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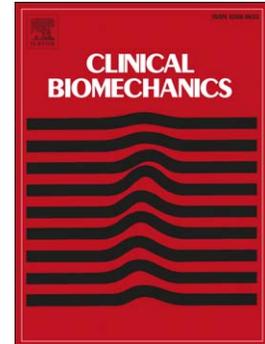
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Gait parameters database for young children:**The influences of age and walking speed**

A. Van Hamme^{1,2,3,4}, A. El Habachi^{1,2,3}, W. Samson⁵, R. Dumas^{1,2,3},
L. Chèze^{1,2,3}, B. Dohin⁵

¹ *Université de Lyon, F-69622, Lyon, France*

² *Université Claude Bernard Lyon 1, Villeurbanne*

³ *IFSTTAR, UMR_T9406, LBMC Laboratoire de Biomécanique et Mécanique des Chocs, F-69675, Bron*

⁴ *CTC, 4 rue Hermann Frenkel 69367 Lyon Cedex 7, France*

⁵ *Laboratory of Anatomy, Biomechanics and Organogenesis, CP 619, Université Libre de Bruxelles (ULB),
Lennik Street 808, 1070 Brussels, Belgium*

⁶ *Université Jean Monnet Saint-Etienne, Service de Chirurgie Pédiatrique CHU Nord,
42055 Saint Etienne cedex 2, France*

Corresponding author: laurence.cheze@univ-lyon1.fr

Laboratoire de Biomécanique et Mécanique des Chocs (Université Lyon 1 / IFSTTAR)

Université Lyon 1, Bâtiment Omega, 43 Bd du 11 novembre 1918, 69 622 Villeurbanne cedex

France. Tel: +33 4 72 44 80 98

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Abstract

Background. Reference databases are mandatory in orthopaedics because they enable the detection of gait abnormalities in patients. Such databases rarely include data on children under seven years of age. In young children, gait is principally influenced by age and walking speed. The influence of the age-speed interaction has not been well established. Therefore, the objective of the present study is to propose normative values for biomechanical gait parameters in children taking into account age, walking speed, and the age-speed interaction.

Methods. Gait analyses were performed on 106 healthy children over a large age range (between one and seven years of age) during gait trials at a self-selected speed. From these gait cycles, biomechanical parameters, such as the joint angles and joint power of the lower limbs, were computed. Specific peak values and the times of occurrence of each biomechanical gait parameter were identified. Linear regressions are proposed for studying the influence of age, walking speed and the age-speed interaction.

Findings. Most of the regressions achieved good accuracy in fitting the curve peaks and times of occurrence, and the normal reference targets of biomechanical parameters could be deduced from these regressions. The biomechanical gait parameters of a pathological case were plotted against the normal reference targets to illustrate the relevance of the proposed targeting method.

Interpretation. The normal reference targets for biomechanical gait parameters based on age-speed regressions in a large database might help clinicians detect gait abnormalities in children from one to seven years of age.

Keywords: healthy children; joint moments; joint power; regression analysis

1. Introduction

During the first years of independent walking, considerable changes occur in joint kinematics and dynamics (Chester and Wrigley, 2008; Chester et al., 2006; Dominici et al., 2007; Grimshaw et al., 1998; Ivanenko et al., 2005). Gait modifications have been studied to better understand gait maturation during the growth of children (Samson et al., 2013; Sutherland, 1997). One of the difficulties in understanding gait maturation is the availability of an age-matched reference databases for children, as suggested by Chester et al. (Chester et al., 2007). The following reference databases for gait in children have been published: the temporal distance, kinematic and dynamic gait parameters of 10 toddlers aged 13.5 to 18.5 months old (Halleman et al., 2005); the ground reaction force patterns of more than 7000 children aged 1 to 13 years old (Müller et al., 2012); and the kinematic and dynamic parameters of 20 Chinese children aged 7 to 12 years old (Bacon-Shone and Bacon-Shone, 2000). These studies demonstrated the influence of age on biomechanical gait parameters. In mid childhood, “sagittal joint kinematics, moments and powers are predominantly characterized by speed of progression, not age”, as reported by Stansfield et al. (Stansfield et al., 2001). The major relevance of the latter study is that dimensionless walking speed should be preferentially considered rather than age to compare healthy and pathological gaits in children. These conclusions are based on children aged 7 to 12 years old and could be different for younger children. Moreover, Schwartz et al. (Schwartz et al., 2008) described the gait of 83 typically developing children walking at a wide range of speeds and displayed spatio-temporal, kinematic, kinetic and electromyographic data for children between 4 and 17 years old. In this study, the influence of speed variation on this population was obvious from the graphs presented, but the age influence was ignored. Stansfield et al. (Stansfield et al., 2006) proposed a regression analysis of biomechanical gait parameters as a function of walking speed; however, the results were obtained with relatively low determination coefficients (R^2)

