 5 min was the only infant profile variable linked to locomotor exploration (fewer bouts and more imbalances); other variables were retained for participant characterization. Missing perinatal data, due to complications, adoptions, or lack of documentation,

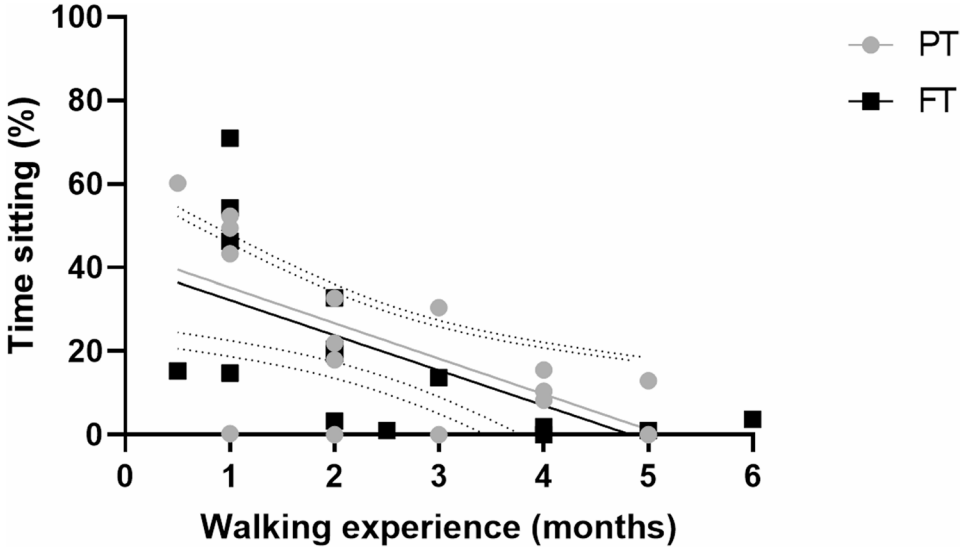

Fig. 4 Linear regression between walking experience and the percentage of time spent in the sitting position for preterm (PT) (gray circles) and full-term (FT) infants (black squares) during the experimental session
Note: A negative trend is observed for both groups of PT and FT infants, indicating that with increasing walking experience, there is a decrease in the percentage of time spent in the sitting position for PT infants (gray solid and dashed lines) ($r^2 = 0.396$, $p < 0.01$) and FT infants (black solid and dashed lines) ($r^2 = 0.392$, $p < 0.01$). Source: the authors

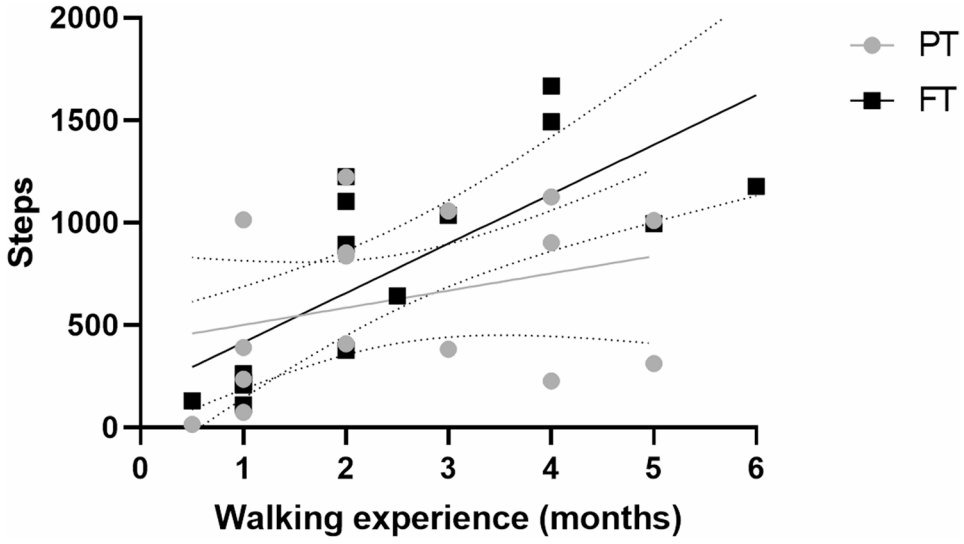

Fig. 6 Linear regression between walking experience and the number of steps for preterm (PT) (gray circles) and full-term (FT) infants (black squares) during the experimental session

