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1Original article:

Effect of age and speed on the step-to-step transition strategies in children

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Abstract:

The development and acquisition of mature walking in children is multifactorial, depending among others on foot interaction with the ground, body dynamics and the knowledge of the 'rules' stemming from the gravity field. Indeed, each step the velocity of the centre of mass must be redirected upwards. This redirection may be initiated by the trailing leg, propulsing forward and upward the body before foot contact, or later by the loading limb after the contact with the ground. While it has been suggested that mature walking develops slowly from first independent steps to about 7 years of age, it is still unknown how children acquire the appropriate loading and propulsion forces during the step-to-step transition. To answer that question, twenty-four children (from 3 to 12 years old) and twelve young adults (from 20 to 27 years old) walked on force platforms at different walking speed. The ground reaction forces under each foot were recorded and the vertical velocity of the centre of mass of the body was computed. With decreasing age and increasing velocity (or Froude number), the occurrence of unanticipated transition is higher, related to a different ratio between the vertical support of the front and back leg. The different transition strategy observed in children indicates that body weight transfer from one limb to the other is not fully mature at 12 years old.

Keywords: neuromechanics; motor development; gait biomechanics; collision; external work

Introduction

Foot-support interactions and gravity have a profound influence on optimization and energetics of walking and its stability. When children start to walk independently, they need to learn the 'rules' of walking in the gravity field, in particular, the pendulum mechanism of walking (Ivanenko et al., 2004; Ivanenko et al., 2007; Dominici et al., 2007). The step-to-step transition strategies are also tightly related to the effect of gravity on walking since they require appropriate loading and propulsion forces at the end of stance. The simple integration of stepping movements with forward translation can be found in the typical strategy of gait initiation in toddlers, whereby gait is initiated by letting the body fall forward, and in a form of early walking, whereby the toddler puts the swing foot forward to brake the fall and bring the body back to the original stance foot (McCollum et al., 1995). McCollum et al identify different types of walking in toddlers corresponding to different forms of early walking, the "twister", the "faller" and the "stepper". Often, the "faller" cannot stop without something to bump into, such as a wall or friendly adult (McCollum et al., 1995). This suggests that toddlers do not anticipate this event and fail to redirect the centre of mass of the body (CoM) before double stance, as adults do. This is also supported by the fact that, in toddlers, virtually no power is generated at the ankle joint before foot-off (Forssberg, 1985; Hallemans et al., 2005). Older children seem to learn the adult-like mechanics and exchange between potential and kinematic energy of the CoM when walking in the gravity field (Cavagna et al., 1983), however, it is not clear to what extent and at what age they also adopt the adult-like gravity-related anticipatory step-to-step transition strategy.

During the acquisition of independent and mature gait, the physical dynamics of the mechanical system (inertia, viscoelastic properties of muscles and tendons and body size) may affect the locomotor behavior (Adolph et al., 2018; Adolph and Robinson, 2015a;. Dewolf et al., 2020b; Thelen, 1995). For example, body size and proportions change dramatically during growth (Haywood and Getchell, 2021), modifying the location of the center of gravity (Payne and Isaacs, 2017), and in turn its stability. Also, walking in toddlers is characterized by high variability of movements, legs wide apart, short steps, and poor balance over the single support leg (Adolph and Robinson, 2015b; Dayanidhi et al., 2011). The body's control balance is assumed to be a milestone for mature walking, and it is not fully acquired before 6 years old (Brenière and Bril, 1998). Furthermore, both in terms of mechanical energy and kinematics, the ability to walk develops slowly from first independent steps to about 7 years of age (Cheron et al., 2001; Cheron et al., 2001; Dominici et al., 2010; Ivanenko et al., 2007, 2005b, 2004), reflecting the progressive, dynamic integration of postural equilibrium and forward propulsion in a gravity-centered frame with age. Changes in limb coordination, center of mass dynamics and balance control may in turn affect the coordinated transfer of weight from the trailing limb to the leading one during the step-to-step transition of walking, most likely not fully acquired before 7 years old.