(*i.e.*, less than 0.3 except for the temporal distance parameters and components of the ground reaction force (GRF)). The study included 16 children aged 7 to 12 years old.

Clinical indices based on kinematic data (the Gillette Gait Index (Schutte et al., 2000), the Gait Deviation Index (Schwartz and Rozumalski, 2008) and the Gait Profile Score (Baker et al., 2009)) and on dynamic data (Rozumalski and Schwartz, 2011) have been proposed. Age and speed variations were not considered in their calculations, and there are difficulties in comparing healthy and pathological gaits in children because of walking speed differences.

The objective of the present study was to propose normative values for biomechanical gait parameters taking into account age, walking speed, and the age-speed interaction. This is not easily achievable with group corridors (*i.e.*, mean \pm standard deviation) unless a very large number of age-speed groups are considered, but can be more simply achieved by establishing normal reference targets based on regression models. Therefore, this study establishes a large database of more than 100 young children (from one to seven years old). Because the objective of the paper is to measure the influence of age and walking speed, the database was collected to provide a wide range of ages and speeds (the children walked at a self-selected speed). The influence of these factors was analysed using regression models that link age, walking speed, and their interaction on biomechanical gait parameters (kinematic and dynamic data). These regressions are important for studying the influence of the tested factors; however, they are somewhat impractical for clinical application. Normal reference targets were constructed based on regression models that allowed the pathological biomechanical gait parameters of children to be plotted against the normative values, taking into account age, walking speed, and the age-speed interaction. The relevance of the method is illustrated with one pathological case.

2. Materials and Methods

2.1 Population and experimental set-up

Gait analysis was performed on 106 healthy children (from one to seven years old). The participant characteristics are presented in Table 1. One child could be measured several times during its growth. All of the children were independent walkers from the first examination, and clinical examination did not reveal any orthopaedic or neurological disorders. The local ethics committee approved the study. The children were included in the study after clinical examination and when their parents consented to involvement after having been informed about the protocol.

Twenty-four skin markers were fixed on anatomical landmarks of the pelvis (the right and left anterior and posterior superior iliac spines) and the lower limbs (the great trochanter, medial and lateral epicondyles, anterior tibial tuberosity, medial and lateral malleoli, calcaneus, first and fifth metatarsal heads and hallux) (Samson et al., 2013, 2009).

The children walked barefoot at a self-selected speed. Fifteen to twenty gait trials were measured for each subject using a Motion Analysis[®] system with eight Eagle[®] cameras (Motion Analysis Corporation, Santa Rosa, California, USA) at 100Hz and three Bertec[®] force platforms (Bertec Corporation, Columbus, Ohio, USA) at 1000Hz. Only trials with valid dynamic data were selected (i.e., one foot and only one foot on one forceplate), providing between one to six gait trials per gait analysis. In total, 1253 gait cycles were retained.

2.2 Data processing

After filtering (low-pass zero-lag, 4th-order, Butterworth filter, with a 6-Hz cut-off frequency), the marker trajectories were obtained in an Inertial Coordinate System (ICS) (Wu and Cavanagh, 1995). The hip joint centre localisation was determined using the regression models established by Harrington et al., selecting only the data from healthy children

