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A cross-sectional study about the relationship between morphology and kinematic parameters in children between 15 and 36 months.

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Short running page heading

Influence of morphology on kinematic parameters in toddlers

Summary

Morphology and kinematic parameters were recorded for 31 children between 15 and 36 months to investigate the relation between morphology and the walking pattern. A full 3D gait analysis using a VICON motion system was performed to gather kinematical data. Next, the differences in kinematic parameters between 4 morphological classes were assigned with a multiple analysis of variance, with a correction for walking experience. Also stepwise linear regressions were performed, to examine the relation between detailed morphological measurements and kinematic parameters. The regression models showed relationships between kinematic parameters of the ankle, hip, thorax and morphology. All results indicated that the upper body played an important role in the coordination of the walking pattern, especially in the frontal plane.

Keywords

Child; preschool; morphology; kinematics; gait

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Introduction

Independent walking is one of the motor skills that is considered to be very important in normal motor development (1). The onset of independent walking occurs in a period where human infants not only experience profound changes in movement capacity, but also undergo dramatic changes in body dimensions. A previous study revealed a significant relationship between morphology and step-time parameters in children between 15 and 36 months (2) i.e. between *pelvis span/ankle spread ratio* and the relative radii of gyration in the frontal plane of head and pelvis. The *upper body hypothesis* explained this result: If the relative radii of gyration of head and pelvis in the frontal plane are large, then the inertia, or the resistance against wobbling, of these segments are also large (3). This can be compared with a dancer on a high rope, holding a large stick horizontal in his hands to prevent himself from falling. By holding the stick, the dancer increases his moment of inertia in the frontal plane, thereby increasing his resistance against sideward movements. As a consequence, the oscillations in the frontal plane will decrease. This will lead to better trunk and head stabilization, and therefore, more stable visual, vestibular and somatosensory information (4). O'Connor and Kuo (5) suggested that during walking integrative visual feedback is used more for controlling balance in the frontal plane than in the sagittal plane. Thus, a more stable visual, vestibular and somatosensory information will lead to a better coordination, especially in the frontal plane. The improvement in coordination will enable the children to walk with relative narrower step widths and the metabolic cost of walking will decrease (6). In general, it was hypothesized that the morphology of head and pelvis plays a role in the coordination of the walking pattern. But the study of Van Dam et al (2), only provided information on step-time parameters, which result from segmental coordinated movements. Detailed information on the kinematics is necessary to test the *upper body hypothesis* and to gain more insight in how morphology interacts with the walking pattern. Therefore, the present paper questions whether a relationship between the kinematics of walking and the morphology of children between 15 and 36 months exists. In order to formulate an answer to this question, a full 3D gait analysis is performed, and data of specific measures of size, body proportions and body composition of children between 15 and 36 months are gathered.

Material and Methods

Subjects

Forty healthy children with at least one month of walking experience (22 boys, 18 girls) between 15 and 36 months of age participated in this study. Children were recruited via family, friends and the university staff. According to the Denver development-screening test (7), all toddlers showed a normal psychomotor, cognitive and affective development. Toddlers had at least one month of walking experience. Parents provided information about the age of the child at walking onset (used criterion = walking 3 meters independently). The exclusion criteria were: duration of pregnancy shorter than 38 weeks, birth weight less than 2.5kg or severe illness during the first year of life. The study was approved by the Ethical Committee, University of Antwerp and written informed consent was obtained from the parents. We were unable to register kinematic data of 7 children, and 2 children were excluded

from analysis because they showed an asymmetry in their walking pattern. Successful data of at least three trials of the remaining 31 children (17 boys, 14 girls) were selected for analysis. The mean age of these children was 24.10 ± 7.51 months with a mean body mass of 12.54 ± 2.30 kg and mean body length of 0.86 ± 0.08 m.

