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Centre of mass motion during gait in persons with myelomeningocele

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Abstract

The movement of the centre of mass in the vertical and lateral directions during gait in children with myelomeningocele was analyzed. The children were classified into five groups depending on the successive paresis of lower limb muscle groups and compared to a control group. In the groups with dorsi- and plantarflexor weakness, the excursions increased and an anterior trend in the centre of mass was observed. In the groups with additional abductor paresis, the lateral excursion was highest and the vertical excursion low due to increased transverse and frontal motion and reduced sagittal motion. With further paresis of the hip extensors, the centre of mass was more posteriorly positioned due to compensatory trunk extension. Improved understanding of individual children's solutions to their muscle paresis can be obtained by visualizing the centre of mass relative to the pelvis. Centre of mass analyses in myelomeningocele offer an important complement to standard gait analysis.

Keywords: Locomotion; Spina bifida; Biomechanics; Center of gravity; Gait analysis

1. Introduction

The ability to reduce centre of mass (CoM) excursions in gait is a topic that has promoted a good deal of controversy and investigation. Early work by Saunders et al. [1] discussed 'determinants' of gait that reduce vertical CoM fluctuation, such as pelvic motion and stance-leg knee flexion. More recent studies challenge the significance of these determinants [2–5] and suggest others play a larger role, particularly heel rise [6,7]. Some recent studies have investigated CoM excursion during gait in myelomeningocele (MMC) [8–11]. The movement of the CoM can be an important descriptive of pathological gait [12,13], and has been used to evaluate gait efficiency and symmetry, often with a calculation of external work in translating the CoM [12,14–19].

Normal muscle functions have been described for their contributions in gait [20,21]. During the 'first ankle rocker', plantarflexion after initial contact is controlled by the ankle dorsiflexors. In the 'second ankle rocker' the tibial advancement over the foot is controlled by the soleus. In the 'third ankle rocker' the soleus-gastrocnemius activity raises the heel and provides power to advance the limb during swing phase. Knee flexion is essentially passive during swing with some activity of the knee flexor muscles late in stance to control knee extension and pre-position the leg for loading. Hip extensors are important in initial contact and loading response: they resist the flexor moment from the ground reaction forces and accelerate the trunk over the femur. Finally, hip abductors provide frontal plane stability during loading response [20,21]. Paresis or weakness of these muscles drastically changes gait patterns. The particular effects of the muscle weakness in MMC on the body CoM are unknown.

In MMC paresis of the lower limbs is proportional to the height of the spinal lesion [22] although children having the same lesion level label have been observed to

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have different functional outcome [23]. Additionally the same labels have been observed to define different extents of muscle paresis [24]. In a clinical gait laboratories, standard Manual Muscle Testing [25] (MMT, 0–5 scale) is often performed based on the gross function around the joints. A classification of successive muscle paresis of the major lower limb muscle groups may provide information for their role in gait in MMC. Gait patterns of children with MMC have been described for several classifications or lesion levels [26–32], as well CoM excursion [8–11]. However, there is little information on patients who have more extensive paresis.

In past studies, the sacrum, pelvis, or trunk [1–7,33,34] has been used to estimate the position of the CoM. This estimation assumes that CoM is stationary within the body, which may be a reasonable assumption in normal gait. In pathological gait, however, this assumption is inaccurate [35,36] and movement of the CoM relative to the body is a measure of the error of this estimation. Only recently has the routine use of a whole-body model to measure the CoM become feasible clinically. Eames et al. [35] validated a similar model for patients with MMC. To date the CoM position has not been linked to patients' anatomy and all body segments should be present with accurate anthropometrical and inertial characteristics to obtain an accurate CoM position based on a kinematic model.

Broadly, the main objective of gait is to displace the body CoM anteriorly. The path of the displacement gives details about the strategy used, the symmetry and possibly the efficiency of the strategy. The aims of this study were to investigate the effect of successive muscle paresis in major lower limb muscle groups on the CoM motion in the vertical and medio-lateral directions and in the transverse plane relative to the pelvis, and to compare between different MMC muscle paresis groups and between MMC and control.

2. Subjects and methods

Ethical approval for this study was obtained from the Karolinska Institute Ethics Committee. Subjects participation was on a volunteer basis.