(Harrington et al., 2007). The inertial parameters were determined using the regressions established by Jensen (Jensen, 1989). The three orthogonal axes (X, Y, and Z) corresponding to each segment coordinate system (SCS) were built following the International Society of Biomechanics recommendations (Wu et al., 2002). The quaternion was extracted from the attitude of these axes in the ICS. The angular velocities of the proximal and distal segments were obtained in the ICS using quaternion algebra and were subtracted to compute the (relative) joint angular velocity, ω . The net 3D joint moments, \mathbf{M} , were computed in the ICS by bottom-up inverse dynamics (Dumas et al., 2004), with the force platform's data re-sampled at 100Hz. The power, \mathbf{P} , was computed in 3D by the dot product between \mathbf{M} and ω . The joint moments, \mathbf{M} , were expressed in the joint coordinate systems (Desroches et al., 2010), and \mathbf{M} and \mathbf{P} were re-sampled on a percentage of the gait cycle and were expressed using the dimensionless scaling strategy (Hof, 1996), with the leg length (the distance from the ground to the great trochanter) used as a metric value. The walking speed was defined from the initial contact of one foot to the next initial contact of the same foot (one gait cycle) and was expressed with a dimensionless parameter (Hof, 1996). The moments are in units of $N.m/m_0gl_0$, the powers are in units of $W/m_0\sqrt{g^3.l_0}$, the GRF is in units of N/m_0g and the walking speed is in units of $m.s^{-1}/\sqrt{g.l_0}$ (with m_0 indicating the body mass, l_0 , the leg length and g , the acceleration of gravity).

The gait trials were not averaged per subject. Data from both right and left strides were included, taking into account the sign conventions. The peak values and the corresponding times of occurrence were identified on the curves displaying kinematic and dynamic parameters (Table 2). The times of occurrence were expressed as a percentage of the gait cycle. The coefficients of the linear regression models were estimated considering age, walking speed, and the age-speed interaction as the model inputs as well as the peak values

and times of occurrence as the model outputs. We computed the confidence intervals of the regression models to define the normal reference targets.

2.3 Data analysis

2.3.1 Regression models

To establish a link between the biomechanical gait parameters (the peak values and times of occurrence) and age, walking speed and their interaction, the regression model used was as follows:

$$Y = a * age + b * speed + c * age * speed + d$$

where Y was the estimated output variable, age and $speed$ were the input variables and a , b , c , and d were the regression coefficients. These coefficients were estimated using the least squares method. The determination coefficients (R^2) and t -test p -values were calculated to evaluate the goodness and relevance of the fit, respectively. The regressions of body mass, m_0 , and leg length, l_0 , with age are also provided to allow for comparison with previous studies that did not use a dimensionless parameter (Table 3).

2.3.2 Normal reference targets

The aim of the study was to propose normal reference targets for clinical use. These reference targets were achieved on the regression residual (*i.e.*, using the difference between the measured output value and its estimation by the regression). The calculation of the standard deviation of the residuals allows for the estimation of the confidence interval of the output variable. The confidence interval was calculated for the peak value and time of occurrence, defining an ellipse of confidence regarding the estimated output variable. For each estimated output variable, the confidence interval at 95% was computed using the following formula: $[Y - 1.96 * SD(Y - Y_{mes}); Y + 1.96 * SD(Y - Y_{mes})]$, where Y_{mes} is the measured output variable (the peak value and time of occurrence). The knowledge of these standard deviation values allows

for the superimposing of the normal reference targets (i.e., the ellipses of confidence centred on each biomechanical parameter peak) on the patient gait curves. As an illustration, a pathological gait was evaluated using the normal reference targets. The patient had cerebral palsy with right hemiplegia. He was seven years old and walked at $0.39 \text{ m} \cdot \text{s}^{-1} / \sqrt{g \cdot l_0}$.

3. Results

3.1 Regression models

Most of the regressions were significant (the *p-values* of the *t-test* were less than 0.05). R^2 was greater for the peak values than for the times of occurrence. R^2 values higher than 0.4 were obtained on some peaks for the values and times of occurrence, especially for the knee and hip dynamic parameters. The standard deviation values, allowing for the computation of the normal reference targets, are provided in Table 3. All of the results of the regression analysis are available in the supplementary materials. The results of a global sensitivity analysis (Plischke, 2010) are also presented. This analysis was performed on age, walking speed and their interaction and provides information about the contribution of each parameter in biomechanical gait parameters.

3.2 Normal reference targets, an application example

Figure 1 shows an example of the application of the normal reference targets to a pathological gait analysis (cerebral palsy with right hemiplegia). The peak values and times of occurrence were calculated for the ankle, knee and hip power on the lower limbs using the regression model (inputs: age 7 and walking speed $0.39 \text{ m} \cdot \text{s}^{-1} / \sqrt{g \cdot l_0}$). Normal reference targets were built for each estimated value, taking into account the confidence interval of the peak values and the times of occurrence. For the ankle, the second peak target was not represented because the regression analysis was not significant (see supplementary materials). The gap between the normal and pathological data was gauged with the proposed targeting method.