Also, foot structure in infants differs from adults (Bosch et al., 2007; Maier, 1961; Price et al., 2018), with for example the presence of a fat pad underneath the foot plantar surface during the first years after birth (Bertsch et al., 2004; Gould et al., 1989). Another interesting observation is the modification of foot contact strategy with age (Hallemans et al., 2006). In toddlers walking, the foot interaction with the ground is still immature because touch-down is with flat-foot or toes-first (Payne and Isaacs, 2017), instead of using the heel-to-toe rolling pattern as in adults. The latter foot contact strategy is progressively adopted (after around 23 months of independent walking (Payne and Isaacs, 2017)). This latter factor is especially important since the heel-to-toe rolling pattern has been related to specific muscle activation patterns and strategy of step-to-step transition (Mesquita et al., 2023).

During the transition from one limb to another, the downward trajectory of the CoM has to be redirected to an upward trajectory (Bastien et al., 2003; Kuo et al., 2005; Meurisse et al., 2019a). In adult walking, the propulsion of the trailing limb redirects the trajectory of the CoM before the contact of the leading limb. This so-called anticipated transition reduces the impact of the leading limb with the ground. The aim of this study is to investigate the development of such transition during gait in children as compared to healthy adults, expanding the analysis of the effect of age on the mechanics of walking. Data of children from 3 to 12 years old walking at speeds from 0.27 to 2.5 m s^{-1} were compared to adults. The forces exerted by each leg were measured and analyzed during the step–to–step transition. Since several gait parameters (e.g. mechanical work, step frequency and variability) exhibit changes in children up to 12 years (Bastien et al., 2003; Hausdorff et al., 1999; Schepens et al., 2004), we hypothesize that younger children would exert less vertical force on the trailing limb and more on the leading limb during the transition than older children and adults, as they progressively deviate from the form of early walking observed in toddlers. We also anticipate a progressive anticipated step-to-step transition with increasing age.

Materials and Methods

Subjects and Experimental procedures

Data were collected at the same time and on the same subjects as in the study of Schepens et al. (Schepens et al., 2001) and the steps analyzed are the same as in the study of Bastien et al., (2003). Experiments were performed on 24 healthy children. For the sake of clarity, in the figures the children were arbitrary divided in five age groups, defined as follows: 3-4, 5-6, 7-8, 9-10, and 11-12 years-old. The 3–4-year-old group included subjects 3·years to <5·years old; the 5–6-year-old group included subjects 5·years to <7·years old, the 7-8-year-old group included subjects 7·years to <9·years old, the 9–10-year-old group included subjects 9·years to <11·years old and the 11–12-year-old group included subjects 11·years to <13·years old. Twelve healthy young adults of 20–27·years of age were also registered. The mean characteristics of each age group are given in Table 1. Informed written consent of the subjects and/or their parents was obtained. The experiments were performed according to the Declaration of Helsinki and were approved by the local ethics committee. All of the subjects wore swimming suits and gym shoes.

Subjects were asked to walk across a force platform at different speeds. The individual signals of the force plates data were collected independently with two different set-ups: either sixteen 1000 mm × 1000 mm force plates as described in Genin et al.(2010), ten 600mm x 400 mm plates, similar to those described by Heglund (1981). The plates were sensitive to forces in the fore-aft and vertical directions and had a linear response to within 1% of the measured value for forces up to 3000·N. The difference in the electrical signal to a given force applied at different points on the surface of the plates was less than 1%. The crosstalk between the vertical and forward axis was less than 1% of the applied force. The individual signals of the plates were digitized by a 12-bit analogue-to-digital converter every 5·ms and processed by means of a desktop computer. The mean speed was measured by two photocells placed at the level of the neck and set 1.5–5.0·m apart depending upon the speed. In each age group, the data were gathered into speed classes of 0.28·m·s^{-1} (1·km·h^{-1}). In most cases, two trials per subject were recorded in each speed class.