2.1. Subjects

Thirty-one consecutive self-ambulatory subjects with MMC and 21 healthy children were recruited to the study. Inclusion criteria were lumbo-sacral MMC with no hip or knee contractures $>20^\circ$ and the ability to walk independently without the use of a walking aid or orthoses that extend beyond the hips. Three subjects were excluded: two who were not able to walk without a walking aid and one who had a cervicocele. Twenty-eight subjects with MMC (6.8–15.6 years, mean 10.3 years) and 21 healthy controls (5.2–14.4 years, mean 10.4 years) were tested using 3-D gait analysis. MMC subjects were tested with a standard MMT. Muscle groups that were able to act against gravity and withstand resistance were assigned '4' for muscle groups involved in paresis. A minimum MMT grade 3 was required for a muscle group to be considered usefully present. The classification was chosen to determine the specific effects of complete paresis (MMT grade ≤ 2) in major lower limb muscle groups. The subjects with MMC were divided into five Muscle Function Groups with Group 1 having the least and Group 5 the most muscle paresis. All 28 subjects had fully functioning hip flexors, hip adductors and knee extensors (Table 1).

2.2. Orthoses

The subjects who habitually used orthoses were tested in them; 10/28 children wore ankle-foot orthoses (AFOs) and 10/28 wore knee-ankle-foot orthoses according to Ferrari (KAFOs) [26]. The shank sections in both AFOs and KAFOs were carbon fiber and the ankle joints in the orthoses were restricted to prevent tibial advancement, aligned at approximately 10° dorsiflexion with the shoes to create slight knee flexion in standing. All soles extended for the entire length of the foot and had some flexibility in the forefoot depending on hip extensor strength. In KAFOs, a thermoplastic thigh cuff was attached via a free-articulating embedded aluminum knee joint to align the thigh, shank, and foot in the frontal and transverse planes. Alignment with orthoses and shoes was tuned to each individual's optimal trunk alignment in the sagittal plane to position the centre of mass approximately above the axis of the hip joints.

Table 1
Groups based on muscle function (0–5 strength scale based on Manual Muscle Testing)

Groups	1	2	3	4	5
Knee Flexion	4	4	4	2-4	2-3
Hip Extension	4	3-4	3-4	+2-4	0-1
Hip Abduction	4	3-4	3-4	0-2	0-1
Ankle Dorsiflexion	3-4	3-4	0-2	0-1	0
Ankle Plantarflexion	+2-4*	0	0	0-1	0
Count	**9**	**6**	**3**	**6**	**4**
AFOs	*1*	*4*	*2*	*1*	*2*
KAFOs	*0*	*2*	*1*	*5*	*2*

All 28 children were assessed as having full function in hip flexion, hip adduction and knee extension. The groups have successive complete muscle paresis (MMT ≤ 2) of the plantarflexors, dorsiflexors, hip abductors, and finally hip extensors. A 2+ grade indicates a subject with a 2 on one side and a 3 on the other. In all cases of asymmetry, an average grade was used and subjects were placed as above.

2.3. Data collection

Subjects were tested using 3-D gait analysis using a motion analysis system and Workstation software (Vicon Motion Systems, England) and walked along a 10 m walkway. Data from two staggered force platforms (Kistler) were used to aid identification of gait events when possible. Retro-reflective markers were placed on bony landmarks or on specific positions. In the case of subjects with AFOs, care was taken to place markers as near as possible to the correct anatomical position. In subjects with KAFOs, the knee marker was placed directly over the orthosis joint and the thigh wand marker on the thigh cuff using the same alignment procedure as on subjects without orthoses. The subjects were asked to walk at a self-selected, comfortable pace and repeated the test 10–15 times from which five left stride cycles were used for analysis. Walking speed and stride length were measured from each subject's five trials. The mean speed and stride of each subject were calculated and entered into a group mean according to Muscle Function Group and Control.

All subjects were tested using a full-body, 34 marker, 15 segment marker set. The lower body was modeled according to the Helen Hayes Marker set [37] and the upper body was modeled as the thorax, upper and lower arms, hands, and head using the Plug In Gait model (Vicon Motion Systems). This model is well-documented and has been validated [38]. A full description of the upper body model is provided in Appendix A.

Data from five left gait cycles for each subject were analyzed. Trajectory of the centre of mass in all directions, as well as hip joint center locations and pelvic rotation angles were imported as ASCII data into Matlab (Mathworks, USA) for further calculations. All data were normalized to 100 points throughout the gait cycle. The vertical displacement of the CoM was defined as the z-component of the CoM trajectory. It was observed that the subjects did not necessarily walk parallel to the x-axis, which was evident as an upward or downward trend in the medio-lateral displacement curve. As such, the medio-lateral displacement was offset by a linear regression of the medio-lateral CoM position between the beginning and end of the gait cycle such that the medio-lateral CoM position began and ended at the same x value.