Experimental set-up

Data were collected at the Department of Health Care, Artesis University College of Antwerp, Belgium, using a Vicon motion system. A walkway (1.5 x 8 m) was surrounded with 6 automated infrared retro-reflective cameras (Mcam 460, 250 Hz). Thirty retro-reflective markers (Figure 1) were attached to a tight fitting suit to prevent marker plucking. Markers were placed bilaterally on the big toe, the heel, the lateral malleolus, midway the shank, the lateral and medial epicondylus of the femur, the trochanter major, the anterior and posterior superior iliacal spine, shoulder, lateral epicondyle of the humerus and the processus styloideus ulnaris and radialis. For the trunk, additional markers were placed on the sternum, the sacrum, C7 and T10. Four markers were attached to a cap which was placed on the head: two on the front and two on the back. The children walked barefoot at self-selected speed. At least 10 trials were performed, with two caregivers standing at each end of the walkway to encourage the child to walk towards them in a straight line. Running trials, trials where the child stopped walking, turned around or fell were excluded.

Anthropometric measurements

Information was obtained on body mass, body length and head circumference for each subject. All measurements were taken according to standard procedures (8). As it is not safe to use calipers with young children further measurements were taken from two scaled high-resolution digital pictures. On these pictures the body was divided into seven segments (head, thorax, pelvis, upper arm, forearm, thigh, leg). The following linear measurements were taken on each segment: total segment length and proximal, medial and distal diameters in both the sagittal and frontal plane. These measurements were used to determine the masses and the two principal moments of inertia of the body segments with a geometric model based on the model of Crompton (9; 10). The first moment of inertia, I_x , accords to rotations in the frontal plane; in this plane abduction-adduction movements take place. Secondly, the moment of inertia, I_y , accords to the sagittal plane, in which flexion-extension movements take place. More information about the geometric model is given in Van Dam et al (10). Using principal component analysis on a subset of 13 morphological measurements (normalised to body length), we distinguished 4 morphological classes characterizing the variation in morphology in this group of toddlers (i.e. chubby children with short legs, chubby children with long legs, slim children with short legs and slim children with long legs) (2). In Table 1 the morphologic characteristics of the 4 classes are shown.

Data analysis

For each successful trial one complete gait cycle was retained. Marker trajectories were labeled using Vicon software (Workstation v4.6). The captured data were analyzed with Visual 3D software (C-motion, Germantown, MD, USA) using standard Euler rotations. The 13-segmented body model (feet, shanks, thighs, pelvis, trunk, head,

upper arms and forearms) was based upon the standard Visual 3D model. The model was adapted to the small toddler posture. For each child a personalized model was created, based on anthropometric measurements. The joint angles give the orientation of the distal segment relative to the proximal segment and are calculated as standard cardan angles. Rotations around the X-axis are defined as flexion-extension movements, rotations around the Y-axis are abduction-adduction movements and movements around the Z-axis give the internal-external rotations of the segments. Based on Benedetti et al (11) a set of 26 kinematic parameters for ankle, knee, hip, pelvis, thorax and head was selected for each complete stride. Definitions of the parameters can be found in Table 2.

Statistical analysis

All statistical analyses were performed in SPSS 15.0 for Windows (SPSS Inc. Headquarters, Chicago, Illinois, USA). Statistical significance was set at $p < 0.05$. Outliers, which could be explained by irregularities in the registration of the walking pattern or other measurement errors, were removed before analysis.

Differences between the classes

Differences between the classes in age, walking experience, and BMI were tested with an ANOVA with class as fixed factor. Since there are differences between the classes in walking experience, this was entered in the model as a continuous variable (Table 3). A multiple analysis of variance to detect the differences in walking speed and kinematic parameters between the 4 morphological classes, was performed with class as fixed factor. When the results of the multivariate model were significant, a post hoc-test with a least significant differences correction (LSD) was performed. If differences in kinematics between the classes can be detected, more detailed stepwise linear regressions between anthropometric measurements and kinematic parameters will be performed.