Data analysis

A complete step was selected for analysis only when the feet were on different force plates and when the subject was walking at a relatively constant average height and speed. Specifically, the sum of the increments in both forward and vertical velocity could not differ by more than 25% from the sum of the decrements (Cavagna et al., 1977). According to these criteria, the difference in the forward speed of the COM from the beginning to the end of the selected step was less than 6% of the mean speed (except in four instances at very low speeds below 0.56·m·s–1, where it was up to 9%), and the mean vertical force was within 5% of the body weight. A total of 895 steps were analyzed (see Table 1).

The double contact phase (T_{DC}) was delimited by the front leg foot contact (FC) and the back leg toe off (TO). Froude number ($\boldsymbol{F_r = v^2 g^{-1} l^{-1}}$) was measured based on the mean speed (*v)* and leg length (*l)* (Table 1). The maximal vertical force exerted by the front leg (F_{front}) and by the back leg (F_{back}) were measured during the step-to-step transition. The ratio between F_{front} and F_{back} was then calculated in order to illustrate the asymmetry in the force generation between the two legs (Dewolf et al., 2022; Meurisse et al., 2019a, 2019b).

The vertical velocity of the CoM was determined from the vertical ground reaction force, using the procedure described in detail in Dewolf et al. (Dewolf et al., 2017, 2016). In short, the vertical acceleration of the CoM was computed as a_v=(F_v-m*g*)/m, where m is the subject' s body mass and *g* is the acceleration due to gravity. The instantaneous velocity in the vertical (V_v) direction was obtained by integration of a_v plus an integration constant (chosen to make the average velocity over a step equal to zero).

The time of occurrence of the minimal vertical velocity of the CoM ($V_{v,min}$) relative to FC expressed in percent of stride and milliseconds was also calculated. The transition mode was defined by the time of occurrence of the $V_{v,min}$ relative to FC. When the $V_{v,min}$ occurs before FC, the redirection of the CoM velocity was 'anticipated' while when $V_{v,min}$ occurs at or after FC, the redirection of the CoM velocity, and in turn the step-to-step transition, was 'unanticipated' (Dewolf et al., 2022; Franz and Kram, 2013; Meurisse et al., 2019b).

Statistics

The statistical analysis was designed to assess the effect of age and speed of progression or Froude number. Regression analyses were conducted with walking speed and age as independent variable. The same analyses were done with the Froude number and age as independent variables. The homoscedasticity, multicollinearity and normality of the residuals was checked. Normality was not assumed for 4 variables (T, T_{DC}, F_{back}, F_{back}/F_{front}). In these cases, an inverse (F_{back}) or log (T, T_{DC}, F_{back}/F_{front}) transform was applied. In all analyses, the significance level was fixed at $p < 0.05$. Note that for the sake of clarity, the figure presents the results of children arbitrary divided in five age groups, but the regression lines with age and speed are presented in Supplementary materials (Fig. S1).

Results

Temporal parameters

Both walking speed and age ($F_{2,988} = 1416.9$, $p<0.001$, $R = 0.861$) or Froude Number and age ($F_{2,988} = 1101.5$, $p<0.001$, $R = 0.831$) statistically predicted stride period. Indeed, the stride period decreased with speed ($p< 0.001$; Fig 1B) and with Froude number ($p< 0.001$) and increased with age ($p< 0.001$). Similar observations were made on the duration of the double stance phase (Fig. 1B). Walking speed and age ($F_{2,988} = 1552.6$, $p<0.001$, $R = 0.871$) and Froude number and age ($F_{2,988} = 1063.4$, $p<0.001$, $R = 0.826$) statistically predicted the double contact period. The double contact decreased with speed ($p< 0.001$), with Froude number ($p< 0.001$), and increased with age ($p< 0.001$).