During the stance phase, the left ankle power is close to zero, whereas the right ankle absorbs negative power more than in healthy children. For the knee and hip, the right hemiplegic limb peak powers are lower than the means of the normal data, and the peak powers on the left lower limb appear to compensate for this phenomenon (even if most of the peaks still fall within normal limits). The child with a pathological gait developed a larger negative or positive power than that of the healthy children, depending on the side, for the knee and hip, especially during the swing phase.

4. Discussion

This study presents a large biomechanical gait output database of healthy young children (younger than seven years old) walking at a self-selected speed. A regression analysis was performed to estimate the normal reference targets for each peak of the biomechanical gait parameters for the healthy children. An application of the normal reference targets in an illustrative pathological case was proposed. More than showing the influence of age and speed, the objective of this study is to provide targets based on the age-speed regressions to compare pathological cases (of given ages and walking at typically lower speeds) with a reference.

Only walking at a self-selected speed could be analysed with this population (i.e., speed could not be imposed on very young children). Yet, a large range of speeds was achieved ($[0.1-0.7 \text{ m}\cdot\text{s}^{-1}/\sqrt{g\cdot l_0}]$), which was a similar result to that of a previous study on older children (Schwartz et al., 2008), where very slow to very fast conditions were imposed.

Although the proposed linear regression model was still relatively simple (taking into account age and speed), it provided a better approximation of peak values than only considering walking speed (Stansfield et al., 2006). More complex models could be explored in future studies to fit the experimental data better (e.g., including the exponential or logarithmic

functions). This simple linear model provided significant regressions for most of the studied biomechanical gait parameters. The difference between R^2 for the peak values and for the times of occurrence could be explained by the fact that the variability of the times of occurrence is higher than the variability of the peak values. The best correlations were found for the dynamic values, perhaps because of the better repeatability of the dynamic rather than the kinematic parameters (Steinwender et al., 2000). The best R^2 values were obtained for the power values. The calculation of power, taking into account the joint angular velocity, was obviously linked to the walking speed and could explain the greater R^2 values. Stansfield et al. (Stansfield et al., 2006) did not find a significant regression for the second peak of the vertical GRF, assuming that this peak could be linked with the body's control of stability instead of with the maintenance of speed. Including age in the model, the regression on the second peak of the vertical GRF was significant and had an acceptable R^2 value in comparison with that of Stansfield's results (i.e., $R^2 = 0.18$ vs. no significance, respectively). These differences could be explained by our younger population.

The standard deviations were large because of the high variability of gait in young children. The calculation of the confidence intervals provided normal reference targets, allowing for the evaluation of any gait cycle and defining the normative values for comparison with pathological cases. These normative values take into account age, walking speed, and the age-speed interaction, which was not possible with simple group corridors (i.e., mean \pm standard deviation). By including all of the gait cycles, the complications linked with group definitions (based on the age and/or speed) and, especially, a definition of the boundaries for groups were avoided. The visual comparison with an illustrative pathological case illustrates the clinical potential of the targeting method. The patient was seven years old, which corresponded to the upper limit of our database of healthy children. Application to younger patients and to a larger number of patients with different pathologies is necessary to confirm the suitability of the

normal reference targets. These targets, based on the age-speed regressions established for a large database, could be a complement to existing clinical indices (e.g., the Gillette Gait Index (Schutte et al., 2000) and the Gait Deviation Index (Schwartz and Rozumalski, 2008)).

5. Conclusion

This study presented a large biomechanical gait parameters database of young healthy children (including more than 100 children) and proposed an original regression of these parameters with age, walking speed, and the age-speed interaction. The regressions were calculated for the peak values of the biomechanical gait parameters and their times of occurrence. A method was proposed to define normal reference targets that might help clinicians detect gait abnormalities in children from one to seven years of age.