Stepwise linear regressions between kinematic parameters and anthropometric measurements

Stepwise linear regressions between detailed anthropometric measurements and the kinematic parameters that differed between the morphological classes were performed. Pearson's correlation coefficients were calculated between walking experience and the kinematic parameters. If the correlation was significant, walking experience was entered in the model as the first explanatory variable, followed by the anthropometrical parameters. Due to the high correlations (>0.80) between several anthropometric measurements, entering all morphology into one regression equation could lead to false conclusions. Therefore, three statistically independent models were created: In the first model, the moments of inertia in the frontal plane (I_x) of all segments were investigated; in the second model, the influence of the moments of inertia in the sagittal plane (I_y), on the kinematic parameters was examined; and in the third model, the length, width and mass of all segments were entered. All analyses were tested for collinearity.

Results

Differences between the classes

Differences between the classes in age, walking experience and BMI are presented in Table 3. After correction for walking experience there are no differences between the classes in walking speed. Four kinematic parameters (A3, A5, H6 and T2; see table 2) differ between the classes. First, children of class 1 use less ankle plantar flexion at push-off (A3) compared to the other three classes. Second, children of class 3 have a larger dorsiflexion/plantarflexion range-of-motion of the ankle (A5) than children of class 1 and class 4. Furthermore, children of class 2 use more hip adduction in stance (H6) compared to children of class 4. Finally, children of class 3 have more trunk movement (T2) in the frontal plane than children of class 1. Mean values and standard deviations for each class and p-values of the differences are presented in Table 3.

Stepwise linear regressions between kinematic parameters and anthropometric measurements

Stepwise linear regressions are performed between the four kinematic parameters (A3, A5, H6 and T2) that differ between the classes and morphology. Significant correlations were found between walking experience, A3 (-0.553; $p=0.002$) and H6 (0.686; $p<0.001$). For these two kinematic parameters, walking experience is entered in the regressions as the first explanatory variable. The results of the analyses are presented in Table 4. For ankle plantar flexion at push-off (A3) walking experience explains between 24% and 28% of the variation. There is no relation between A3 and I_x and I_y of the segments. In the third model 8.5% of the variation is owing to thigh length and upper arm length stands for another 7%. In total, this model explains 43.5% of the variation in A3. All models for the plantar/dorsiflexion ROM of the ankle (A5) show a positive relationship with one of the parameters of the forearm: I_x , I_y and forearm length explain resp. 12.6%, 14.5% and 17.6% of the variation in A5. For hip adduction during stance (H6) all three models show a positive relation with walking experience, which explains around 45% of the variation. In the first model an additional 9.2% was explained by I_x of the shank. In the second model, I_y of the head and thorax, stand resp. for 12.9% and 7.5%. The results of the third model show that 10% of the variation is due to the mass of the head and an additional 7.4% is explained by the mass of the shank. In total, these three models explain between 54% and 63% of the variation in H6 in toddlers. For trunk movement in the frontal plane (T2), 11.7% of the variation is assigned to I_x of the forearm. In the second model, we found no significant relation between T2 and I_y of the segments. In the third model, 26.8% of the variation in T2 is explained by pelvis width.

Discussion

Subjects and Method

The *upper body hypothesis* was formulated in a previous study (2) on the relationship between morphology and step-time parameters in 68 toddlers between 15 and 36 months. Since the step-time parameters of gait were primarily determined by movements of the segments, we performed a full 3D gait analysis on 31 new children.

Considering it was time consuming and difficult to record these data in small children, we were fortunate that our efforts resulted in reliable kinematical data of 31 toddlers.

To test the *upper body hypothesis*, it is important to know if the two different test populations have a comparable morphology. A χ^2 -test showed that the distribution of the children over the classes is equal in both datasets ($\chi^2=0.667$; $p=0.881$). A T-test was used to compare age, walking experience, body mass, body length, Body Mass Index (BMI) and head circumference between the two datasets. No significant differences could be found in these parameters between the datasets. Except a difference in BMI was found; children of the current dataset had a higher BMI compared to children of the large dataset used for testing differences in step-time parameters. With an ANOVA, we tested if BMI was distributed similarly over the four morphological classes in the two datasets. The results showed no interaction effect between class and dataset ($p=0.684$) for this parameter. We can conclude that BMI is equally distributed over the classes in the two datasets. From these results, we can conclude that for morphology the current dataset is comparable with the large dataset.

