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Developmental Changes In Spatial Margin Of Stability In Typically Developing Children Relate To The Mechanics Of Gait

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Highlights

- The spatial margin of stability decreases with increasing age
- Development of dynamic balance control results in changes in step-time parameters
- Changes in step width and single stance relate to the decrease in margin of stability
- These features suggest improvements in dynamic balance control with increasing age

Abstract

Background: Immature balance control is considered an important rate limiter for maturation of gait. The spatial margin of stability (MoS) is a biomechanical measure of dynamic balance control that might provide insights into balance control strategies used by children during the developmental course of gait.

Research Hypothesis: We hypothesize there will be an age-dependent decrease in MoS in children with typical development. To understand the mechanics, relations between MoS and spatio-temporal parameters of gait are investigated.

Methods: Total body gait analysis of typically developing children (age 1 -10, n = 84) were retrospectively selected from available databases. MoS is defined as the minimum distance between the center of pressure and the extrapolated center of mass along the mediolateral axis during the single support phases.

Results: MoS shows a moderate negative correlation with stride length (rho = -0.510), leg length (rho = -0.440), age (rho = -.368) and swing duration (rho = -.350). A weak correlation was observed between MoS and walking speed (rho = -.243) and step width (rho = .285). A stepwise linear regression model showed only one predictor, swing duration, explaining 18% of the variance in MoS. MoS decreases with increasing duration of swing (β= -0.422). This relation is independent of age.

Significance: A larger MoS induces a larger lateral divergence of the CoM that could be compensated by a quicker step. Future research should compare the observed strategies in children to those used in adults and in children with altered balance control related to pathology.

Keywords

Gait – child – development - balance control – margin of stability – step-time parameters

Introduction

At walking onset, between 10 and 15 months of age, infants walk at slow speed with steps shorter than their leg length [1, 2]. A high variability and low stability of gait is characteristic [3]. Already a few months after the onset of walking, speed and step length dramatically increase [1, 4] and occasionally steps larger than leg length can be observed [2]. Other features of an immature gait pattern are a wide base of support and a prolonged duration of stance as well as increased double support [5, 6]. Generally, walking gait is considered to be adult-like around the ages of 7 – 8 years old [5, 7]. Nevertheless, recent work has shown that immature gait characteristics retain during late childhood and early adolescence when walking at adult-like speeds and this relation is dependent upon leg length [8]. Parameters such as double support time, single support time and base of support are only mature in females around the age of 14 years and in males age of maturation is as high as 18 years [8]. Also consistency in variability of gait develops well into adolescence [9].

Thus, maturation of walking continues well after childhood. Changes in gait parameters can partially be explained by growth and changes in the dimensions of body segments [7, 8]. It is accepted that maturationof balance control is another contributing factor in the maturation of gait [9-11]. Features of an immature gait, such as the prolonged duration of stance, increased double support time and the wider base of support are considered characteristic for an immature control of balance.

In a static (standing) situation, balance is achieved when the vertical projection of the center of mass falls within the base of support [12-14]. However, this condition is insufficient in dynamic situations and the velocity of the center of mass should also be accounted for [14]. Based on the inverted pendulum model, Hof [14] showed it can be simply done by replacing the CoM by the XCoM, a point defined as projection on the ground of the COM augmented by a quantity proportional to its velocity. By doing so, similar balance principles apply: the XCoM moves away (diverges exponentially) from the center of pressure and balance can be maintained only if the CoP can be placed outward of the XCoM. As the CoP is constrained to remain within the BoS, there are two possible situations: 1) the XCoM lies within the BoS and it can be captured by shifting the CoP within the BoS, or 2) it lies ouside and a step has to be performed in order to enlarge the BoS before being abble to capture the XCoM.

Regarding gait stability, balance control is more critical in the ML direction, where it is ensured by active foot placement strategies that require central nervous system control [15]. Based on the above mentioned balance principles, Hof showed that this foot placement strategy is primarily driven by the distance between the CoP and the XCoM at foot-of [16], referred to as “spatial margin of stability (MoS)”. If the MoS is too small, there is a risk of crossover steps, if it is too large, it forces the person to have a large step width and/or a small stance time leading to a non-efficient gait. Since, this quantity has proved to be a very interesting window into the balance control of gait [15].