Peak-to-peak displacements, or 'excursions', of the CoM in the medio-lateral and vertical directions were determined for each individual as the mean of the excursions in the five stride cycles. The excursions were normalized by each individual's average leg length. A group average and standard deviation of CoM excursions in the lateral and vertical directions were determined from the excursions for each subject in each Muscle Function Group and in the Control group.

The pelvis-fixed CoM trace was calculated as follows: the CoM position relative to the midpoint between the hip joint centres was determined in the global coordinate system (Fig. 1). The trace was normalized to one-half of each individual's inter-hip joint centre distance as calculated by the model. The trace was then rotated by the pelvic rotation angle to a coordinate axis fixed on the hip joint centres. The result observed is a trajectory of the CoM in the horizontal plane relative to the joint centres. For each subject, a mean trace was calculated as the ensembled average of the five stride cycles and was used for further analysis.

Average antero–posterior position of the pelvis-fixed CoM was calculated for each individual's CoM trace. Group averages were calculated for each Muscle Function Group and the Control group. Average vertical position of the CoM throughout the gait cycle was calculated as a percentage of body height from the floor.

Statistical significance was determined with nonparametric tests using commercially available software, SPSS. The Kruskal Wallis test was used to determine whether differences existed between all six groups. The Mann–Whitney test was used for subsequent comparisons between a Muscle Function Group and Control or between two Muscle Function Groups. A P-value of 0.05 or less was considered statistically significant.

3. Results

Walking speed was observed to be slightly higher in Control (1.31 m/s) than in MMC Groups 1–4 (average 1.1 m/s) and considerably higher than in Group 5 (0.6 m/s). Stride length was higher in Control (1.23 m) than in MMC Groups 1–4 (average 1.06 m) and Group 5 (0.69 m) (Fig. 2).

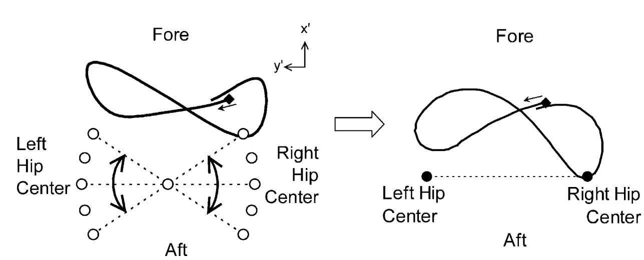

Fig. 1. Method used to determine the pelvis-fixed CoM trace. The CoM in the transverse plane was first determined in the global coordinate system relative to the point between hip joint centres. Pelvis rotation can be observed on the first figure. The trace was normalized to each individual's inter hip joint centre distance, as calculated by the model. The second figure shows the CoM trace rotated by the pelvic rotation angle and relative to the axis between hip joint centres (data from a Group 5 subject).

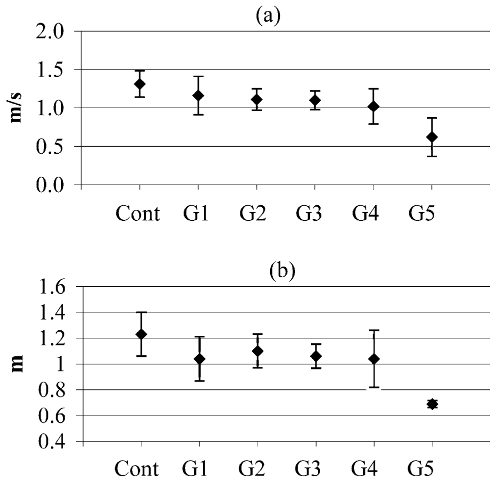

Fig. 2. (a) Walking speed (±1 SD); and (b) stride length (±1 SD) classified into Muscle Function Group and Control.