Kinematics and morphology

Based on the results of the regression models, we formulate hypotheses concerning how morphology will interact with kinematics. For the regression models with low R^2 -values (< 0.2), we didn't formulate hypotheses because these results are of little significance. We believe that attempting to formulate a hypothesis for these observations, would lead to over-interpretation of the results. First, we discuss if the *upper body hypothesis* is confirmed. Therefore, we take a closer look at the results of hip and trunk.

Hip

More hip adduction during stance (H6) is used by the children of class 2 compared to children of class 4 during walking (Table 3). From the morphological classes, we know that children of class 2 have a high BMI, a large pelvis width and broad arms and legs (Table 1). We expect a positive relationship between H6 and the mass, moments of inertia and width of the pelvis, arms, and/or legs. The regression models show that part of the variation in hip adduction during stance (H6) can be explained by walking experience and several morphological parameters (Table 4). To explain the results we formulate two complementing hypotheses.

First, the results are consistent with the *upper body hypothesis* as formulated in our previous study (2) because there is a positive relation between H6 and the moment of inertia in the sagittal plane (I_y) of the thorax. This indicates that children with a large moment of inertia of the thorax in the sagittal plane (I_y) walk with more hip adduction. Since I_y of the thorax is highly correlated (> 0.9) with I_x , mass, length and width of the thorax, we can state that children with a large, heavy upper body have more hip adduction during stance. From the literature, we know that more hip adduction, leads to a smaller step width (12). This confirms the *upper body hypothesis*, which states that a large, more stable upper body, will lead to better trunk and head stabilization, and therefore, more

stable visual, vestibular and somatosensory information (4). This will lead to a better coordination, especially in the frontal plane. The improvement in coordination will enable the children to walk with relative narrower step widths and the metabolic cost of walking will decrease (6). In conclusion, the upper body plays an important role in the coordination of the walking pattern, especially in the frontal plane.

The second hypothesis explains the positive relation between the moment of inertia in the sagittal plane (I_y), the mass of the shank and H6. As we expected, children with heavy shanks and a large moment of inertia of the shank in the frontal plane (I_x) have more hip adduction during stance. The heavier the shank is, the more muscle force is needed to abduct the shank during swing, which results in more adduction in stance. Although the results were not significant, we noticed that children of class 2 also have less abduction during swing, compared to slim children with long legs. This reinforces our hypothesis. As such, the effect of shank morphology on hip adduction could be a purely passive phenomenon.

Finally, the regression models also showed a negative relationship between the mass and I_y of the head and H6. In our opinion, there is no functional explanation for this observation. But from the morphological classes we know that children with a large head, have short shanks. This is probably a reflection of allometric growth. Since there is a relationship between the morphology of the shanks and hip adduction, this may be the reason why the morphology of the head also shows a significant relationship with H6.

Trunk

From the comparisons between the classes, we know that the ROM of the trunk in the frontal plane (T2) is larger in children of class 3 compared to children of class 1. Children of class 3 are children with a low BMI, a small pelvis width, small arms and legs. Based on this information, we expect a negative relationship between T2 and the mass, moments of inertia and widths of the pelvis, arms and/or legs. The results confirm our expectations, as the width of the pelvis has a negative relation with T2. In other words, children with a broad pelvis walk with less thorax movement in the frontal plane. This is in agreement with the *upper body hypothesis*, as formulated before.