So, control of balance is immature at the onset of walking and is a factor that drives changes in gait pattern throughout childhood. The spatial margin of stability is a measure derived from biomechanics characterizing dynamic balance control mechanisms during gait. We hypothesize there will be an age-dependent decrease in the spatial margin of stability in children with typical development that can be related to changes in the spatio-temporal characteristics of gait.

Methods

Study design

Data on 3D gait analysis in typically developing children (age 1 – 10) were retrospectively included in this cross-sectional study to investigate age-related changes in gait stability using the extrapolated center of mass and spatial margin of stability concepts. The study protocols have been approved by the local ethical committees. Parents gave written informed consent at the time of study inclusion and were aware that data could be used retrospectively for further research. Data collection took place between October 2002 and November 2012.

Setting

Gait analysis data were collected using an integrated set-up with an optometric movement registration system (6 – 8 cameras, Vicon Mcam 460 or T10 series, Vicon®, Oxford, UK or Motion Analysis® system with 8 Eagle® cameras, Motion Analysis Corporation, Santa Rosa, USA) and multiple force plates (2 – 4 platforms, AMTI OR6-7 or Bertec®, Columbus, USA, dimensions 0.4 x 0.5m). Both systems were integrated in the walkway and synchronized at sampling frequencies of 100 Hz and 1000 Hz, respectively. Reflective markers (diameter 14 mm) were attached following the Davis model [17] or custom [18].

Children were introduced to the walkway and were given time to explore and get used to the surroundings. After attaching the markers, again a short habituation period was provided. Data registration was started after the children were no longer aware of the attached markers when moving around. After performing a static anatomical calibration trial in which all markers were visible, dynamic trials were collected. During the dynamic trials one or two caregivers were standing on each end of the walkway to encourage the child to move towards them in a straight line. All children walked barefoot at self-selected speed.

Participants

Out of databases from previous studies all 3D gait analysis of typically developing children that met following inclusion criteria were selected: a total body gait analysis with clear foot strikes on the force plates and full marker visibility for at least two consecutive strides. Details of participant selection in the previous studies is dependent upon the study and can be found in previous publications [18-22].

Variables of interest

Anthropometric measurements

For each subject, information was obtained on age (in years), body mass, body length and leg length. All measures were taken according to standard procedures.

Gait parameters

Walking speed, stride length, step width and duration of swing were used to characterize the temporo-spatial characteristics of gait. Gait parameters were considered as absolute as well as dimensionless values, i.e. normalized to leg length according to Hof [23].

Extrapolated Center of Mass (XCoM)

The “position of the extrapolated center of mass” (XCoM) is the vector sum of the center of mass position and a proportion of its velocity. In human movement, balance is typically related to the vertical projection of the body center of mass on the ground, that should fall within the base of support. This condition is insufficient in dynamic situations, in this case the velocity of the center of mass should also be accounted for. Thus, Hof (2005) defined this new vector quantity (XcoM) where the center of mass position is extrapolated in the direction of its velocity.

Spatial margin of stability (MoS)

The minimum spatial margin of stability was defined as the minimum distance between the center of pressure and the XCoM along the mediolateral axis during the single support phases. The medio-lateral axis was defined as the axis in the transversal plane (XY plane) perpendicular to the walking direction, which was derived from the CoM coordinates. The spatial margin of stability is expressed in absolute values (mm, MoS) and normalized relative to leg length (MoS_LL)

Data measurement

Marker trajectories were labeled in the Vicon Workstation (version 4.6 for Windows) or Nexus (version 1.8.x for Windows) software or Cortex software (Motion Analysis). Based on the force plate data and the ankle marker (malleolus lateralis) trajectories instances of foot strike and foot off were determined [19].

The total body center of mass was calculated using either the standard Vicon clinical model (Plug-In Gait application for Vicon Workstation and Nexus software) or custom (Appendix 1).

The .c3d files were then exported to Matlab and a custom written script was used to calculate the XCoM and MoS according to the formulas described by Hof [14, 16]. Spatio-temporal parameters were calculated from the left and right ankle marker (malleolus lateralis) trajectories.