Ground reaction force

Fig 2 presents the differences between the age-groups for the peak of ground reaction forces. The normative data of adults were computed as the linear regression with Froude number as independent variable. The grey area corresponds to the slope plus and minus the 95% confidence interval. Both walking speed and age ($F_{2,988}$ = 118.4, p<0.001, R = 0.440) or Froude Number and age ($F_{2,988}$ = 70.0, p<0.001, R = 0.352) statistically predicted the peak of force developed by the back leg (F_{back}). F_{back} increased with speed (p< 0.001) and Froude number (p< 0.001) and increased with age (p<0.001). The peak of force developed by the front leg (F_{front}) could also by predicted by speed and age ($F_{2,988}$ = 1138.9, p<0.001, R = 0.835) or Froude number and age ($F_{2,988}$ = 1415.4, p<0.001, R = 0.861). F_{front} increased with speed (p< 0.001) and Froude Number (p< 0.001) but decreased significantly with age (p< 0.001). As a result, ratio between F_{front} and F_{back} was greater at fast walking speed (p< 0.001), high Froude Number (p< 0.001) and decreased with age (p< 0.001) .

Step-to-step transition mode

The Fig 3B presents the time of occurrence distribution of $V_{v,min}$ relative to foot contact (FC) at all speeds as a function of age-groups in % of stride. Both walking speed and age ($F_{2,988}$ = 117.1, p<0.001, R = 0.438) or Froude Number and age ($F_{2,988}$ = 136.2, p<0.001, R = 0.465) statistically predicted the delay between $V_{v,min}$ and FC. The delay decreased with increasing speed (p< 0.001) and Froude Number (p< 0.001). Also, $V_{v,min}$ occurred earlier relative to FC with age (p< 0.001).

Fig 3C illustrates the relative percentage of unanticipated transitions (when $V_{v,min}$ occurred after FC) as a function of age-groups and Froude Number. As the delay between the $V_{v,min}$ and FC decreased with Froude number (and speed), the occurrence of unanticipated transition increased, going sometimes up to 100% of the recorded steps at the fastest speeds. By comparing the younger and older children, it can be seen that this effect of Froude Number is dependent on age: in the youngest group, the occurrence of unanticipated transition was higher than in the other group and increased more rapidly with increasing Froude number.

Discussion

The present study aimed to investigate the step-to-step transition in children younger and older than 7 years old and compare it with adults. To do that, we measured the vertical ground reaction forces under each foot during a walking step, compared the force exerted by the leading and trailing limb during the weight transfer from one foot to the other (Fig.3A), and classified the transition as originally proposed by Meurisse et al. (Dewolf et al., 2022; Meurisse et al., 2019b) in older adults: when the down-to-up redirection of the centre of mass of the body (COM) begins during the double stance, the transition is considered as non-anticipated whereas the anticipated transition mode occurs when the redirection begins before the contact of the leading leg, initiated by the vertical push of the trailing leg. According to Meurisse et al. (Meurisse et al., 2019a), the transition mode is dependent on speed. Therefore, we also analyzed the transition at different speeds and corresponding Froude numbers (see Table 1). Our findings revealed a higher rate of non-anticipated transition modes in younger infants and at fast walking speed (Fig. 3).

The modified transition is related to a different distribution of vertical ground reaction forces between the leading and the trailing limb (Fig. 2), with a reduced propulsion of the trailing limb compensated by a higher peak of force under the front foot. Some previous study has suggested that after the age of 4 years old, step parameters are already 'adult-like' (Sutherland, 1997). More recently, it has been suggested that, in terms of center of mass dynamics and lower-limb kinematics, gait maturity is reached around 7 years of age (Cheron et al., 2001; Cheron et al., 2001; Dominici et al., 2010; Ivanenko et al., 2007, 2005b, 2004). By comparing children younger and older than 7 years old to adults, the results of the present study indicate that the gait is not yet fully mature at the age of 7 years old. Indeed, both younger and older children do not anticipate the foot contact and fail to redirect of the CoM motion before double stance, as adults do. While it should be taken into account that the degree of gait maturity does not always relate directly to the chronological age of the child (Bach et al., 2021), the difference with mature gait was, however, greater in the younger groups. One possibility is that peripheral, biomechanical factors may play the critical role in determining why children walk the way they do. For example, strength and balance are keystones of improvements in walking skill (Bäckman et al., 1989), and the deviation from adult gaits in infancy may also be related to adaptive strategies for limiting the muscle activation demands (Hubel and Usherwood, 2015). This is also supported by the lack of power generated at the ankle joint before foot-off (Forssberg, 1985; Hallemans et al., 2005).