Ankle

The chubby children with short legs (class 1) walk with less ankle flexion at push-off (A3) compared to the other three classes. The step-wise linear regressions show that the majority of variation in A3 can be explained by walking experience. However, when taking a closer look at the results, we noticed that walking experience is not significant after the thigh length was added to the model. This is probably due to the high correlation ($r=0.78$) between walking experience and thigh length. Therefore, it is impossible to distinguish which of both parameters is related to A3. We can conclude that the amount of ankle plantar flexion at push-off cannot be explained exclusively by walking experience or morphology. Furthermore, slim children with short legs (of class 3) have a

bigger ROM of the ankle (A5) during walking than children of class 1 and 4. It will be a challenge for future research to gain further insight into the relationship between morphology and ankle kinematics.

Conclusion

The main research question of this paper was: Is there a relationship between the kinematics of gait and morphology in toddlers? Based upon the data of 31 children between 15 and 36 months, differences between the morphological classes were found in four kinematic parameters (A3, A5, H6 and T2), after correction for walking experience. In order to investigate the relationship between detailed morphology and these four kinematic parameters, stepwise linear regressions were performed. The regression models established the relations between hip adduction in stance and several morphological parameters. First, the revealed relationship between the moment of inertia of the thorax in the sagittal plane and hip adduction is consistent with the *upper body hypothesis*, as formulated in Van Dam et al (2). Furthermore, the results showed that children with heavy shanks and a large moment of inertia of the shank in the frontal plane (Ix) had more hip adduction during stance (H6). It was hypothesized that the effect of shank morphology on hip adduction is a pure passive phenomenon. Next, it was observed that children with a broad pelvis walk with less thorax movement (T2) in the frontal plane. This is also in agreement with the *upper body hypothesis*. Finally, for the kinematics of the ankle (A3 and A5), the regression equations showed no clear effect of morphology. In conclusion, all results indicate that the upper body plays an important role in the coordination of the walking pattern, especially in the frontal plane.

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289 **Table 1 Morphological characteristics of the 4 classes.**

Class 1 = Chubby with short legs	Class 2 = Chubby with long legs	Class 3 = Slim with short legs	Class 4 = Slim with long legs
High BMI	High BMI	Low BMI	Low BMI
Broad pelvis	Broad pelvis	Small pelvis	Small pelvis
Broad upper arms	Broad upper arms	Small upper arms	Small upper arms
Broad forearms	Broad forearms	Small forearms	Small forearms
Broad thighs	Broad thighs	Small thighs	Small thighs
Broad shanks	Broad shanks	Small shanks	Small shanks
Large head circumference	Small head circumference	Large head circumference	Small head circumference
Broad thorax	Small thorax	Broad thorax	Small thorax
Short shanks	Long shanks	Short shanks	Long shanks
Short thighs	Long thighs	Short thighs	Long thighs

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292 **Table 2 Definition of the kinematic parameters**

Kinematic parameter (°)	Definition
A0	Ankle dorsiflexion at foot contact
A1	Ankle plantarflexion at loading response
A2	Maximal ankle dorsiflexion in stance
A3	Ankle plantar flexion at push-off
A4	Maximal ankle plantar flexion in swing
A5	Ankle dorsiflexion/plantar flexion ROM
K0	Knee flexion at foot contact
K1	Knee flexion at loading response
K2	Knee extension in mid-stance
K3	Knee flexion at toe off
K4	Maximal knee flexion in swing
K5	Knee flexion/extension ROM
H0	Hip flexion at foot contact
H1	Hip flexion at loading response
H2	Maximal hip extension
H3	Hip extension at toe off
H4	Maximal hip flexion in swing
H5	Hip flexion/extension ROM
H6	Maximal hip adduction in stance
H7	Maximal hip abduction in swing
P1	Pelvis ROM in the sagittal plane (tilt)
P2	Pelvis ROM in the frontal plane (obliquity)
T1	Trunk ROM in the sagittal plane
T2	Trunk ROM in the frontal plane
HD1	Head ROM in the sagittal plane
HD2	Head ROM in the frontal plane

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Table 3 Results of the multivariate analysis of variance for differences between the classes in kinematic parameters. P-values, means and standard deviations are presented for significant results.

