

3D joint dynamics of walking in toddlers A cross-sectional study spanning the first rapid development phase of walking

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Abstract

This study aims at giving an insight into the causative forces of walking in toddlers. Therefore, joint angle, moment and power profiles of 10 toddlers with less than 6 months of walking experience are compared to the stereotype adult patterns. In general, joint moments are small, which can be explained both by the small size of toddlers and differences in walking strategy. Also mass specific powers are reduced due to the low average walking speed. Balance problems in toddlers lead to a dominance of hip and knee extending moments throughout stance. The joint moment profiles are characterized by a reduced complexity, which might suggest an immature control of movement. Another feature of toddler gait is that virtually no power is generated at the ankle joint prior to foot-off (no active push-off).

We also examined the effect of walking experience on the toddler gait pattern. In general, an evolution towards a more mature gait becomes evident after 4 months of independent walking. Changes are observed in step-time parameters, ankle dorsiflexing moment and power absorption at the hip joint.

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1. Introduction

The gait pattern of early walkers differs from adult gait. Most striking is the large amount of variability, characteristic for a learning process. Differences in spatio-temporal features of gait are well described: toddlers show a low average walking speed, high cadence, short step length, a wide support base [1–4] and a prolonged double support phase [2,5,6]. Kinematic differences are the guard position of the arms, external rotation of the feet, the absence of heel strike, simultaneous flexion of the hip and knee in swing and the absence of complete hip and knee extension in stance [3,7–9]. A lack of muscle force, balance problems and

immature control of movement have been postulated as the major causes for the observed differences between adult and toddler gait [4]. With increasing walking experience, the children's gait pattern matures, showing two distinct phases. The first one spans the first 5–6 months after a child started to walk, leading to rapid changes in all gait parameters. The second phase represents a further fine-tuning of the gait pattern, lasting until the age of 8 [1,10,11].

To understand how walking is controlled, it is important to determine the forces driving the observed movements. Two possible techniques exist, both with their own advantages and drawbacks. The *first* possibility is to estimate the muscle forces from EMG-recordings. EMG can give accurate information on the onset and offset of individual muscle activity. In optimal circumstances the intensity of muscle activation can be translated into a relative force measurement [12–14]. But the quality, reliability and repeatability of the EMG signal are very

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sensitive to electrode placement, soft tissue movements and damping caused by the presence of fat tissue. The resulting high variability in EMG measurements makes comparisons between different trials and subjects rather difficult. The *second* possibility is to determine the driving forces through inverse dynamical analysis (IDA). From measured joint kinematics and ground reaction forces (GRF) the net joint moments and powers are calculated. The net joint moment causes the observed movement pattern in a particular joint. It is the resultant moment generated by all structures spanning that joint (muscles, ligaments, capsule, skin . . .). It can be assumed that in dynamic systems muscular activity is the most important contributing factor to the net joint moment [15–17]. The net joint power reflects the net effort spent to sustain the observed movement. The major drawback of IDA is that no information is available on how agonists and antagonists cooperate.

Ideally, IDA and EMG should be combined to come to a full understanding of how active (muscle) and passive (gravity, forces from ligamentous and tendinous structures) forces work together to generate a smooth movement [18]. In literature some information on EMG of walking toddlers is available from case studies [19,20]. It would be very interesting to expand the available database. However, it is our belief that EMG can appear drastic for these young children and their parents (note that the manuscripts on EMG in toddlers report data from 1 child only). The entire procedure (i.e. scraping the skin, sticking electrodes, walking with wires) might alter their walking pattern or even lead to failure to cooperate. These practical considerations led to the choice of limiting our study to IDA focusing on the first development phase of walking [1,10,11]. To our knowledge nothing is known yet on joint moment and power

profiles in this age group. The EMG data from literature will be used to interpret the obtained kinetic time-profiles.

2. Materials and methods

2.1. Study subjects

The gait pattern of 10 healthy children (four boys, six girls) aged between 13.5 and 18.5 months (Table 1) was analyzed. Parents gave their informed consent to participate in this study. The children's walking experience (WE) ranged from 2 weeks to 5 months after performing their first independent steps.

Recordings were also made of adult walking (10 individuals, 20–30 years old, three males, seven females) using exactly the same marker-set and analyzing techniques. The kinematic and kinetic profiles of adult walking were compared to literature data [21–26]. All profiles showed to be similar.

2.2. Experimental set-up

Data were collected at the HIKE (Department of Health Care, Hogeschool Antwerpen, Belgium). Study subjects were encouraged to walk over the registration platform at self-selected speed towards a parent or experimenter.

While walking over the instrumented walkway (3 m × 1.50 m) their movements were captured by an automated infrared retro-reflective camera system (Vicon Motion Systems, six camera's, Mcam 460, 250 Hz.). An adjusted version of the Helen–Hayes marker set-up [27] (Fig. 1) was used for measuring full body kinematics.

Table 1
Detailed information about the study subjects (T, toddler; A, adult)

	Age	Gender	Walking experience (weeks)	Body mass (kg)	Length (m)	Leg length (m)	Number of trials
T1	13.5 months	Female	2	11.8	0.73	0.31	4
T2	15 months	Female	6	8.4	0.74	0.29	4
T3	15.5 months	Male	11	9.8	0.74	0.32	3
T4	16.5 months	Female	11	11.7	0.76	0.33	5
T5	15.5 months	Male	13	10.9	0.76	0.28	5
T6	16.5 months	Female	14	9.0	0.76	0.30	4
T7	15.5 months	Male	15	12.4	0.77	0.34	4
T8	18.5 months	Male	22	12.1	0.80	0.31	3
T9	14 months	Female	1	10.4	0.71	0.29	4
T10	15 months	Female	20	9.1	0.70	0.28	3
A1	30 years	Female	–	56	1.72	0.94	3
A2	23 years	Female	–	59	1.65	0.90	3
A3	21 years	Female	–	65	1.74	0.91	3
A4	21 years	Male	–	59	1.73	0.90	3
A5	20 years	Female	–	65	1.62	0.89	3
A6	21 years	Female	–	87.3	1.63	0.79	3
A7	21 years	Male	–	72.8	1.80	0.87	3
A8	20 years	Female	–	43	1.55	0.76	3
A9	21 years	Male	–	88	1.70	0.79	3
A10	20 years	Female	–	61	1.68	0.79	3