Another possibility is that practice is the critical factor for the developmental course of walking. In fact, the constant learning and exploration of movement patterns in children suggest that motor locomotion patterns are not fixed but are flexible. The progressive transition to anticipated transition, as adult do, can be related to the acquisition of the adult-like heel-to-toe rolling pattern of the foot (Dewolf et al., 2020a; Hallemans et al., 2006) and the acquisition of the adult-like mechanics and exchange between potential and kinematic energy of the CoM when walking in the gravity field (Cavagna et al., 1983). From a metabolic point of view, since step-to-step transition is major determinant of the overall cost of walking (Kuo et al., 2005), the higher energy cost of walking observed in children until the age of 10 years old (De Jaeger et al., 2001) may be also explained by the greater collision at foot contact than adults at the same speed (Fig. 2).

Interestingly, similar results were observed in older adults. Indeed, a greater contribution of the leading limb compensating a reduced vertical support of the trailing leg has been observed. As a result, the transition is initiated later in the gait cycle with age (Dewolf et al., 2022; Meurisse et al., 2019a, 2019b). Also, the late CoM redirection was associated with age-related decline of gait, such as poorer static balance, modification of limb coordination, greater mechanical work, and differential organization of spinal motor output (Dewolf et al., 2022). Based on the previous consideration, one may expect that the step-to-step transition in children as in older adults may reflect a deviation from adult mature gait.

Conclusion

In conclusion, our results show that the rate of unanticipated transition decreased with age, as speed and Froude number increased. Because the modification of step-to-step transition has been related to the modification of neuromuscular control of gait, assessing step-to-step transition in clinical practice could be used as a quantitative assessment of the development of locomotion.

Conflicts of Interest statement

The authors declare no conflict of interest.

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Data Availability Statement

Data on walking in children are available upon reasonable request.

Figure Legends

Figure 1. Typical traces of step-to-step transition in a child of 7 years old and general gait parameters in children and adults. (**A**) The upper illustration schematically represents the step-to-step transition consequences of walking like an inverted pendulum. The grey and blue arrows indicate the velocity of the CoM before and after its redirection. At the bottom, the curves correspond to the vertical force (F_v) acting upon each leg separately; the continuous grey line is the force back (F_{back}) of the trailing leg; the dotted black line is the force front (F_{front}) of the leading leg as a function of time. The continuous black line below corresponds to the vertical velocity (V_v) of the CoM during walking. The blue rectangle delimits one step-to-step transition (from min to max V_v). (**B**) The black and grey dots correspond to the stride period (T) and double contact time (T_{DC}) in children, respectively. The dashed lines represent T and T_{DC} in adults (linear regression as a function of the walking speed).

Figure 2. Vertical ground reaction force under each foot during step-to-step transition. The upper graph illustrates the vertical force exerted by the front (F_{front}) and back (F_{back}) leg during the step-to-step transition (blue rectangle). From top to bottom, the F_{back}, F_{front}, and F_{front}/F_{back} ratio are plotted as a function of Froude number in children (black dots) in each group age (3-4; 5-6; 7-8; 9-10; 11-12 years). The black dashed line and the grey area correspond to the adult normative data. The normative data of adults were computed as the linear regression with Froude number as independent variable. The grey area corresponds to the slope plus and minus the 95% confidence interval.