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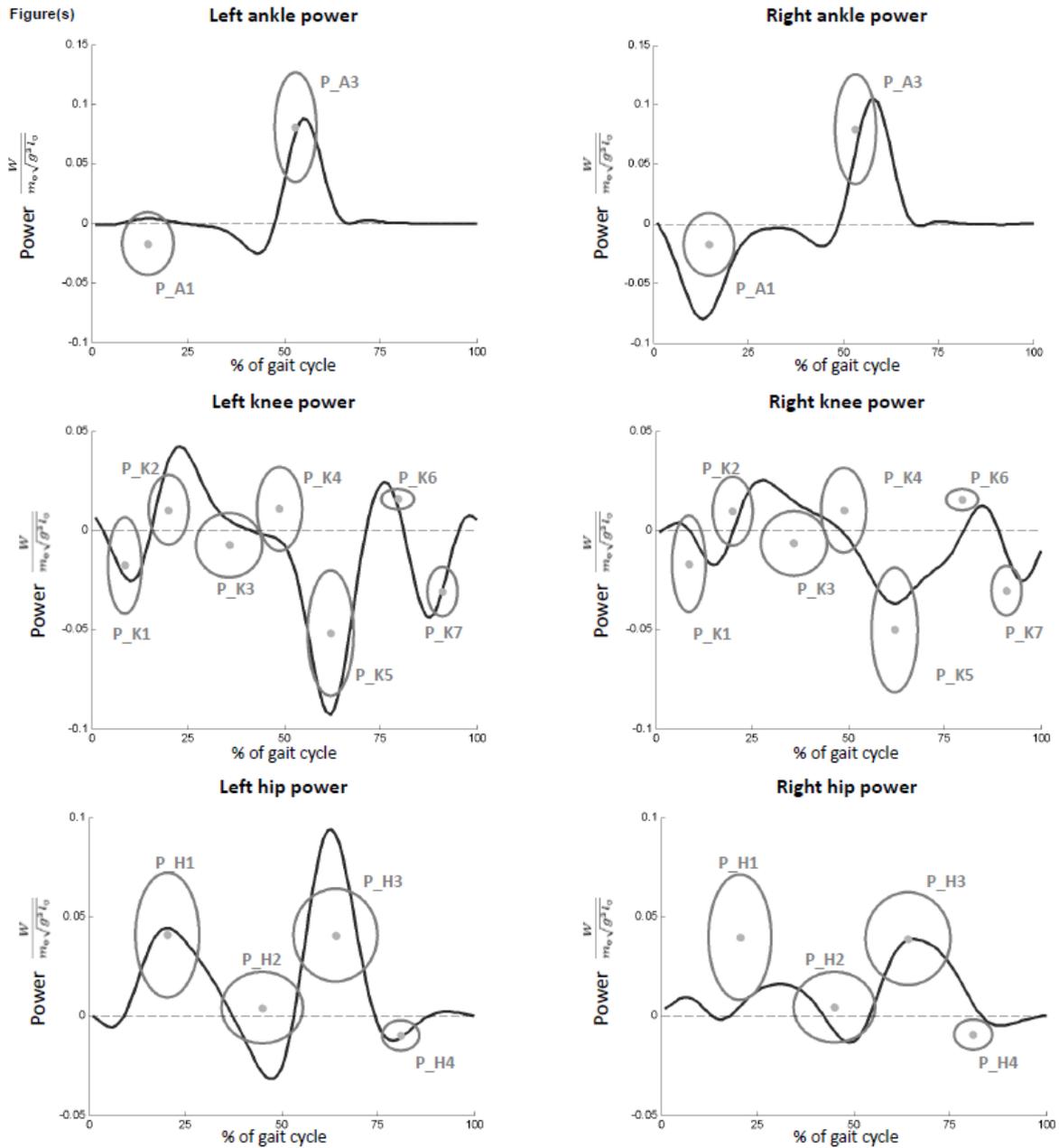


Figure captions

Figure 1: Ankle, knee and hip powers (in $W/m_0\sqrt{g^3 \cdot l_0}$) of a hemiplegic child for the left and right leg (m_0 : mass; l_0 : leg length; g : acceleration of gravity).

The grey points represent the estimated value and time of occurrence (estimated by the regression models based on the data of healthy children). The ellipses correspond to the normal reference targets (confidence intervals)

Table captions

Table 1: Participant characteristics according to age. For each group, age boundaries (e.g., [1-2[for the 1st group) mean that all children between their 1st birthday plus one day and 2nd birthday were included. An exception was accepted for the last group (i.e., [6-7]) in which one child who had already had his 7th birthday was included.