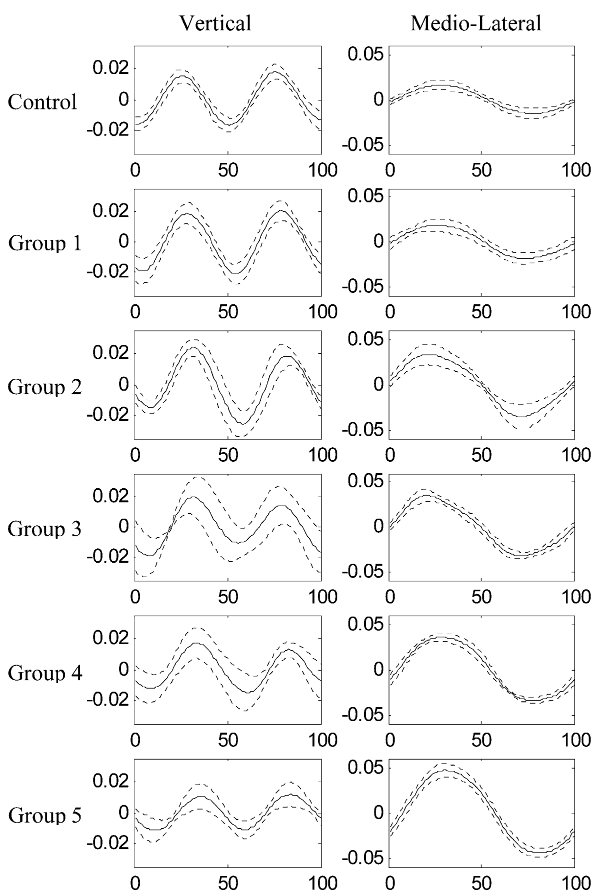

Fig. 3. Vertical and lateral displacement of the CoM ±1 SD normalized to leg length during one gait cycle for each Muscle Function Group. Five left gait cycles from each subject were averaged and normalized by each subject's leg length and the categorized into muscle function groups.

3.1. CoM excursions

Displacements of the CoM in the vertical and lateral directions are shown (Fig. 3). Group 5 had the largest lateral excursion at nearly three times that of Control (Table 2, Fig. 4). The excursion was observed to decrease with decreasing muscle paresis. Statistical analysis revealed significant differences between the six groups ($P < 0.001$). Subsequent nonparametric tests revealed differences in lateral CoM excursion between Control and MMC Groups 2–5 ($P < 0.01$ in all cases) and inter-MMC Group differences between Groups 1 and 2 ($P = 0.018$) and between Groups 4 and 5 ($P = 0.033$). The entire group of MMC displayed a higher lateral CoM excursion than Control ($P < 0.001$).

Vertical CoM excursion did not display a direct relationship to Muscle Function Group and was higher than Control in only Groups 2 and 3. Statistical examination showed significant differences between the six groups ($P = 0.003$). Subsequent statistical analysis showed differences from Control in Groups 2 ($P = 0.002$) and 3 ($P = 0.010$). No inter-MMC Group differences were observed. The entire group of MMC displayed a higher vertical excursion than Control ($P = 0.011$).

A much larger CoM trace relative to the pelvis was observed in Groups 4 and 5, with a smaller trajectory in groups with less muscle paresis and in Control (Fig. 5). In groups with no hip abduction strength, the CoM was at times lateral to the hip joint centre.

An anterior trend in CoM average position relative to the pelvis was observed from Control to Groups 1, 2, and 3, then a posterior trend observed in the groups with greater muscle paresis Groups 4 and 5 (Fig. 6). Significant differences were found between the six groups ($P = 0.004$). Subsequent statistical showed a difference from Control in Groups 2, 3, and 5 ($P = 0.036$, 0.006, and 0.047, respectively). One inter-MMC Group difference was determined between Groups 3 and 4 ($P = 0.039$). No difference was found between the entire group of MMC and Control.

An example of a pelvis-fixed CoM trace in a Group 5 subject is shown with the phases of double and single support indicated (Fig. 7). The left gait cycle begins in the anatomical middle with the first phase of double support lasting until the CoM is near the left hip joint centre. The subject maintains single support until the CoM is again around the middle, when the right foot contacts the floor, and a similar process is observed for the right leg.

The average position of the CoM in the body throughout the gait cycle as calculated by the model was at 55% height from the floor (SD 1.6%). The position did not vary significantly between the six groups.