Figure 3. Anticipated versus unanticipated transition. (A) Three representative examples of the force under each foot during a step-to-step transition in 2 children (4.7 and 8.4 years old) and one adult. The bottom curves represent vertical velocity of the CoM (V_v). The red and blue arrows correspond to foot contact and $V_{v,min}$, respectively. (B) The bar histograms present the occurrence of the delay between $V_{v,min}$ and foot contact in adults and children (green) (C) Schematic illustration of the step-to-step transition mode with representative corresponding vertical forces. The bar graphs below indicate the percentage of unanticipated transition (when the redirection occurs after foot contact) in each age group as a function of Froude number.

Figure S1. Graphical representation of linear regression. Relationship between walking speed and age (independent variables) and the different dependent variables. The linear fits were obtained using the Basic fit tools of MATLAB (2022 - MathWorks). Statistical analyses indicated for each dependent variable were performed with the statistical software package SPSS (version 23.0; IBM).

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Table 1. Subjects characteristics

Age group (years)	# of subjects (male)	Age (years)	Leg length (m)	Number of steps analyzed per speed class (m/s)								
				0.28	0.56	0.84	1.12	1.4	1.68	1.96	2.24	2.52
3-4	5 (1)	4.5±0.2	0.49±0.01	2	8	14	20	16	5	0	0	0
5-6	5 (2)	6.2±0.8	0.52±0.01	4	14	20	19	36	14	1	0	0
7-8	5 (1)	8.2±0.4	0.59±0.03	5	10	22	36	23	23	12	8	1
9-10	5 (3)	10.3±0.3	0.65±0.01	0	12	37	42	32	23	27	11	3
11-12	4 (2)	11.9±0.7	0.75±0.02	5	11	21	36	25	33	24	9	0
Adults	12 (6)	22.8±1.9	0.85±0.02	2	18	57	57	70	56	40	19	8

Conflicts of Interest statement

The authors declare no conflict of interest.