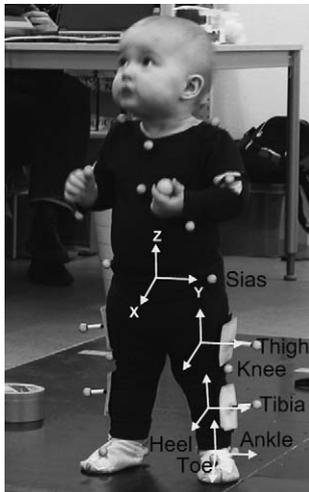


Fig. 1. The Helen-Hayes marker set was used for measuring full body kinematics. In toddlers, markers were attached to a tight fitting suit since the children did not put up with sticking markers on their skin. In adults, the markers were taped directly on the skin. Joint angles are expressed as Euler rotations of the more distal to the more proximal segment over the X - Z axes, representing add/abduction, flexion/extension and int/ext rotation. Angles are zero when standing upright, as shown here.

In toddlers, the retro-reflective markers (14 mm) were attached to a tight fitting suit to prevent problems with “marker plucking”. Foot markers were attached to socks or soft leather shoes. Prior to recording, an experimenter checked the marker positions. In adults, markers were taped directly on the skin.

Two force platforms (AMTI, 0.5 m \times 0.4 m, 250 Hz.) were used to record GRF under the left and right foot separately. For recordings of adult gait both force plates were placed in series. When working with toddlers, the force platforms were placed next to each other and the toddler walked over the middle with one foot touching each plate.

2.3. Morphometrical analysis

To personalize the model, for each subject, information was obtained on body mass, body length, leg length, knee width and ankle width. Morphometrical data for toddlers were taken from standardized pictures (Fig. 2), since it was not safe to use calipers in these young children.



Fig. 2. A father holds his child for obtaining morphometrical data. For each subject, following morphometrical information was obtained: body mass, body length, leg length, knee width and ankle width. In toddlers, morphometrical data had to be obtained from standardized pictures, since it was not safe to use callipers.

2.4. Data analysis

Only trials for which separate GRF measurements of the left and right foot were available were chosen for analysis (three to five for toddlers, three for adults; Table 1). From each successful trial a complete gait cycle was retained for analysis without distinguishing between left and right sides. In total 39 toddler cycles and 30 adult cycles were incorporated in this study.

Marker trajectories were labeled and filtered (quintic spline) using the Vicon[®] software (Workstation V4.6.6).

2.4.1. Spatio-temporal parameters

For each selected gait cycle, the instances of left and right foot-contact and -off were determined from the trajectories of the heel and toe markers. Using the Plug-in-gait-module (Vicon Motion Systems), we calculated cadence, Froude number, stride time, single support time, double support time, stride length and step width (Table 2). Spatio-temporal parameters were scaled to body size according to Hof [28].

Table 2
Formulas of the spatio-temporal parameters calculated

Parameter	Formula/definition
Cadence (steps/min)	$= 2(1/\text{stride time})$
Froude number	$= v^2/g \text{ leg length}$
Stride time (s)	Time between FC and following FC of the same foot
Single support (%)	Fraction of the gait cycle during which only 1 ft is on the ground
Double support (%)	Fraction of the gait cycle during which both feet are on the ground
Stride length	Distance traveled by the center of mass during one stride, scaled to leg length (according to Hof)
Step width	Lateral distance between left and right heel when both feet are on the ground during double support, scaled to leg length (according to Hof)

2.4.2. The 15-segment body model

Full body kinematics and kinetics were calculated using the Vicon Clinical Model based on the Kadaba and Davis model [21,27,29,30]. Joint rotations are calculated as Euler rotations of the distal versus the proximal segment around the X–Z axes (Fig. 1), respectively representing adduction/abduction, flexion/extension and internal/external rotation.

Angles are zero when standing upright in anatomical position (cf. Fig. 1). To correct for small differences in marker placement between subjects, a static calibration was performed to determine offset angles.

We choose to focus on the lower extremities, looking especially at hip flexion/extension, hip abduction/adduction, knee flexion/extension and ankle plantar flexion/dorsiflexion. Joint (dorsi) flexion and adduction are positive. Joint extension (plantar flexion) and abduction are negative. The reported moments are the net joint moments (sum of all the internal moments in a particular plane in a particular joint) which counteract the moments caused by gravity, inertial forces and gravitational forces. The net joint moments are scaled for body mass (Nm/kg). (Internal) extending moments are positive, (internal) flexing moments are negative. (Internal) abducting moments are positive (internal) adducting moments are negative.

The kinematic and kinetic time profiles were first averaged for each subject. Then the obtained data were averaged again to obtain the global patterns of walking. The global average kinematic and kinetic profiles were plotted as a function of gait cycle duration.

2.4.3. Statistical analysis

For each individual stride the spatio-temporal data and a set of 28 kinematic and kinetic variables (Table 3, Fig. 3) were evaluated. The different numbers of values per subject for each variable were averaged to prevent pseudo-replication. Each variable was compared between the adult and toddler group using a multiple ANOVA. Statistical significance was set at $p < 0.05$. Border line differences are reported when $p < 0.1$. A Bonferroni correction for multiple comparisons was made.