Table 2
Subjects, characteristics, CoM excursions and positions

Subject	Gender	Age (years)	Height (mm)	Leg length (mm)	Inter-HJC[a] distance (mm)	Orthoses[b]	Vertical CoM excursion mean (SD) (mm)	Lateral CoM excursion mean (SD) (mm)	Anterior CoM position[c] (mm)	Vertical CoM height[d]
Control										
Cont1	F	11.7	1500	835	58		33 (5)	26 (5)	46	0.56
Cont2	F	12.6	1420	835	61		28 (5)	13 (4)	48	0.60
Cont3	M	12.6	1520	805	50		30 (4)	32 (9)	30	0.52
Cont4	F	12.0	1505	856	56		40 (3)	32 (11)	48	0.55
Cont5	F	11.8	1510	860	58		32 (4)	20 (4)	50	0.56
Cont6	M	10.0	1445	780	50		24 (4)	25 (5)	23	0.56
Cont7	M	11.8	1565	860	56		22 (2)	27 (9)	49	0.55
Cont8	M	10.0	1425	780	51		54 (7)	44 (14)	44	0.55
Cont9	M	9.3	1370	725	57		27 (4)	36 (2)	18	0.55
Cont10	M	5.2	1130	587	46		28 (2)	28 (11)	20	0.54
Cont11	F	9.7	1325	715	54		22 (3)	23 (8)	27	0.55
Cont12	F	9.7	1305	700	52		30 (3)	13 (5)	20	0.55
Cont13	M	5.3	1070	525	52		23 (5)	16 (8)	14	0.52
Cont14	F	12.6	1410	755	68		35 (6)	26 (5)	20	0.55
Cont15	M	10.8	1540	810	66		32 (3)	24 (7)	27	0.55
Cont16	M	14.4	1795	980	81		39 (3)	34 (6)	45	0.55
Cont17	M	12.7	1560	855	59		30 (2)	19 (9)	24	0.56
Cont18	F	10.6	1425	780	57		29 (3)	25 (8)	11	0.56
Cont19	F	11.1	1435	790	56		39 (3)	27 (6)	10	0.55
Cont20	M	9.2	1355	715	68		32 (4)	23 (5)	41	0.55
Cont21	F	5.9	1180	600	62		24 (5)	21 (4)	0	0.54
Group 1										
1a	M	7.2	1120	560	61	A	19 (3)	33 (8)	19	0.56
1b	M	11.5	1400	750	61	–	33 (8)	45 (9)	55	0.54
1c	F	9.5	1350	738	58	–	32 (3)	25 (7)	28	0.54
1d	M	10.5	1380	750	54	–	52 (4)	17 (4)	45	0.54
1e	F	9.4	1470	800	62	–	39 (3)	21 (6)	50	0.55
1f	F	15.7	1640	885	69	–	30 (5)	42 (6)	31	0.54
1g	M	8.8	1350	705	62	–	35 (10)	18 (6)	45	0.54
1h	F	9.0	1450	785	79	–	42 (3)	36 (8)	38	0.53
1i	M	8.6	1290	690	54	–	48 (8)	29 (6)	61	0.53
Group 2										
2a	F	13.9	1620	875	63	A	39 (3)	47 (4)	20	0.55
2b	M	8.0	1230	630	60	K	44 (5)	67 (12)	47	0.55
2c	M	11.3	1525	770	49	K	41 (5)	50 (4)	67	0.54
2d	F	9.1	1290	715	65	A	39 (6)	25 (10)	54	0.56
2e	M	7.0	1120	555	49	A	42 (6)	46 (11)	50	0.54
2f	M	10.2	1320	705	59	A	34 (8)	54 (11)	49	0.58
Group 3										
3a	M	6.8	1245	635	65	A	45 (11)	50 (20)	89	0.53
3b	M	11.7	1356	730	50	A	37 (4)	44 (8)	65	0.55
3c	M	10.3	1400	745	71	K	40 (6)	48 (8)	69	0.56

Table 2 (*Continued*)

Subject	Gender	Age (years)	Height (mm)	Leg length (mm)	Inter-HJC[a] distance (mm)	Orthoses[b]	Vertical CoM excursion mean (SD) (mm)	Lateral CoM excursion mean (SD) (mm)	Anterior CoM position[c] (mm)	Vertical CoM height[d]
Group 4										
4a	M	8.1	1160	585	51	K	17 (5)	52 (11)	5	0.55
4b	M	7.9	1290	650	51	K	28 (4)	47 (10)	33	0.56
4c	F	13.0	1570	824	58	A	39 (7)	60 (18)	61	0.55
4d	M	13.9	1530	845	52	K	54 (9)	56 (13)	37	0.56
4e	M	8.0	1250	645	51	K	26 (6)	42 (7)	4	0.56
4f	M	12.3	1390	698	59	K	46 (4)	60 (6)	41	0.54
Group 5										
5a	F	15.8	1460	763	71	A	37 (5)	69 (10)	36	0.55
5b	F	15.6	1450	775	60	A	15 (3)	77 (8)	−24	0.60
5c	F	7.8	1110	560	41	K	14 (2)	60 (5)	−35	0.54
5d	F	7.8	1140	585	53	K	20 (5)	49 (10)	11	0.54

[a] 'HJC' = Hip Joint Center.
[b] 'A' = Ankle-Foot Orthoses, 'K' = Knee-Ankle-Foot Orthoses, '–' = none.
[c] Positive indicates CoM position anterior to the hip joints, negative indicates posterior position.
[d] Expressed as a fraction of body height from the floor.