Figure 1 Click here to access/download;Figure;Figures_1.pdf

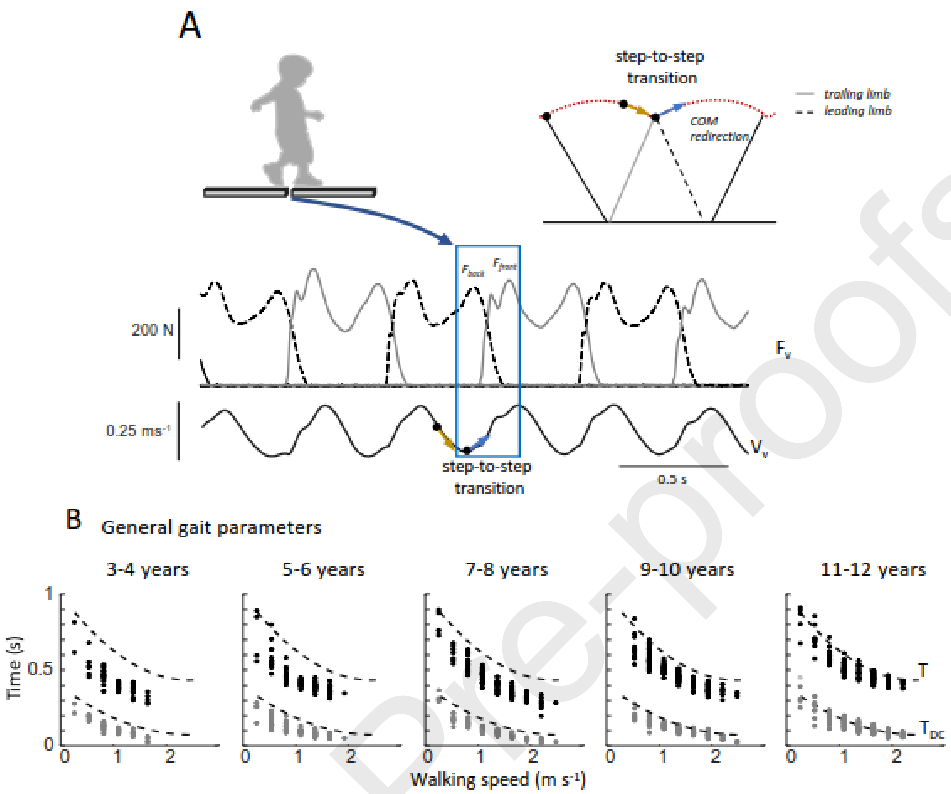


Figure 2

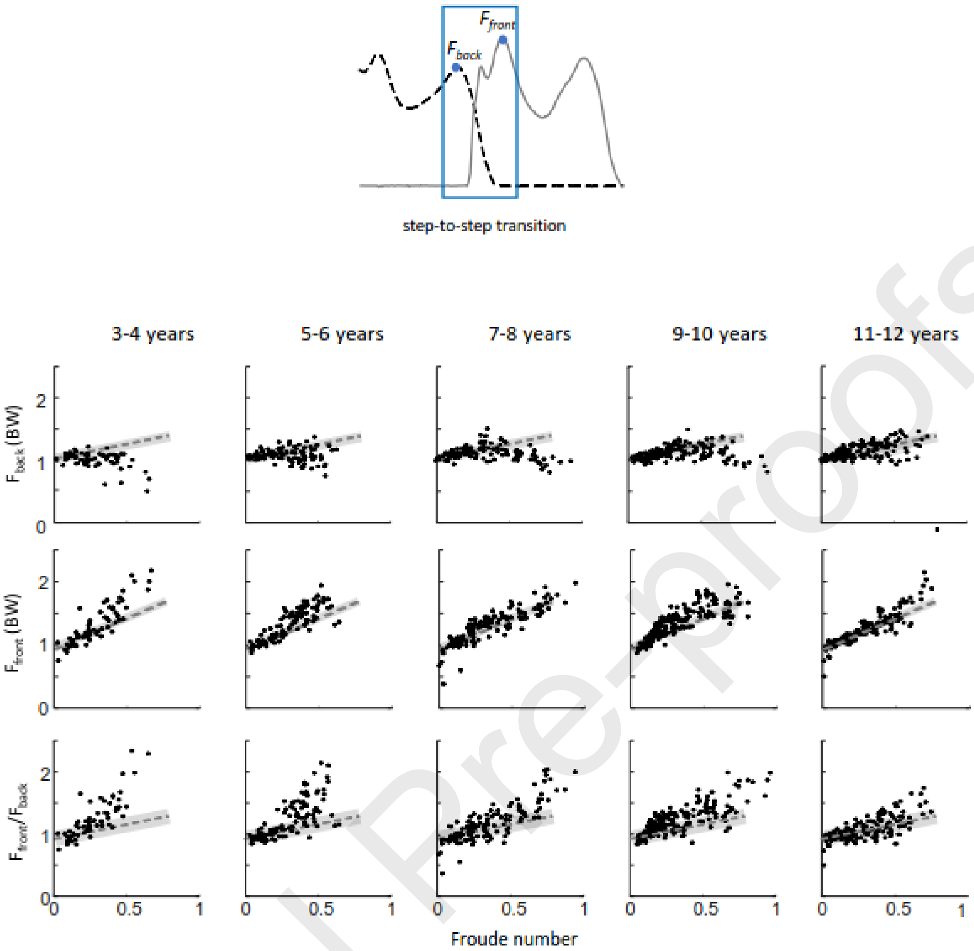
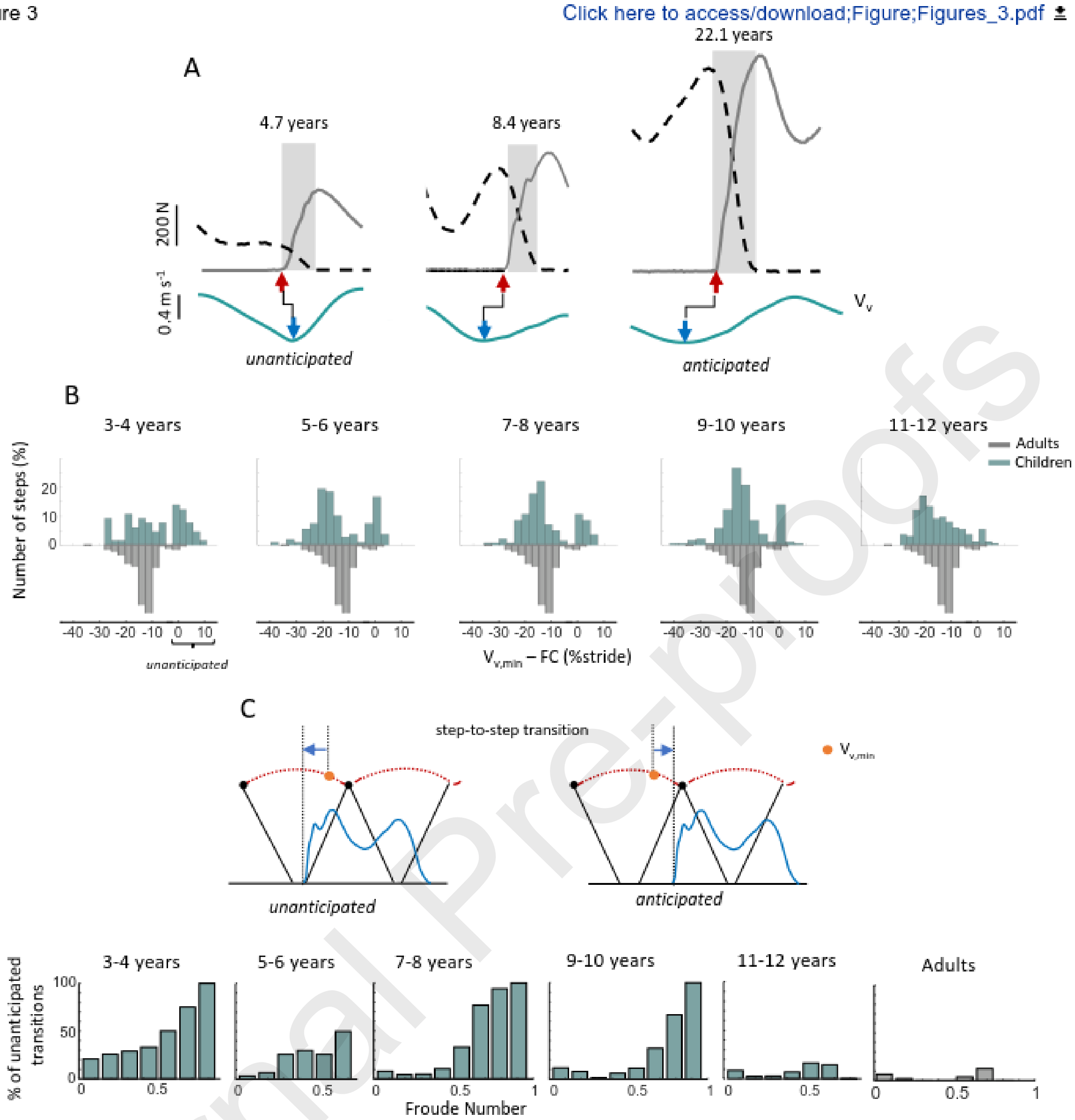

F_{front}
F_{back}
step-to-step transition
3-4 years
5-6 years
7-8 years
9-10 years
11-12 years
F_{back} (BW)
F_{front} (BW)
F_{front}/F_{back}
Froude number

Figure 3


A
4.7 years
8.4 years
22.1 years
200 N
0.4 m s-1
Vv
unanticipated
anticipated
B
3-4 years
5-6 years
7-8 years
9-10 years
11-12 years
Adults
Children
Number of steps (%)
20
10
0
-40 -30 -20 -10 0 10
unanticipated
Vv,min – FC (%stride)
C
step-to-step transition
Vv,min
unanticipated
anticipated
3-4 years
5-6 years
7-8 years
9-10 years
11-12 years
Adults
% of unanticipated transitions
100
50
0
0 0.5 1
Froude Number