2.4.4. The effect of body size

Joint kinetic data of pediatric populations (age 3–7 years old) previously reported in literature [26] are characterized by their small amplitudes in comparison to joint moments reported in adults, which is said to be caused by the small size of the body segments. To investigate the actual effect of differences in body size between toddlers and adults on the magnitude of the reported kinetic data, the mass specific net joint moments and powers were scaled to leg length.

2.4.5. The effect of walking experience

Our primary goal was to compare mature and immature gait concerning 3D kinetics. However, our toddler group spans a large range of WE during which rapid changes are known to occur in step-time and kinematic parameters. Comparable changes might be expected in the driving forces of movement. To investigate the effect of WE, our toddler group was subdivided into four categories: 1 month of WE or less (three individuals), 2 months of WE (two individuals), 3 months of WE (two individuals) and 4 months of WE or more (three individuals). The selected gait parameters were compared between the four subgroups using a multiple ANOVA. Post hoc Bonferroni comparisons were performed. Statistical significance was set at $p < 0.05$.

3. Results

3.1. Spatio-temporal parameters

Table 4 lists the average spatio-temporal data for the toddler and adult group, 95% confidence intervals and F - and p -values from the multiple ANOVA. Cadence, double support time, stride time and step width is significantly larger in toddlers. Froude number and single support time is significantly smaller. No differences could be found in stride length, after correction for size differences.

Table 3
The 28 kinematic and kinetic variables selected for statistical analysis

Variable	Variable	Variable	Variable
H1	Maximum hip flexion in stance	Hm1	Maximum hip extending moment
H2	Maximum hip extension in stance	Hm2	Maximum hip flexing moment
H3	Maximum hip flexion in swing		
H4	Maximum adduction	Hm3	First hip abducting moment peak
H5	Maximum abduction	Hm4	Second hip abducting moment peak
K1	Maximum knee flexion in stance	Km1	First knee extending moment peak
K2	Maximum knee extension in stance	Km2	Maximum knee flexing moment
K3	Maximum Knee flexion in swing	Km3	Second knee extending moment peak
A1	Ankle plantar flexion after heel contact	Am1	Maximum ankle dorsiflexing moment
A2	Maximum ankle dorsiflexion	Am2	Maximum ankle plantar flexing moment
A3	Maximum ankle plantar flexion	Ap1	Ankle power absorption
		Ap2	Ankle power generation

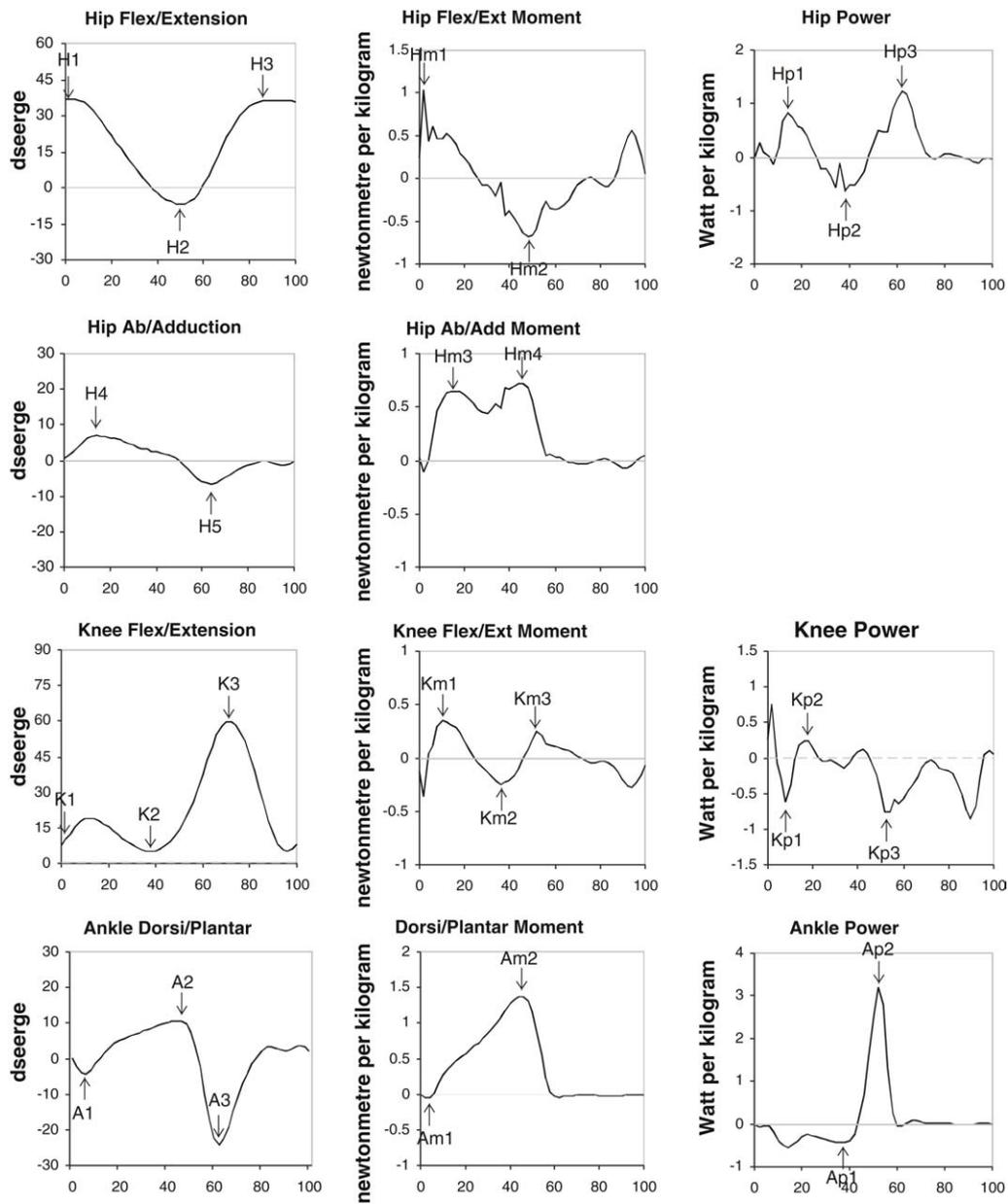


Fig. 3. The 28 kinematic and kinetic variables selected for statistical analysis are indicated. Explanation of symbols can be found in Table 3.