Note: A positive trend is observed for the FT infants' group (black solid and dashed lines) indicating that with increasing walking experience, there is an increase in the number of steps ($r^2 = 0.565$, $p < 0.001$). Such a relationship was not observed in the PT infants' group (gray solid and dashed lines) ($r^2 = 0.094$, $p > 0.05$). Source: the authors

affected both PT and FT groups and reflects common challenges in pediatric records and parental recall [18].

Locomotor exploration

Contrary to our expectations, there were no differences between PT and FT groups in locomotor exploration behaviors (e.g. walking, bouts, steps, and falls). The only exception was the time spent in the lying-down position, which, despite being statistically significant, represented a minimal portion of the session (less than 3% for PT infants) and is unlikely to be clinically meaningful. This finding contrasts with previous studies, as Hempel [12] reported significant qualitative motor differences between PT and FT children, though his study's more heterogeneous sample with higher developmental risks may have amplified these differences. Similarly, in an assessment conducted 14 days after PT infants achieved the ability to walk 5 meters independently, Groot, Groot, and Hopkins [13] found qualitative challenges in the walking patterns of these children, classifying them as "near poor" and "poor" due to difficulties with balance and coordination, especially when walking fast, changing direction, stopping, and picking up objects during locomotor exploration.

Besides that, in our study, we observed greater variability in the overall behavior of PT infants and their infant profile, while FT infants had more homogeneous characteristics. One possible explanation may be related to the requirements of the behavioral task. Perhaps the experimental situation was not sufficiently challenging to highlight subtle differences in the locomotor skills of PT infants. In the study by Adolph and colleagues [14], for example, the exploratory environment included a larger room, stairs, cushions, different elevations, and toys, resulting in up to 17.4 falls per hour on average for infants with walking experience. These findings suggest that falls are not necessarily indicators of poor motor control, but part of a natural and adaptive learning process. In our study, we observed that infants showed similar locomotor exploration, spending most of their time in standing locomotion (PT: 24.93%, FT: 35.46%) and exhibiting similar locomotor behaviors (i.e. average PT: 623 steps and 2 falls, FT: 995 steps and 3.27 falls). Interestingly, FT infants also showed a wider range in the number of falls, with some participants falling up to eight times during the session.

In fact, falling is one of several typical outcomes of spontaneous locomotor bouts, alongside stopping or taking steps in place [11]. Rather than reflecting failure, falls can be understood as opportunities for infants to gather information about their bodies, balance, and the environment, helping to refine motor strategies over time. Thus, the presence of falls, particularly when accompanied by varied bouts of movement, can indicate active engagement in exploration and ongoing motor learning, rather than indicate motor impairment.

Walking experience and its role in locomotor exploration

Examining the relationship between locomotor exploration variables and infant profile characteristics of all infants, our results showed that increasing walking experience over the first six months of life may affect how FT

infants move and interact with objects in the environment, which is expected for the initial development of independent walking [14, 19]. As a novelty, our study also showed that an increase in walking experience is correlated with a decrease in the time spent in sitting and crawling positions, which have not been considered in other studies focusing on locomotor exploration [10, 14, 15, 19].

However, the fact that PT infants did not show a similar trend despite experiencing the same months of walking seems to be a relevant finding in our study. Positive effects of walking experience on locomotor exploration behavior [14, 15, 19] do not appear to apply to PT infants. As Adolph and Hoch argue [5], motor development is not only embodied, constrained by the current status of the body, but also enabling, as each new motor skill opens opportunities for learning and exploration. For PT infants, the same amount of walking experience may not translate into equivalent exploratory behavior due to differences in how their bodies cope with postural control, balance, and biomechanical constraints. These infants may require not only time to walk, but also qualitatively diverse and adaptive experiences to fully benefit from the developmental opportunities enabled by locomotor practice.