4. Discussion

The most important findings of the study are that of increasing lateral CoM excursions with increasing muscle paresis, and of the CoM movement analysis of Group 5, whose documented self-ambulation without walking aids is practically non-existent in the literature. Their gait was characterized by large lateral and transverse movements in the trunk and pelvis, with an internally rotated trunk and pelvis in mid-stance [32]. These motions have not always been correlated to higher lateral CoM excursions in different laboratories [10]. The findings of highest vertical excursions in the middle-range groups and a reduction in the groups with the most muscle paresis were interesting. The subsequent pelvis-fixed CoM movement analysis was performed to gain insight on the strategy used by these groups for forward propulsion.

Our findings of differences in CoM excursions in both lateral and vertical directions contradict findings of Bare et al. [9] who found no differences in the either direction. These investigators only tested subjects who had high sacral level MMC, which would correspond to our Group 1, in which we found no differences. The increase of lateral CoM excursion with increasing muscle paresis contradicts the findings of Eames et al. [11], who tested four groups (approximately equivalent to this study's Groups 1–4). They only found increased lateral CoM excursion in L4-5 MMC, corresponding approximately to our Group 3, and found no differences in vertical CoM excursion. In a later study [10] with three MMC groups approximating this study's Groups 1–3, investigators found differences in vertical CoM excursion in only their L5 MMC group, corresponding approximately to our Group 2. The discrepancy between their results and ours may be due to the different models used to calculate the CoM position or differences in classification definitions. The discrepancy, however, may also be due to a different gait strategy used by the children at our centre who have a different orthotic prescription. Vertical CoM excursion in our study was observed to vary depending on muscle paresis, which agrees with the findings of Eames et al. [10]. A strict relationship between CoM excursion and vertical CoM excursion can be eliminated when considering the walking speed and cadence of the groups.

Particular strengths and compensatory motions employed by each respective group had different effects on the vertical CoM excursion. In Group 2, the paresis of the ankle plantarflexors caused an increase in both vertical, though not statistically significant, and mediolateral excursions, which we attributed to the inability to perform the third ankle rocker ('heel rise') and subsequent compensatory movements. These findings are in accordance with Kerrigan et al. [6] who determined heel rise to be a major factor reducing vertical CoM

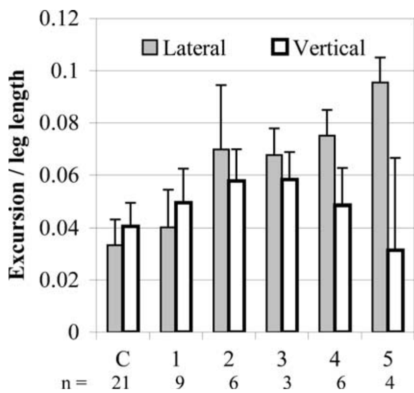

Fig. 4. Lateral and vertical CoM excursions (±1 SD) normalized to leg length for each Muscle Function Group.

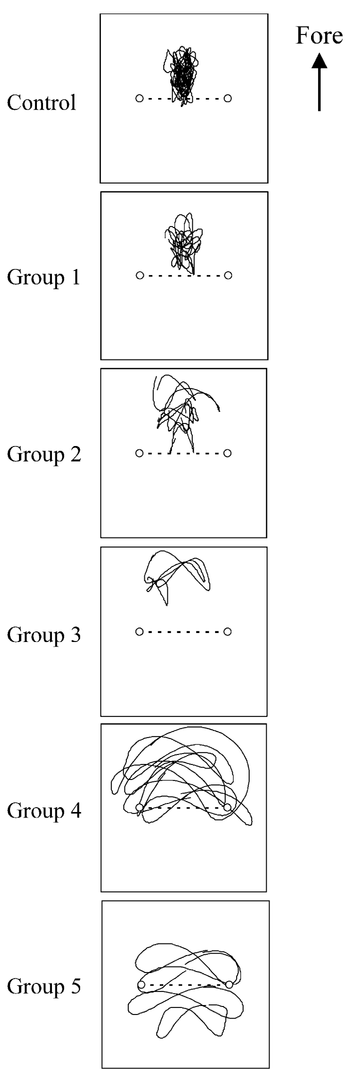

Fig. 5. Pelvis-fixed CoM trace for each Muscle Function Group. The mean trajectory of 5 left gait cycles for each subject is displayed. In each case, the trajectory is normalized to the inter-hip joint centre distance and rotated to an axis through the hip centers. The small circles represent the subjects' left and right hip joint centres.