Table 4
Spatio-temporal parameters are compared between the adult and toddler group

Parameter	Toddler		Adult		d.f.	F	p
	Averages	95% Confidence interval	Averages	95% Confidence interval			
Cadence (steps/min)	163	[150, 178]	114	[100, 129]	1	27.59	0.000
Froude number	0.28	[0.22, 0.35]	0.38	[0.31, 0.46]	1	4.41	0.050
Stride time (s)	0.14	[0.12, 0.16]	0.11	[0.09, 0.12]	1	9.47	0.007
SS (%)	69	[64, 73]	83	[77, 88]	1	17.43	0.001
DS (%)	31	[27, 36]	17	[12, 23]	1	17.43	0.001
Stride length	1.14	[0.92, 1.36]	1.37	[1.13, 1.60]	1	2.27	0.150
Step width	0.16	[0.14, 0.18]	0.11	[0.09, 0.14]	1	9.63	0.006

Averages, 95% confidence intervals, degrees of freedom (d.f.) and F- and p-values for the multiple analysis of variance are shown. Statistical significance is set at $p < 0.05$.

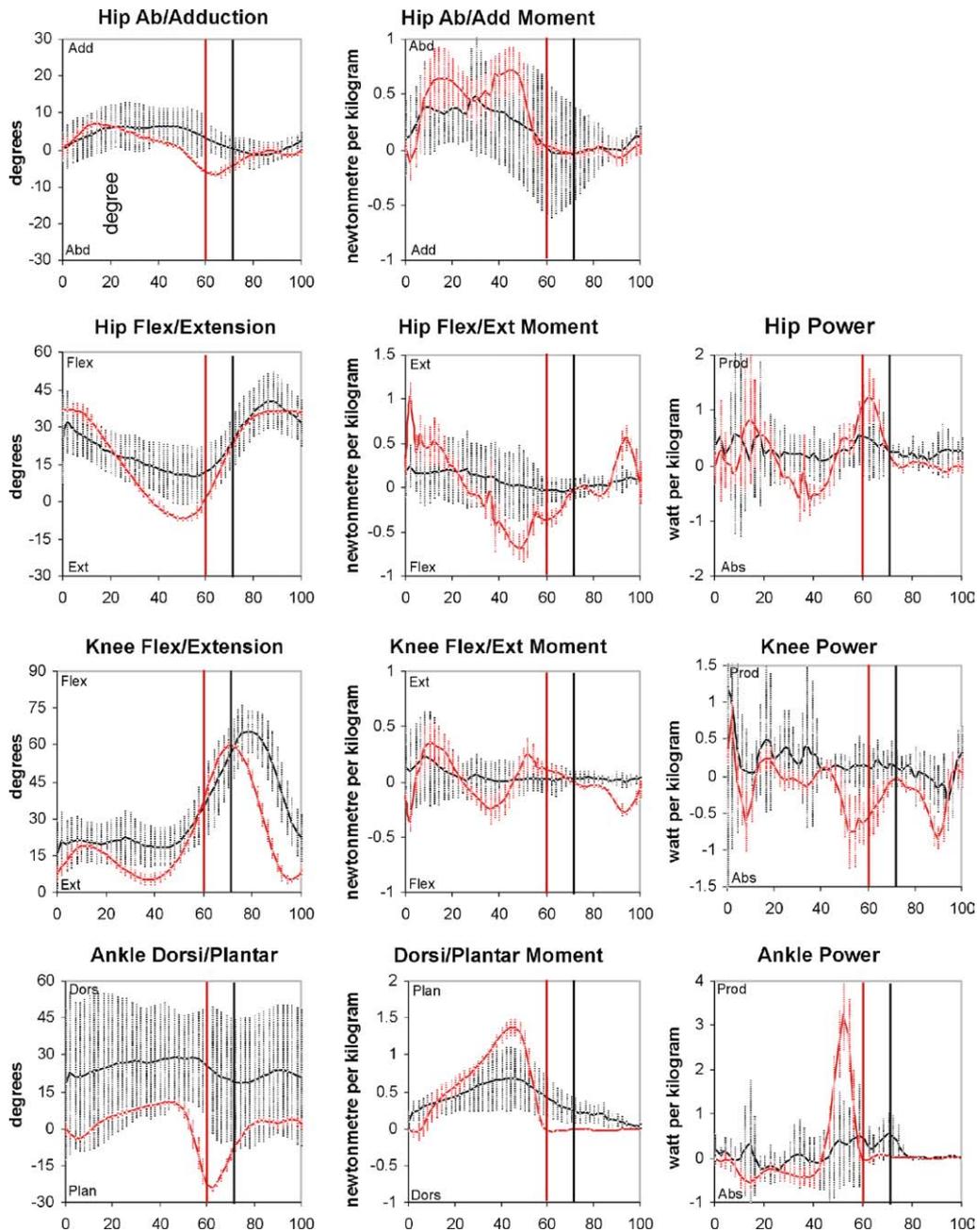


Fig. 4. The black lines represent the average joint kinematic and kinetic patterns of toddlers with less than 6 months of walking experience. Average adult patterns are shown in red. Standard deviations are represented by the shaded area. The vertical lines indicate FO in adults (red) and toddlers (black). Joint moments and powers were scaled to body mass (kg) to allow for comparison. Angles are zero when both segments are completely aligned. Adduction and (dorsi)flexion are positive while abduction and extension (plantar flexion) are negative. The joint moments are internal moments, counteracting the moments caused by gravity and accelerations. Extending (plantar flexing) and abducting are positive and flexing, (dorsi) flexing and adducting moments negative. Power generation is positive, power absorption is negative.