Bias

All children in this study were volunteers so some form of selection bias cannot be excluded. Children were assumed to show a typical development if no developmental problems were reported by the parents. No additional developmental tests were performed. It is therefore possible that a small number of children might be diagnosed with developmental problems or delay at a later age, especially in the younger age groups.

Study Size

The study is descriptive in nature. Therefore, a sample size calculation cannot be performed. As a rule of thumb, a sample size of 50 children is considered good while sample of 100 children is excellent when providing reference data [24].

Statistical methods

Prior to further analysis, outcome parameters were averaged over the different number of strides that were included for each participant. Outliers were either corrected if possible or removed from the dataset. The Shapiro Wilk test showed that the assumption of normality of the distribution was violated for the outcome variables MoS and MoS_LL. Thus, non-parametric statistics were used. To describe the outcome parameters, median and interquartile range (IQR) were calculated per biological age. To explore the relation between the spatial margin of stability MoS or MoS_LL, age, leg length and gait parameters Spearman rank correlation coefficients were calculated.

Variables showing a significant correlation ($p < 0.05$) with the spatial margin of stability were afterwards added to a stepwise linear regression model starting with the variable showing the highest coefficient of correlation. Two models were generated, for both (non-)normalized variables. Normalized values were considered to remove the effect of growth. Variables were entered into the model in case the probability of F was < 0.05. Variables were removed from the model in case the probability of F was >0.10. Goodness of fit was investigated by R^2 values. Residuals were checked for normality using a histogram and normal P – P plot of regression standardized residual. Statistical analysis was performed using IBM® SPSS® statistics software (version 23.0.0 for Windows, IBM corporation).

Results

Descriptive data

Out of the available databases, a total number of 447 trials in 93 children were eligible for data analysis. After checking for outliers and missing data, data of 84 children with a mean age of 4.7 ± 2.7 years (age range 1 year – 10 years 8 months) were included in the final analysis. Table 1 provides an overview of the number of children in each age range and presents their anthropometric characteristics.

INSERT TABLE 1 HERE

Outcome data

Descriptives of gait parameters and spatial margin of stability can be found in Table 2.

INSERT TABLE 2 HERE

Main results

Pearson correlation coefficients

Table 3 presents bivariate Spearman rank correlation coefficients based on the non-normalized data. The spatial margin of stability MoS shows a highly significant but moderate negative correlation with stride length (rho = -0.510, p < 0.001), leg length (rho = -0.44. p < 0.001), age (rho = -.368, p = 0.001) and duration of swing (rho = -.350, p = 0.004). A weak but significant correlation was observed between the MoS and walking speed (rho = -.243, p = 0.026) and step width (rho = .285, p = 0.012).

INSERT TABLE 3 HERE

Table 4 presents bivariate Spearman rank correlation coefficients on the normalized data. Normalized spatial margin of stability MoS_LL shows a significant and strong positive correlation with dimensionless step width (rho = .757. p < 0.001). A significant and strong negative correlation was found with age (rho =- .677, p < 0.001) and duration of swing (rho = -.659, p < 0.001). A weak but significant correlation was found between MoS_LL and dimensionless stride length (rho = .295, p = 0.026). No significant correlation was observed between the normalized spatial margin of stability MoS_LL and dimensionless walking speed.

Stepwise linear regression

The test results of the stepwise linear regression model using the non-normalized data indicated one predictor, explained 18% of the variance in spatial margin of stability MoS ($R^2 = 0.178$, $F(1,36) = 7.780$, $p = 0.008$). It was found that duration of swing significantly predicted the spatial margin of stability ($\beta = -0.422$, $p = 0.008$). Figure 1 shows the linear relation between spatial margin of stability and duration of swing. Age, leg length, stride length, step width or walking speed did not significantly explain any additional variance in spatial margin of stability.

INSERT FIGURE 1 HERE

The test results of the stepwise linear regression model using the normalized data values, indicated three predictors, explained 66% of the variance in normalized spatial margin of stability MoS_LL ($R^2 = 0.662$, $F(3,34) = 22.159$, $p < 0.001$). It was found that dimensionless step width ($\beta = 0.755$, $p < 0.001$), dimensionless stride length ($\beta = 0.421$, $p = 0.005$) and duration of swing ($\beta = -0.364$, $p = 0.014$) significantly predicted the normalized spatial margin of stability. So, accounting for the leg length, children who take relatively wider steps, who take relatively longer steps and who show a shorter duration of swing have a larger normalized spatial margin of stability (Figure 2).