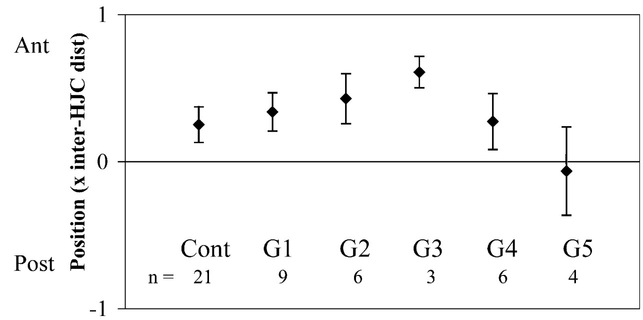

Fig. 6. Mean (±1 SD) of antero–posterior CoM position during one gait cycle relative to hip joint centre axis for each group.

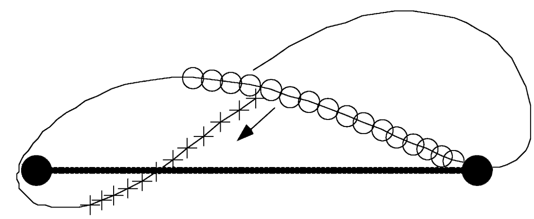

Fig. 7. Pelvis-fixed CoM in a Group 5 child. The arrow marks the initial contact of the left foot. The phases of double support time are indicated with '+' and 'o'.

excursion. Additional paresis of the ankle dorsi-flexors (Group 3) made very little difference on the CoM excursion, but the CoM position was somewhat more anterior, but not statistically significant, indicating a more flexed position of the trunk. Two of the three children in this group had knee flexion contractures (15–20°), which may have led to a more crouched position. Group 4 is distinguished from Group 3 by greater paresis of the hip abductors, which resulted in a pendulum gait wherein the upper body was positioned over the hip joint center in stance to avoid hip a abduction moment [28,32]. The lateral CoM excursion was greater due to higher upper body lateral motion, mediated by a stable hip. Group 4, however, had a lower vertical CoM excursion than the stronger groups. Group 4 also had the CoM positioned significantly more posteriorly than Group 3, attributable to pelvic protraction during loading response and retraction at pre-swing [32], as described by Vankoski et al. [27] and Duffy et al. [28,29]. Group 5 was distinguished from the other groups because of paresis of the hip extensors. Even greater medio-lateral CoM excursion was present than in Group 4 but the vertical CoM excursion was smaller than even the Control group. Gait in MMC has been described to have a lower range of knee flexion [27–30] and hip extension [29]. Reduced sagittal plane motion and the small stride length may have resulted in reduced CoM vertical excursions in Groups 4 and 5. The posterior position of the CoM in Group 5 could have been obtained by an extended position of the trunk. This would avoid excessive internal hip extensor moments which, combined with excessive pelvic protraction and lateral lean during loading response, would position the CoM approximately over or just behind the hip joint in single stance.

The pelvis-fixed CoM trace shows that the compensatory gait pattern in MMC resulted in relative movement of the pelvis under the CoM to support the body during single stance. A larger relative movement between the CoM and pelvis was observed with increasing muscle paresis. The example in Fig. 7 illustrates how child (Group 5) who has so little lower leg strength copes with double and single support stance. At the beginning of the left stance phase, the CoM is medial to the left hip centre, and double support is required until CoM is near the hip centre, illustrating the principle of hip abductor avoidance. The pelvis-fixed CoM trace permits a clear anatomical definition of CoM displacement and location and enables inter-subject comparisons. The anatomy of the pelvis is not necessarily proportional to age [39] and is most likely gender-dependent and so there is an advantage to be able to observe the CoM in each individual's anatomy. The accuracy of this method, however, is clearly dependent on the accuracy of the biomechanical gait model, which defines the hip joint centre as a function of pelvis marker placement, inter-anterior superior iliac spine distance, and leg length [40] and is based on the anatomy of adult subjects.

5. Conclusions

While determinants of vertical CoM excursion during normal gait have been studied and defined, a CoM analysis offers important additional information to the different mechanisms used during gait in MMC. The highest CoM vertical excursion was observed in the mid-weakness range of ambulatory groups where only the ankle muscles were totally paretic. In the most paretic groups that involved the hip abductors and extensors as well, the CoM vertical excursion was low and the lateral excursion instead high. In these groups, the pelvis and CoM, and hence upper and lower body, required large relative motions. All efforts to stabilize the lower extremities and accommodate large upper body motion to allow this method of progression should be preserved to maintain ambulation in even the most paretic children.