3.2. Joint kinematics and kinetics

3.2.1. Global average kinematic and kinetic time profiles

Fig. 4 compares the mass-specific net joint moments (internal) and powers of toddler and adult gait, plotted as a function of gait cycle duration. Standard deviations are indicated for both age groups.

3.2.1.1. The hip joint. First consider the hip motion in the frontal plane. In toddlers, similar to adults, at FC the hip is in a neutral position. During early stance, an external adducting moment (caused by the GRF) leads to adduction of the hip joint (7° in toddlers, 12° in adults). As the internal abducting moment increases (0.56 Nm/kg in toddlers, 0.87 Nm/kg in adults), further adduction of the hip is prevented. In adults

maximal adduction is reached at 15% of the gait cycle. Next, hip abduction is observed reaching a maximum around FO (-7° in adults). During swing, hip abduction decreases again. In toddlers hip adduction continues during the major part of stance. At 50% of the gait cycle, a decrease in hip adduction is observed caused by the sustained abducting moment. The swing phase is entirely passive and the hip is still abducting reaching a maximum (-11° in toddlers) at 85% of the gait cycle. In both age groups, a small adducting moment observed during late swing, decreases the abduction angle for correct positioning of the hip joint prior to the next FC. The most important difference between adults and toddlers is found in the shape of the internal abducting moment generated during stance. While in adults a bi-modal pattern is observed, toddlers only show a uni-modal abducting moment reaching a peak at midstance.

In the saggital plane, both in adults and toddlers the hip is flexed (28° in toddlers, 33° in adults) at FC. Hip extension is initiated by an internal hip extending moment (0.35 Nm/kg in toddlers, 1.20 Nm/kg in adults) going along with power generation (0.75 W/kg in toddlers, 0.86 W/kg in adults). This extending moment is small in toddlers. In midstance, adults show a shift in the net joint moment from extending to flexing to slow down hip extension (-1.23 Nm/kg in adults). At this time power is absorbed. (-1.29 W/kg in adults). In

toddlers the internal moment remains extending throughout the major part of stance. Maximal extension (-12° in adults) in adult gait is reached at 50% of the gait cycle. In toddlers, the hip remains slightly flexed (minimum angle of 4° in toddlers at 55% of the cycle). In both age groups, swing is initiated in late stance by actively (internal flexing moment) rotating the thigh forward (power generation: 0.75 W/kg in toddlers, 1.44 W/kg in adults). Again, in toddlers, the hip flexing moment and the power generation peak are much smaller than in adults. Maximal hip flexion (39° in toddlers, 33° in adults) is reached at 85% of the gait cycle. In preparation of FC the hip starts to extend again.

3.2.1.2. The knee joint. The toddlers' knee is more flexed at FC (16° in toddlers, 8° in adults) compared to mature gait. In adults, FC is followed by a small passive (no internal flexing moment observed) knee flexion causing power absorption (-1.46 W/kg in adults). As the internal extending moment increases, the knee is actively extended again (4° in adults). In toddlers this shock-absorbing knee flexion-extension wave is absent. The knee remains its slightly flexed position throughout the first two-third of stance. During the first half of stance, in both age groups the internal moment is extending (0.11 Nm/kg in toddlers, 0.87 Nm/kg in adults) to prevent collapse of the knee due to gravity. As the GRF

Table 5

Kinematic and kinetic parameters are compared between the adult and toddler group. Averages, 95% confidence intervals, degrees of freedom (d.f.) and F and p values for the multiple analysis of variance are shown. Statistical significance is set at $p < 0.05$

Parameter	Toddler		Adult		d.f.	F	p
	Average	95% Confidence interval	Average	95% confidence interval			
H1°	28	[23, 34]	33	[23, 42]	1	1.22	.286
H2°	4	[-3, 10]	-12	[-20, -5]	1	11.90	.003
H3°	39	[33, 46]	33	[20, 46]	1	1.27	.179
H4°	7	[4, 10]	12	[8, 16]	1	5.73	.029
H5°	-11	[-16, -7]	-7	[-12, 0]	1	3.73	.070
K1°	16	[11, 20]	8	[-1, 17]	1	6.33	.022
K2°	11	[7, 16]	4	[-2, 8]	1	7.28	.015
K3°	69	[66, 73]	62	[57, 65]	1	9.75	.006
A1°	7	[2, 11]	-3	[-8, 2]	1	7.48	.010
A2°	26	[21, 32]	15	[9, 20]	1	10.48	.005
A3°	-4	[-16, 8]	-19	[-31, -6]	1	3.27	.088
Hm1 Nm/kg	0.35	[.14, .57]	1.20	 [.96, 1.45]	1	30.33	.000
Hm2 Nm/kg	-0.22	[-.51, .07]	-1.23	[-1.55, -.90]	1	23.89	.000
Hm3 Nm/kg	0.56	[.36, .75]	0.87	 [.65, 1.09]	1	5.29	.035
Hm4 Nm/kg	0.51	[.35, .68]	0.82	 [.63, 1.01]	1	6.67	.020
Km1 Nm/kg	0.11	[-.20, .41]	0.87	 [.53, 1.20]	1	12.63	.003
Km2 Nm/kg	-0.13	[-.32, .05]	-0.21	[-.41, -.01]	1	.33	.574
Km3 Nm/kg	0.09	[-.01, .19]	0.36	 [.25, .48]	1	14.45	.002
Am1 Nm/kg	-0.08	[-.26, .10]	-0.33	[-.53, -.12]	1	3.62	.075
Am2 Nm/kg	0.62	[.48, .76]	1.31	 [1.15, 1.47]	1	48.26	.000
Hp1 W/kg	0.75	[.07, 1.42]	0.86	[.06, 1.67]	1	.06	.820
Hp2 W/kg	-0.72	[-1.33, -.11]	-1.29	[-2.02, -.57]	1	1.67	.220
Hp3 W/kg	0.75	[.33, 1.17]	1.44	 [.94, 1.95]	1	5.12	.040
Kp1 W/kg	-0.74	[-1.45, -.03]	-1.46	[-2.31, -.61]	1	1.92	.190
Kp2 W/kg	0.60	[.14, 1.05]	1.06	[.52, 1.60]	1	1.96	.180
Kp3 W/kg	-0.57	[-.87, -.26]	-1.03	 [-1.39, -.67]	1	4.46	.050
Ap1 W/kg	-1.04	[-1.36, -.73]	-0.91	[-1.29, -.53]	1	.34	.570
Ap2 W/kg	1.12	[.70, 1.54]	3.33	 [2.83, 3.83]	1	52.16	.000