INSERT FIGURE 2 HERE

Discussion

Key results

The objective of this study was to investigate age related changes in spatial margin of stability as a model of studying development of dynamic balance control during locomotion in childhood. We hypothesized that the spatial margin of stability would be large at the onset of walking and would decrease with increasing age. These changes would be related to changes in the temporo-spatial characteristics of gait. This hypothesis was confirmed. Changes in the spatial margin of stability as a function of age, could be explained by changes in duration of swing. Furthermore, when normalizing for leg length, relations are found between the normalized spatial margin of stability, dimensionless step width, dimensionless stride length and duration of swing. Thus, the spatial margin of stability is primarily related to gait biomechanics. Off-course, these changes in gait biomechanics are age-dependent.

Limitations

Despite its interesting findings, this study has some limitations. All children who participated in this study, did so on a voluntary basis which possibly introduces a selection bias. Furthermore, the lab setting creates an unnatural situation that might introduce small changes in the gait pattern of children compared to a real life situation. The distribution of ages is not homogeneous, there are slightly more younger children in the dataset than older children. However, normalized gait parameters are mature-like after the age of 3. Therefore, a minimal effect on our results is expected.

Data from different research centers and study protocols were pooled. Use of different marker protocols might influence the data. However, differences between the different protocols were statistically investigated using a one-way ANOVA and no differences were found.

Interpretation

Changes in gait pattern are driven by the interactions between growth, maturation and experience [8, 25, 26]. It is difficult to separate these items from each other. Here we observed a significant decrease of spatial margin of stability with age. However, when pooled with spatio-temporal parameters, age did not come out as a primary factor in the stepwise regression model of the spatial margin of stability. Does this mean that dynamic balance control during locomotion does not change throughout childhood? Probably not, since significant relations were found between the spatial margin of stability when normalized to leg length and different gait parameters. Changes in these specific gait parameters, i.e. duration of swing, stride length and step width are known to be age dependent [5, 6].

Interestingly, relations between spatial margin of stability and gait parameters could be linked to the mechanics of gait control in the medio-lateral direction, i.e. the direction where stability constraints are the most pregnant [15]. In particular, during the single stance phase, and by neglecting the small center of pressure adjustments under the stance foot, it showed that the center of mass diverges proportionally to the margin of stability and exponentially with time. Thus, a larger spatial margin of stability induces a larger lateral divergence of the CoM that could be compensated by a larger and/or a quicker step. Our data are in line with these predictions: the normalized spatial margin of stability showed both a positive correlation with step width and a negative one with duration of swing (Figure 2). Moreover, an immature balance control requires an increase of the MoS to avoid frequent falls.

Larger step width and shorter single stance duration could be an adaptation to his immature balance control.

Values of spatial margin of stability found in this study appeared coherent with previous findings on adults. As an example, Hof [14, 16] reported values during walking in the range of 1.5 – 3 % of leg length. If younger children displayed larger normalized MoS values, older children reached this range from the age of 7 years old.

Future research

Further research should focus on how children actually regulate their stability in the medio-lateral direction, and how this regulation evolves with age. In particular, it could be interesting to see if we can observe an evolution in the fine regulations of the center of pressure under the foot during stance phase [16] with age, that could be related to the biomechanical maturation of ankle joint dynamics around the age of four [18].

Conclusion

The spatial margin of stability, MoS, decreases with increasing age. However, development of dynamic balance control, represented by these changes in MoS, is linked to changes in step-time parameters of gait.

Conflict of Interest

None.

Acknowledgements

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Figure Captions

Figure 1: Relation between the spatial margin of stability and duration of swing. The linear regression line with 95% confidence interval was fitted using the least squares error method.