Table 2: Description of peak identification and corresponding abbreviation

Table 3: Regression models for mass, m_0 ; leg length, l_0 ; and the biomechanical gait parameters with $R^2 > 0.1$ for the peak value and the time of occurrence: a, b, c, and d: Regression coefficients, R^2 : determination coefficient, p : p-value (****: $p < 10^{-5}$), SD: standard deviation of errors. N/A: Not Applicable. Abbreviations (e.g., A_A2) are detailed in Table 1.

Table 1:

Age Group (years old)		[1-2[[2-3[[3-4[[4-5[[5-6[[6-7]	Total
Age (years)	Mean	1,52	2,40	3,38	4,44	5,42	6,55	3,62
	SD	0,26	0,29	0,27	0,28	0,28	0,34	1,62
Number of gait analysis		45	54	52	38	40	24	253
Number of trials		205	246	267	198	204	133	1253
Leg length (m)	Mean	0,34	0,40	0,45	0,50	0,55	0,59	0,46
	SD	0,02	0,03	0,03	0,03	0,04	0,03	0,08
Mass (kg)	Mean	11,04	13,00	15,33	17,52	20,05	22,31	15,80
	SD	0,93	1,32	1,92	2,23	2,57	3,02	4,12

Table 2:

Angles	Ankle	A_A1	max plantarflexion (0-25%)	Moments	Ankle	M_A1	max plantarflexion moment (0-100%)
		A_A2	max dorsiflexion (26-50%)			M_A2	max internal rotation moment (0-25%)
		A_A3	max plantarflexion (51-75%)			M_A3	max external rotation moment (40-65%)
		A_A4	max dorsiflexion (76-100%)			M_A4	max inversion moment (0-25%)
		A_A5	max external rotation (0-25%)			M_A5	max eversion moment (40-65%)
		A_A6	max internal rotation (40-65%)		Knee	M_K1	max extension moment (0-25%)
		A_A7	max external rotation (66-80%)			M_K2	max flexion moment (26-55%)
		A_A8	max eversion (20-50%)			M_K3	max extension moment (50-80%)
		A_A9	max inversion (51-70%)			M_K4	max flexion moment (81-100%)
			M_K5			max abduction moment (0-30%)	
	Knee	A_K1	max flexion (0-25%)	M_K6	min abduction moment (31-50%)		
		A_K2	min flexion (26-55%)	M_K7	max abduction moment (40-60%)		
		A_K3	max flexion (56-100%)	M_K8	max internal rotation moment (0-25%)		
		A_K4	max abduction (50-70%)	M_K9	min internal rotation moment (26-50%)		
		A_K5	max adduction (71-100%)	M_K10	max internal rotation moment (51-80%)		
		A_K6	min external rotation (0-30%)	Hip	M_H1	max extension moment (0-30%)	
		A_K7	max external rotation (30-60%)		M_H2	max flexion moment (50-75%)	
		A_K8	max internal rotation (61-100%)		M_H3	max extension moment (76-100%)	
			M_H4		max abduction moment (0-30%)		
			M_H5		min abduction moment (31-45%)		
			M_H6		max abduction moment (46-60%)		
			M_H7		max external rotation moment (0-25%)		
			M_H8		max external rotation moment (30-60%)		
	Hip	A_H1	max flexion (0-15%)	Powers	Ankle	P_A1	max absorbed power (0-25%)
		A_H2	min flexion (40-60%)			P_A2	max absorbed power (26-45%)
		A_H3	max flexion (70-100%)			P_A3	max generated power (46-65%)
		A_H4	max adduction (0-25%)		Knee	P_K1	max absorbed power (0-15%)
		A_H5	max adduction (26-50%)			P_K2	max generated power (16-30%)
		A_H6	max abduction (51-100%)			P_K3	max absorbed power (31-40%)
		A_H7	max internal rotation (0-25%)			P_K4	max generated power (41-50%)
		A_H8	max internal rotation (26-50%)			P_K5	max absorbed power (51-65%)
		A_H9	max external rotation (60-80%)			P_K6	max generated power (6-80%)
		A_H10	min external rotation (81-100%)			P_K7	max absorbed power (81-100%)
			Hip	P_H1	max absorbed power (0-30%)		
				P_H2	min absorbed power (31-55)		
				P_H3	max absorbed power (56-75%)		
				P_H4	max generated power (76-100%)		
GRF		Fx1	max posterior force (0-40%)				
		Fx2	max anterior force (41-70%)				
		Fy1	max vertical force (0-30%)				
		Fy2	min vertical force (20-45%)				
		Fy3	max vertical force (40-70%)				
		Fz1	max medial force (0-30%)				
		Fz2	min medial force (20-45%)				
		Fz3	max medial force (40-70%)				