passes in front of the knee joint in adults, the internal moment becomes flexing (-0.21 Nm/kg in adults). In new walkers the internal extending moment decreases but does not shift to a flexing moment (Fig. 4). During late stance, knee flexion initiates swing. In mature gait power is absorbed (-1.03 W/kg in adults) as this movement is slowed down by an internal extending moment (0.36 Nm/kg in adults). This power absorption is not observed in toddlers. Adults reach maximal knee flexion during the first one-third of swing (62° in adults). Then the knee passively extends (no internal extending moment observed). Prior to FC, a small knee flexing moment slows down knee extension causing power absorption. In toddlers, maximal knee flexion is reached shortly after FO (69° in toddlers), at 80% of the gait cycle. The knee passively extends during the rest of swing.

3.2.1.3. The ankle joint. In toddlers, contrary to adults, plantar flexion following FC is absent (7° in toddlers, -3° in adults). Therefore also the small dorsiflexing moment (-0.33 Nm/kg in adults), necessary to prevent foot slap, is absent in toddlers. The ankle immediately goes into dorsiflexion as the shank rotates over a fixed foot. Both in adults and toddlers, dorsiflexion is slowed down by an internal plantar flexing moment leading to power absorption (-1.04 W/kg in toddlers, -0.91 W/kg in adults). Maximal dorsiflexion is reached at 50% of the cycle in adults and at 60% of the cycle in toddlers (26° in toddlers, 15° in adults). Prior to FO, the ankle goes into plantar flexion under influence of the plantar flexing moment (0.62 Nm/kg in toddlers, 1.31 Nm/kg in adults), generating power (1.12 W/kg in toddlers, 3.33 W/kg in adults) for an active push-off. In toddlers ankle plantar flexion (-4° in toddlers, -19° in adults) and power generation is small.

3.2.2. Statistical analysis of the kinematic and kinetic variables

Table 5 lists the average kinematic and kinetic data for the toddler and adult group, 95% confidence intervals and F - and p -values from the multiple ANOVA. Significant differences ($p < 0.05$) are shown in bold. Border line differences ($p < 0.1$) are identified in hip abduction in swing (H5), ankle plantar flexion at FO (A3) and the ankle dorsiflexing moment (Am1).

3.2.3. The effect of body size

Fig. 5 compares the net joint moments and powers of toddler and adult gait divided by body weight and leg length. After scaling for differences in size, net joint moments at the hip and knee are of comparable magnitude in both age groups. The net joint moment around the ankle is much larger in toddler gait, and is sustained throughout swing. When investigating powers, at the hip and knee only power generation is observed. At the ankle, some power absorption is seen during the first half of stance. Scaling for size, reduces the difference in power generation at the ankle prior

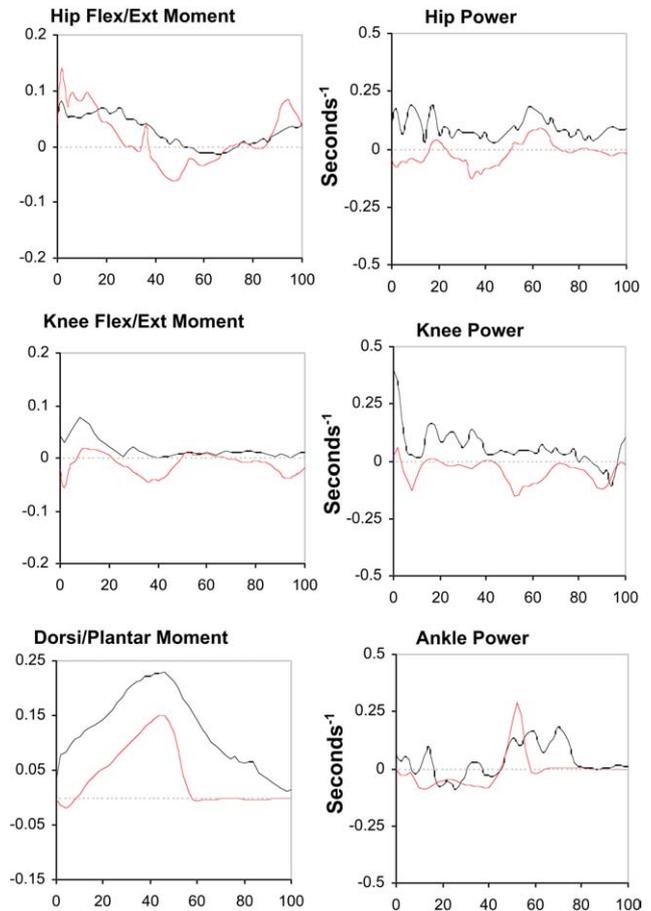


Fig. 5. Net joint moments and powers are scaled to leg length and compared between adults (red) and toddlers (black) to investigate the effect of size. Net joint moments are dimensionless and joint powers are reported in per seconds.

to FO between adults and toddlers but it remains larger in adults.