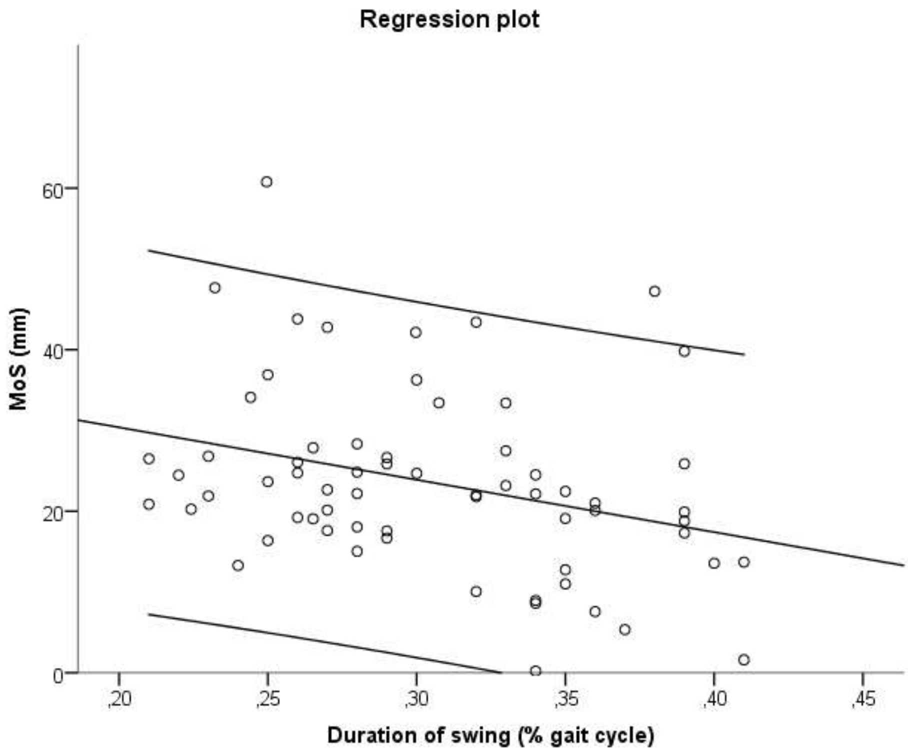


Figure 2: Relation between the normalized spatial margin of stability (% of leg length, MoS_LL) as dependent variable and dimensionless step width (first panel), dimensionless stride length (second panel) and duration of swing (third panel). The linear regression line with 95% confidence interval was fitted using the least squares error method