Table 3:

		a	b	c	d	R ²	p	SD	
Mass	m_0	2,27E+00	N/A	N/A	7,59E+00	0,79	****	1,87E+00	
Leg length	l_0	4,94E-02	N/A	N/A	2,78E-01	0,91	****	2,57E-02	
Angles	Peak values	A_A2	-3,18E-01	-1,17E+01	7,08E-02	2,11E+01	0,11	****	3,86E+00
		A_A3	-1,70E+00	-6,15E+01	4,34E+00	6,60E+01	0,33	****	6,35E+00
		A_H2	-2,66E+00	-2,29E+01	3,64E-02	2,42E+01	0,38	****	6,88E+00
	Times of occurrence	A_A2	-3,13E-01	-7,70E+00	-2,80E-01	5,87E+01	0,21	****	2,40E+00
		A_A3	-1,18E+00	-2,85E+01	9,57E-02	7,68E+00	0,22	****	6,31E+00
		A_H2	-7,11E-01	-1,50E+01	8,41E-01	7,22E+01	0,27	****	2,16E+00
Moments	Peak values	M_K1	-6,44E-03	1,13E-01	1,93E-02	2,17E-02	0,20	****	3,69E-02
		M_K2	6,07E-02	9,08E+00	-7,21E-01	1,12E+01	0,11	****	1,90E+00
		M_H1	6,91E-03	-7,81E-02	-1,43E-02	-1,65E-02	0,16	****	2,76E-02
		M_H2	8,04E-01	-1,68E+01	-6,53E-01	4,83E+01	0,18	****	3,87E+00
		M_H3	2,08E-02	-4,92E-02	-3,09E-02	-1,47E-01	0,18	****	3,60E-02
	Times of occurrence	M_K1	-1,40E+00	-2,05E+01	2,09E+00	2,15E+01	0,24	****	2,60E+00
		M_K2	1,75E-03	1,02E-01	8,32E-03	-1,04E-02	0,60	****	1,34E-02
		M_H1	-1,24E+00	-1,98E+01	7,08E-01	7,12E+01	0,29	****	3,87E+00
		M_H2	8,63E-04	-5,87E-02	-8,95E-03	8,97E-03	0,62	****	8,20E-03
		M_H3	-2,47E-01	-1,31E+01	8,86E-02	9,45E+01	0,25	****	2,40E+00
Powers	Peak values	P_A3	1,78E-03	9,21E-02	6,15E-03	1,43E-02	0,28	****	2,35E-02
		P_K6	-4,31E-01	-2,43E+01	9,37E-01	6,31E+01	0,34	****	2,78E+00
		P_H3	6,05E-04	7,62E-04	3,43E-03	1,60E-03	0,66	****	2,64E-03
		P_H4	4,88E-02	-8,43E+00	1,81E-01	8,20E+01	0,10	****	2,15E+00
	Times of occurrence	P_A3	-8,67E-03	3,04E-02	2,21E-02	2,74E-02	0,47	****	1,19E-02
		P_K6	3,70E+00	3,90E+01	-6,32E+00	4,03E+01	0,19	****	5,60E+00
		P_H3	2,30E-03	-2,38E-02	-7,14E-03	3,53E-03	0,61	****	3,89E-03
		P_H4	-5,40E-01	-9,98E+00	4,14E-01	8,76E+01	0,16	****	2,50E+00
Ground Reaction Force	Peak values	Fx2	4,98E-03	1,65E-01	9,75E-03	3,26E-02	0,46	****	2,87E-02
		Fy1	-1,36E-01	-1,41E+01	6,93E-01	5,63E+01	0,10	****	3,33E+00
	Times of occurrence	Fx2	-1,81E-03	8,08E-01	-4,43E-04	7,76E-01	0,31	****	1,08E-01
		Fy1	2,12E-01	-1,80E+00	-1,23E+00	1,76E+01	0,13	****	2,22E+00

Research highlights

- This study included more than 100 healthy children between one to seven years old.
- Our study considered both age and speed of progression influence on children gait.
- Regression models were processed for the peak values and their times of occurrence.
- An original method of normal reference targets was proposed.
- The normal reference targets might help clinicians in detecting gait abnormalities