3.2.4. The effect of walking experience

Fig. 6 compares the average kinematic and kinetic data for the four subcategories of walking experience. The 95% confidence intervals and F - and p -values from the multiple ANOVA are listed in Table 6 (only significant differences are reported).

First consider the spatio-temporal parameters. Group 4 (4 months of WE or more) shows a larger Froude number and stride length compared to the other three groups. Single support is prolonged compared to group 1 (1 month of WE or less), consequently the double support phase is shorter. An improvement in balance becomes evident from the smaller base of support after 4 months of walking. No significant differences could be identified considering step-time parameters between groups 1–3.

Considering the kinematic data, no significant differences could be identified between different walking experiences.

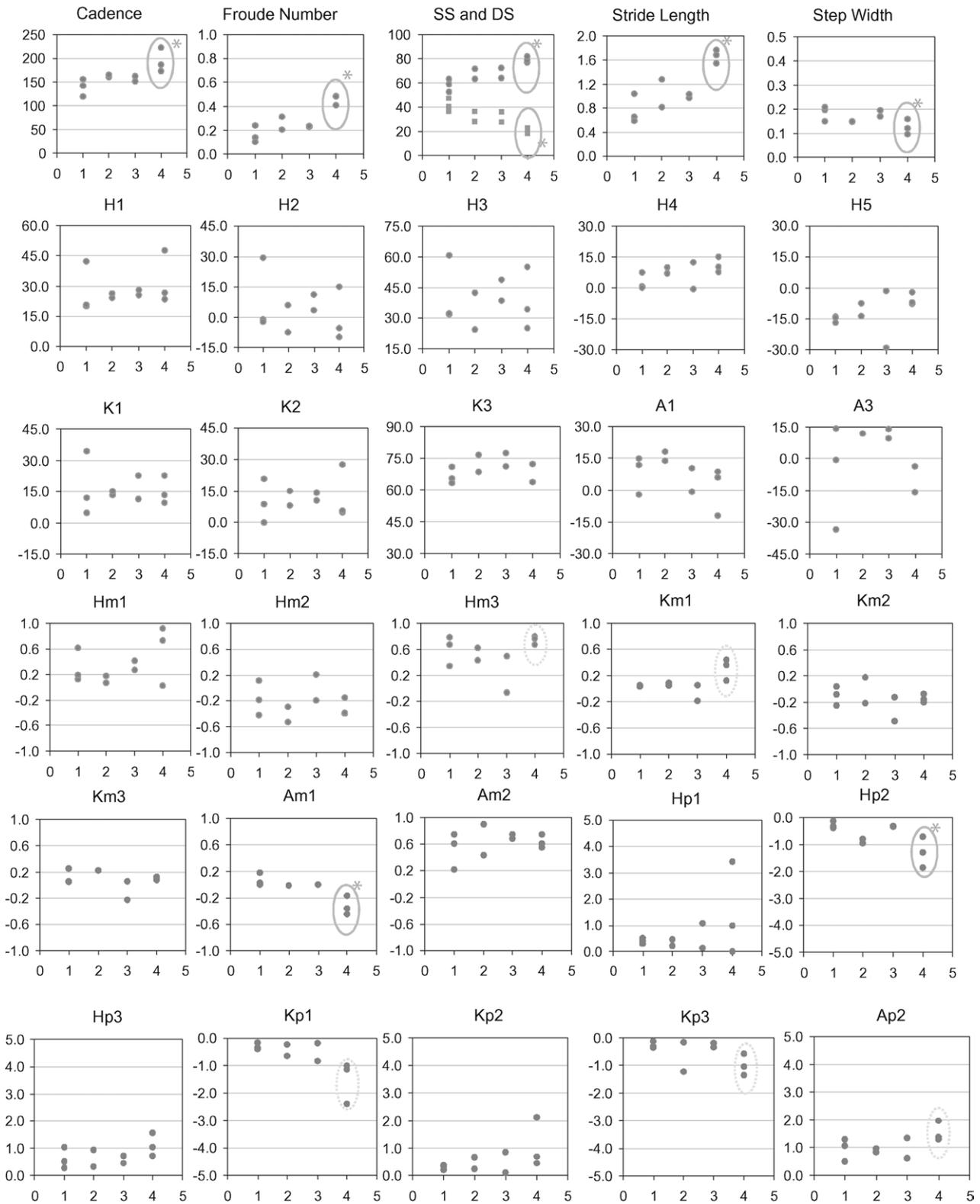


Fig. 6. Spatio-temporal, kinematic and kinetic variables are compared between the four subgroups of walking experience in toddlers. An asterisk is shown when significant ($p < 0.05$) differences were found using an ANOVA to compare the four groups. (1) 1 month of walking experience or less, (2) 2 months of walking experience, (3) 3 months of walking experience, (4) 4 months of walking experience or more). Border line differences ($p < 0.10$) are indicated by the dotted circles.