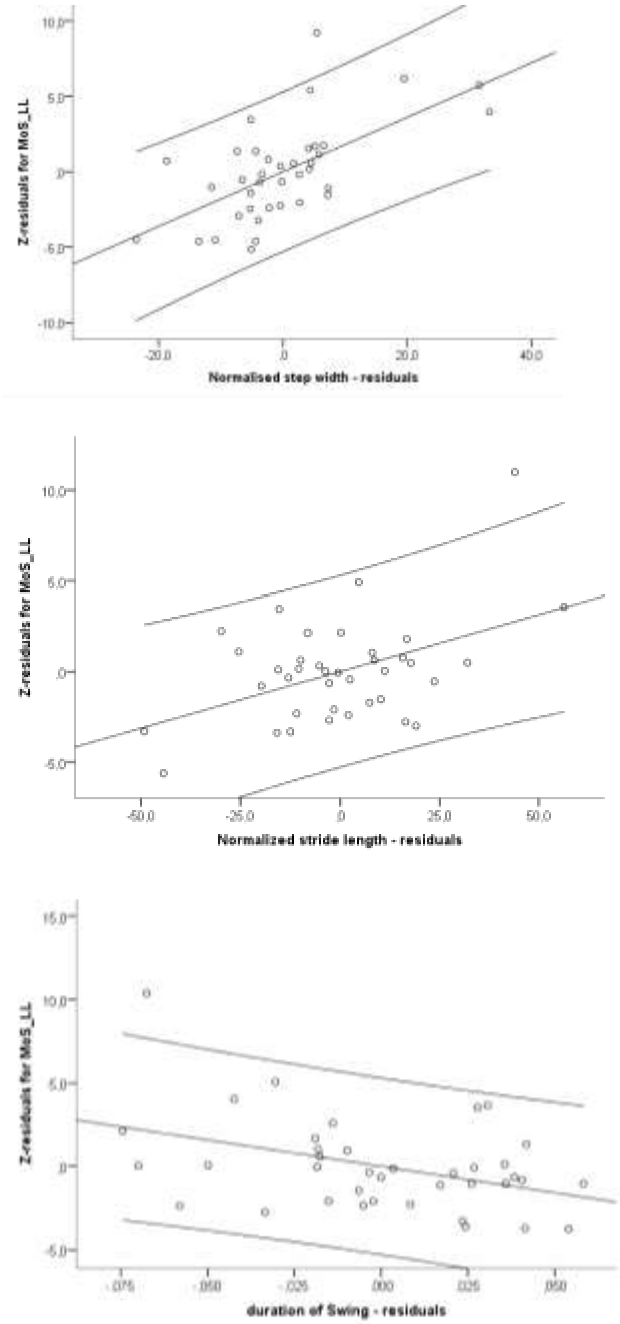


Table 1: Descriptive data of the study sample including the age ranges, mean ages and anthropometric characteristics (N = number of children, F = number of females)

Age Groups			Age (years)		mass (kg)		body height (mm)		BMI		leg length (mm)	
	N	F	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1 year – 1 year 11 months	17	12	1.4	.2	10.98	1.17	791	43	17.7	2.0	311	35
2 years – 2 years 11 months	12	7	2.3	.2	13.55	1.61	915	46	17.3	2.1	350	53
3 years – 3 years 11 months	8	4	3.4	.3	16.10	2.37	1004	50	17.0	1.9	454	45
4 years – 4 years 11 months	11	8	4.5	.3	17.80	2.64	1065	51	16.9	1.9	514	33
5 years – 5 years 11 months	10	6	5.4	.3	18.67	2.36	1098	51	16.6	1.9	527	28
6 years – 6 years 11 months	10	4	6.3	.3	21.12	3.07	1175	61	16.6	1.8	586	33
7 years – 7 years 11 months	4	2	7.5	.2	24.60	.78	1256	18	16.6	1.8	654	27
8 years – 8 years 11 months	4	2	8.5	.3	25.30	2.95	1319	13	16.4	1.8	691	23
9 years – 9 years 11 months	3	1	9.4	.3	33.77	3.40	1383	23	16.2	1.5	717	15
10 years – 10 years 11 months	5	2	10.5	.2	32.78	2.89	1432	46	16.1	1.5	766	21
All	*84*		*4.7*	*2.7*	*18.29*	*6.77*	*1054*	*198*			*491*	*148*

Table 2: Descriptive data of gait parameters and spatial margin of stability presented according to biological age: both absolute values and relative values normalized to leg length (%) are represented as median (IQR) for each biological age group

Age Groups	Spatial margin of stability		walking speed		stride length		step width		swing
	mm	%	m/s	-	mm	%	mm	%	%
1 y – 1 y 11 m	28 (27)	9 (11)	.67 (.37)	.25 (.21)	425 (180)	141 (78)	130 (73)	44 (34)	24 (4)
2 y – 2 y 11 m	47 (30)	16 (11)	.84 (.23)	.39 (.31)	640 (85)	211 (32)	110 (12)	31 (9)	26 (0)
3 y – 3 y 11 m	20 (13)	5 (2)	.86 (.23)	.22 (.12)	715 (188)	165 (27)	110 (25)	25 (10)	29 (5)
4 y – 4 y 11 m	25 (7)	5 (1)	1.10 (.43)	.27 (.17)	860 (105)	165 (29)	110 (20)	23 (3)	29 (8)
5 y – 5 y 11 m	22 (6)	4 (1)	1.00 (.16)	.43 (.29)	865 (130)	164 (9)	113 (38)	23 (8)	29 (6)
6 y – 6 y 11 m	23 (19)	4 (3)	1.20 (.12)	.23 (.22)	1055 (115)	177 (35)	116 (23)	20 (3)	32 (5)
7 y – 7 y 11 m	20 (22)	3 (3)	1.25 (.10)	.49 (.03)	1055 (90)	163 (10)	120 (5)	19 (2)	36 (3)
8 y – 8 y 11 m	19 (9)	3 (1)	1.32 (.07)	.51 (.04)	1160 (85)	166 (21)	120 (3)	17 (1)	34 (4)
9 y – 9 y 11 m	17 (6)	3 (1)	1.32 (.04)	.49 (.02)	1180 (60)	164 (12)	110 (20)	15 (3)	36 (2)
10 y – 10 y 11 m	14 (12)	2 (2)	1.29 (.03)	.47 (.01)	1240 (30)	161 (7)	100 (50)	11 (7)	40 (2)
All	*24 (12)*	*5.0 (2.0)*	*.99 (.30)*	*.35 (.14)*	*828 (298)*	*165 (33)*	*120 (33)*	*26 (16)*	*31 (5)*