Parameter	Differences between the classes	p-values	Mean and Standard Deviation
Age (months)	1 < 2	0.000	Class 1 = [17.10 ± 1.63]
	1 < 4	0.000	Class 2 = [29.17 ± 2.10]
	2 > 3	0.016	Class 3 = [21.20 ± 2.30]
	3 < 4	0.007	Class 4 = [29.50 ± 1.63]
BMI (kg/m²)	1 > 3	0.000	Class 1 = [18.31 ± 0.38]
	1 > 4	0.000	Class 2 = [17.69 ± 0.49]
	2 > 3	0.002	Class 3 = [15.14 ± 0.53]
	2 > 4	0.002	Class 4 = [15.58 ± 0.38]
Walking experience (months)	1 < 2	0.000	Class 1 = [3.95 ± 1.63]
	1 < 4	0.000	Class 2 = [15.67 ± 2.11]
	2 > 3	0.018	Class 3 = [7.80 ± 2.31]
	3 < 4	0.006	Class 4 = [16.20 ± 1.63]
A3 (°)	1 > 2	0.001	Class 1 = [-1.55 ± 3.43]
	1 > 3	0.001	Class 2 = [-20.31 ± 2.71]
	1 > 4	0.015	Class 3 = [-19.58 ± 3.32]
			Class 4 = [-13.48 ± 2.20]
A5 (°)	1 < 3	0.012	Class 1 = [26.77 ± 2.49]
	3 > 4	0.035	Class 2 = [33.44 ± 1.97]
			Class 3 = [35.54 ± 2.41]
			Class 4 = [28.67 ± 1.60]
H6 (°)	2 > 4	0.023	Class 1 = [14.19 ± 2.40]
			Class 2 = [18.79 ± 1.90]
			Class 3 = [14.13 ± 2.32]
			Class 4 = [13.09 ± 2.32]
T2 (°)	1 < 3	0.026	Class 1 = [3.33 ± 0.78]
			Class 2 = [5.05 ± 0.62]
			Class 3 = [5.76 ± 0.76]
			Class 4 = [4.27 ± 0.50]

Table 4 Overview of the results of the linear regressions. Regression coefficients, p-values, R²-values and the percentage of the variation explained by the predictor are presented for significant results with Ix is the moment of inertia in the frontal plane and Iy is the moment of inertia in the sagittal plane.

Segment	Dependent measure	Model	Predictor	Regression coefficient B	p-value	Variation expl. by predictor (%)	R ²
Hip	H6 (°)	Model 1	Walking experience	0.242	0.137	45.2	0.544
			Ix Shank	5.054	0.015	9.2	
		Model 2	Walking experience	0.507	0.000	42.6	0.630
			Iy Head	-1.143	0.001	12.9	
			Iy Thorax	0.158	0.019	7.5	
		Model 3	Walking experience	0.440	0.003	45.2	0.626
			Mass Head	-5.328	0.007	10	
			Mass Shank	17.306	0.018	7.4	
Trunk	T2 (°)	Model 1	Ix Forearm	-4.833	0.002	11.7	0.117
		Model 2	-	-	-	-	-
		Model 3	Width Pelvis	-78.557	0.002	26.8	0.268
Ankle	A3 (°)	Model 1	Walking experience	-1.151	0.002	28	0.280
		Model 2	Walking experience	-1.019	0.004	24	0.240
		Model 3	Walking experience	-0.664	0.185	28	0.435
			Length Thigh	-466.102	0.031	8.5	
			Length Upper arm	321.220	0.047	7	
	A5 (°)	Model 1	Ix Forearm	17.851	0.046	12.6	0.126
		Model 2	Iy Forearm	18.228	0.034	14.5	0.145
		Model 3	Length Forearm	184.005	0.021	17.6	0.176

309 **Figure 1** The 13-segmented body model (feet, shanks, thighs, pelvis, trunk, head, upper arms and fore- arms) was
310 based upon the standard Visual 3D model but adapted for the toddlers to match to their small posture.
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312 **Figure 1**

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