Table 6
Spatio-temporal, kinematic and kinetic parameters are compared between the four groups of walking experiences

Parameter	1	2	3	4	d.f.	<i>F</i>	<i>p</i>
Froude							
Average	0.16	0.26	0.24	0.46*	3	14.34	0.004
[95% CI]	[0.08, 0.24]	[0.15, 0.36]	[0.13, 0.34]	[38, 0.54]			
SS							
Average	59	68	68	79*	3	9.08	0.010
[95% CI]	[52,65]	[59,76]	[60,77]	[72,86]			
DS							
Average	41	32	32	21*	3	9.09	0.010
[95% CI]	[35,48]	[24,41]	[23,40]	[14,28]			
Stride length							
Average	0.76	1.05	1.00	1.67*	3	10.40	0.010
[95% CI]	[0.47, 1.05]	[0.69, 1.40]	[0.64, 1.36]	[1.38, 1.96]			
Step width							
Average	0.19	0.15	0.18	0.13*	3	5.71	0.030
[95% CI]	[0.18, 0.20]	[0.14, 0.16]	[0.17, 0.19]	[0.11, 0.14]			
Am1 (Nm/kg)							
Average	0.07	-0.02	0	-0.31*	3	8.70	0.010
[95% CI]	[-0.08, 0.21]	[-0.19, 0.16]	[-0.17, 0.17]	[-0.47, -0.18]			
[95% CI]	[0.22, 0.83]	[0.29, 1.03]	[0.34, 1.08]	[0.33, 0.93]			
Hp2 (W/kg)							
Average	-0.29	-0.88	-0.33	-1.30*	3	5.29	0.040
[95% CI]	[-0.78, 0.20]	[-1.47, 0.28]	[-0.93, 27]	[-1.79, -0.89]			

Averages, 95% confidence intervals, *F*- and *p*-values from the multiple analysis of variance are shown. Significantly different groups are indicated by an asterisk. Statistical significance is set at $p < 0.05$.

When investigating the net joint moments, the ankle dorsiflexing moment (Am1) is larger in group 4 compared to group 1. No differences could be identified in the other joint moment variables.

When looking at powers, again group 4 differs from the others showing larger power absorption in the hip joint (Hp2). Despite the fact that it was not significant, the results suggest a trend towards larger power generation in the hip (Hp3) and the ankle at push off (Ap2; Fig. 6).

4. Discussion

To our knowledge, this study is the first to report kinetic profiles in toddlers. We are aware of the limitations of our study, especially in relation to the diversity of walking experiences in our study group and the use of a suit for marker placement. The suit will inevitably have introduced error and decreased accuracy of the kinematic recordings due to tissue movements. However, we were forced to use a suit since the children did not tolerate sticking markers on their skin. We tried to minimize the error by using a very tight fitting suit made of highly elastic material. The kinematic time-profiles we obtained were very similar to the profiles reported in literature [1–9]. Therefore, we feel our data are valid for describing general features of 3D kinetics in toddlers.

Our primary goal was to compare the global patterns of walking in toddlers and adults. In general mass-specific net joint moments are small in toddlers. In part this can be explained by differences in inertial parameters between adults and toddlers that result from size differences (since after scaling for size differences, the differences between the pediatric and adult population partially disappear). But also differences in walking speed and walking strategy (which will be discussed further) might play a role. Mass-specific power production around a joint is also reduced in toddlers, most likely because of the low self-selected walking speed.

Comparing the toddler's kinetic profiles to the stereotype adult patterns, some important differences in shape and amplitude can be identified. A *first* feature of immature gait is the dominance of the hip and knee extending moments throughout stance, together with a sustained power production observed around these joints. These findings are supported by the previously reported [19,20] continuous activity of the vastus medialis and gluteus maximus in toddlers. Vastus medialis is known to be important for balance control. Balance problems are suggested in toddlers by the prolonged double support phase, wide base of support and guard position of the arms. Balance problems might also explain the bent position of the hip and knee observed in toddlers throughout stance, as it lowers body's centre of mass and therefore increases stability. This squatted position causes the GRF to pass behind the knee and in front of the

hip during the major part of stance. Internal extending moments are necessary to counteract the flexing moment caused by the GRF to prevent collapse of the hip and knee joint. A *second* remarkable feature is the reduced complexity of the joint moment profiles in toddlers, for example shown in the uni-modal pattern of the hip abducting moment, which differs from the bi-modal pattern observed in adults. Reduced complexity can also be observed at the knee and ankle joint (absence of internal knee flexing moment prior to FC, absence of the dorsiflexing moment in the ankle following FC). This reduced complexity most likely is caused by the less “dynamic” gait pattern of toddlers that probably results from an immature control of walking. A *third* feature of toddler gait is that mass-specific power generation at the ankle prior to FO is small while in adults power generation at the ankle is the most important contributing factor to generating push-off forces [31]. The observed small plantar flexion movement of the ankle is likely to be a passive movement possibly only reflecting the action of gravity on the foot segment. These results are consistent with the findings of Sutherland [32] that no activity was seen in the lateral gastrocnemius-soleus couple prior to FO in children up to the age of seven.

When investigating the effect of WE on the toddler’s gait pattern, in general an evolution towards a more mature pattern could be observed after 4 months of independent walking, as significant changes are observed in step-time parameters and power production. We could not identify significant differences in joint angles and moments between the four subcategories of walking experience, despite the fact that we know from literature that, at least concerning joint kinematics, changes must occur during this first developmental phase. The inability of finding significant relations can most likely be attributed to the cross-sectional nature of our study and the small number of subjects (two to three) per category. Because of the large inter- and intra-subject variability of toddler gait, a longitudinal study would be more appropriate to investigate subtle changes in the 3D joint kinematics and kinetics due to maturation and experience. This is therefore one of our future goals.

5. Conclusion

This cross-sectional study showed to be valid in comparing joint kinetic profiles between toddler and adult gait. Three important features concerning joint dynamics in immature walking could be identified. First, balance problems most likely lead to a dominance of the extending moments throughout stance. Second, immature control of movement becomes evident from the reduced complexity of the joint moment profiles. Third, virtually no push-off forces are generated at the ankle.

Furthermore, our results suggest an early maturation of gait after 4 months of independent walking. However,

further research (preferable in a longitudinal set-up) is necessary to investigate the subtle effects of maturation and experience on joint dynamics in toddler gait.

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