*Table 3: Bivariate Spearman's rank correlation coefficients: * correlation is significant at the 0.05 level ** correlation is significant at the 0.01 level*

	age	leg length	walking speed	stride length	step width	duration of swing
margin of stability	-.368**	-.440**	-.243*	-.510**	.285*	-.350**
age		.956**	.819**	.957**	-.160	.767**
leg length	.956**		.795**	.914**	-.142	.780**
walking speed	.819**	.795**		.887**	-.249*	.602**
stride length	.957**	.914**	.887**		-.508**	.782**
step width	-.160	-.142	-.249*	-.508**		.025

*Table 4: Bivariate Spearman rank correlation coefficients between age, margin of stability normalized to leg length (MoS_LL) and gait parameters normalized to leg length: * correlation is significant at the 0.05 level ** correlation is significant at the 0.01 level*

	age	Dimensionless walking speed	Dimensionless Stride length	Dimensionless Step width	Swing
Normalised margin of stability	-.677**	-.164	.295*	.757**	-.659**
Age		.296**	-.026	-.837**	.767**
Dimensionless walking speed	.296**		.369**	-.260**	.565**
Dimensionless Stride length	-.026	.369**		-.060	.395**
Dimensionless Step width	-.837**	-.260**	-.060		-.617**
Swing	.767**	.565**	.395**	-.617**	

Appendix: Methodology used to estimate the whole body center of mass from LBMC's data

The following procedure was used to estimate the whole body center of mass from marker trajectories:

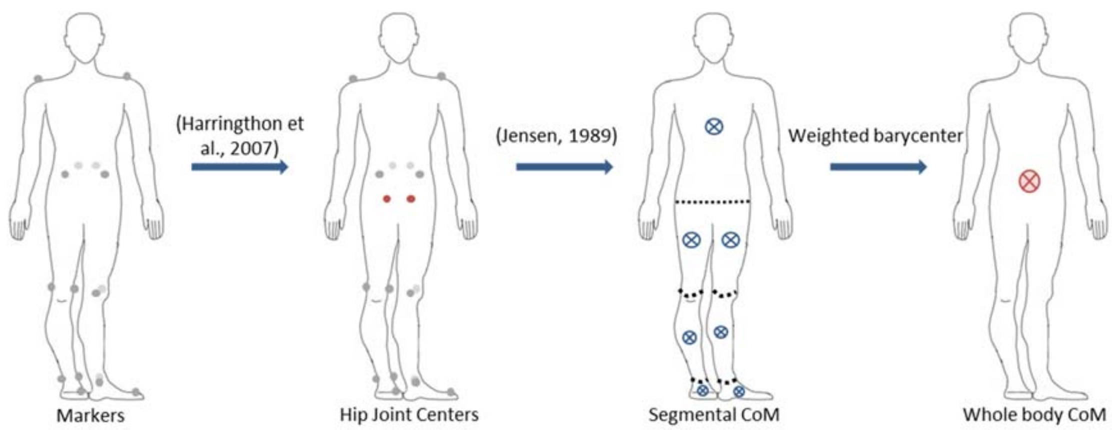
1- Sixteen (16) reflective markers were placed on particular anatomical points of the trunk, pelvis and lower limbs: left and right acromions, anterior and posterior iliac spines, medial and lateral femoral epicondyles, medial and lateral maleolli and first metatarsal heads.

2- Regressions from Harington et al. (2007) dedicated to healthy children were used to estimate the hip joint centers.

3- Mass and position of the center of mass of 7 segments (feet, shanks, thighs and Head-Arm-Trunk) were then estimated from these markers and hip joint centers using regressions from Jensen (1989), considering children's age.

4- The whole body center of mass was then obtained as the weighted barycenter of segment's centers of mass.

This procedure is summarized in the figure below:



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Appendix II: The spatial margin of stability and the normalized spatial margin of stability plotted per age group