Our findings align with recent literature suggesting that walking experience alone may not be sufficient to enhance exploratory behavior in all infants. Graciosa et al. [20] demonstrated that the emergence of locomotor behaviors is not only tied to developmental status, but also to how FT infants aged 5 to 15 months interact with their environment and parental practices. For PT infants in our study, the combination of altered developmental trajectories and fewer adaptive stimulation opportunities may reduce the functional benefits of walking experience on locomotor exploration.

There is a lack of research on whether there are early differences in gait among PT infants and, in addition, whether they improve with age and more walking experience [4]. To our knowledge, this is the first study to find that the amount of walking experience does not appear to mitigate the effects of prematurity on the locomotor skills used to drive new exploratory experiences. This finding is important since subtle alterations in PT infants may be hard to identify, leading many of them to be excluded from early intervention programs. These programs might compensate for possible motor delays, families' lack of knowledge about prematurity-related issues, and low-quality parent-child interactions [21]. Furthermore, changes in neuropsychomotor function, coupled with a lack of opportunities to move, may compromise the developmental cascades [22]. Studies have shown that different neural networks are formed in response to the quantity and quality of experiences that infants are exposed to during the first few months of life [23].

Therefore, the investigation of the exploration of non-object-oriented situations has been underexplored in PT infants, despite its importance [24]. We aim to bridge the gap in understanding the walking experience and exploratory behavior in an ecological setting, simulating a scenario similar to a typical family's daily routine. Based on our regression results and previous evidence, PT infants may follow a different developmental trajectory, with subtle impairments in non-object-oriented exploratory behaviors that could affect reaching, object exploration, and cognition [9, 25].

Important aspects of locomotion such as form (i.e., gaits) and function (i.e., mobility) improve with independent walking experience [26]. The focus on mobility provides a more accurate, inclusive, and rich portrait of infant locomotion than just focusing on gait shape, given that infants are challenged daily to make various motor adjustments during periods of exploration. These motor solutions, in addition to making the world more accessible, depend on moment-to-moment relationships between the body and the environment [26]. Considering the linear regression results, we speculate that despite showing similar characteristics of exploratory walking, the functionality of locomotor exploration seems to be impaired in this population. In this sense, we encourage health professionals and caregivers to pay attention to how premature infants solve locomotor problems, and not just be concerned about whether they present the locomotor milestones expected for the age group.

A limitation of our study was the small sample of infants born prematurely, which presented with a wide range of gestational ages and varying risks for developmental delays. Although we did not systematically assess co-morbidities - such as visual impairments or mild motor dysfunctions which are more frequent in PT infants - using formal clinical screening tools, we did have access to participants' medical records and parental reports to check for exclusion criteria. Importantly, all participants in our sample were able to walk independently and engage in the task. In addition, we were able to pair PT infants with FT peers, which enabled us to answer the questions we posed in this study.

Conclusion

PT and FT infants showed similar locomotor exploration, spending most of their time in standing locomotion and exhibiting similar locomotor behavior. Walking experience can predict developmental changes in the exploratory locomotor behavior of FT infants, but not of PT infants, who exhibit different developmental trends compared to their peers. We conclude that the opportunities gained with the increase in independent walking

experience in the first six months of age do not seem to minimize the subtle impacts associated with being born prematurely on locomotor exploration, which reinforces the necessity for monitoring these infants in early intervention programs, even without motor or mental impairments.

Abbreviations

PT pre-term
FT full-term control
SD standard deviation
GA gestational age

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Authors' contributions
RNB and AAR (study design, data collection, data analysis, manuscript writing); ABO and JSS (data collection, data analysis, manuscript review); PFP (study design, data analysis, manuscript writing, manuscript review, supervision of study).

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
The Ethics Committee of the Sao Paulo State University, School of Sciences - Bauru, approved the study (n. #60800622.0.0000.5398). The procedures used in this study adhere to the tenets of the Declaration of Helsinki. Parental or guardian's written informed consent was required for infant participation in the study.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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