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Appendix A: Plug-in-Gait Model details (Vicon Motion Systems, Ltd, Oxford, England)

Segment	Markers	Origin	Primary axis	Secondary axis	Segment CoM	Radius of gyration	Mass (% body mass)
Lower Body	(as reported by Kadaba et al. [37])						
Thorax	C7 = 7th cervical vertebrae	1/2 marker diameter along x axis from Clav	z = Strn-T10 midpoint to Clav-C7 midpoint	x = C7–T10 midpoint to Clav-Strn mid-point	63% dist from Cerv7[1] to L5[2]	31% dist from Cerv7[1] to L5[2]	35.5
	T10 = 10th thoracic vertebrae Clav = notch between clavicals Strn = sternal notch Rbak = antisymmetry on back						
Humerus	Sho = acromion	EJC[4]	z = EJC to SJC[3]	x = approx. x axis between EJC and JC	56.3% dist. from EJC to SJC	32.2% dist. from EJC to SJC	2.8

Table 2 (*Continued*)

Segment	Markers	Origin	Primary axis	Secondary axis	Segment CoM	Radius of gyration	Mass (% body mass)
	Elb = Lateral humeral condyle						
Radius	WrA = thumb-side of bar on wrist WrB = little finger-side of said bar	WJC[5]	z = WJC to EJC	y = approx. y axis of humerus	57% dist. from WJC to EJC	30.3% dist. from WJC to EJC	1.6
Hand	Fin = third metatarsal head	Chord function of WJC, Fin—1/2 hand width in plane of WrA–WrB midpoint	z = hand origin to WJC	y = approx. y, line between WrA and WrB	62.05% dist. from hand origin to WJC	22.3% dist. from hand origin to WJC	0.6
Head	FHd = frontal bone above temples on band (L = left, R = Right) BHd = parietal bones posterior and superior to ears on said band (L = left, R = Right)	LFHd–RFHd midpoint	x = LBHd–RBHd midpoint to origin	y = RFHd–RBHd midpoint to LFHd–LBHd midpoint	52% dist. along x from front to back	49.5% dist. from head CoM to Cerv/	8.1

[1]7th Cervical Spine (Cerv7): Used in kinetic modeling of trunk, the location of Cerv7 is 1/2 the marker diameter offset in the thorax x axis.
[2]5th Lumbar Vertebrae (L5): Also used in kinetic modeling of trunk, the L5 lies above the pelvis along the z axis 0.925 times the distance between hip joint centers.
[3]Shoulder Joint Center (SJC): A direction is defined perpendicular to the line from the thorax origin to the Sho marker, and the thorax x-axis. This is used to define a virtual shoulder 'wand' marker. The chord function is then used to define the SJC from the measured distance from acromion to estimated shoulder center, thorax origin, Sho marker and shoulder 'wand'.
[4]Elbow Joint Center (EJC): A construction vector direction is defined as perpendicular to the plane defined by the SJC, Elb and the midpoint of WrA and WrB. The elbow joint center is the defined using the chord function in the plane defined by the SJC, the elbow marker and the previously defined construction vector.
[5]Wrist Joint Center (WJC): The wrist joint center (WJC) is calculated by offsetting from the midpoint of the wrist bar markers 1/2 the marker diameter plus 1/2 the dorsal–ventral width of the joint along a line perpendicular to the line along the wrist bar and the line joining the wrist bar midpoint to the elbow joint center.

References

[1] Saunders JBD, Inman VT, Eberhart HD. The major determinants in normal and pathological gait. J Bone Joint Surg Am 1953;35:543–58.
[2] Gard SA, Childress DS. The influence of stance-phase knee flexion on the vertical displacement of the trunk during normal walking. Arch Phys Med Rehabil 1999;80:26–32.
[3] Gard SA, Childress DS. What determines the vertical displacement of the body during normal walking? J Prosthet Orth 2001;13:64–7.
[4] Gard SA, Childress DS. The effect of pelvic list on the vertical displacement of the trunk during normal walking. Gait Posture 1997;5:233–8.
[5] Kerrigan DC, Riley PO, Lelas JL, Della Croce U. Quantification of pelvic rotation as a determinant of gait. Arch Phys Med Rehabil 2001;82:217–20.
[6] Kerrigan DC, Della Croce U, Marciello M, Riley PO. A refined view of the determinants of gait: significance of heel rise. Arch Phys Med Rehabil 2000;81:1077–80.
[7] Della Croce U, Riley PO, Lelas JL, Kerrigan DC. A refined view of the determinants of gait. Gait Posture 2001;14:79–84.
[8] McDowell B, Cosgrove AP, Baker R. Estimating mechanical cost in subjects with myelomeningocele. Gait Posture 2002;15:25–31.
[9] Bare A, Vankoski SJ, Dias L, Danduran M, Boas S. Independent ambulators with high sacral myelomeningocele: the relation between walking kinematics and energy consumption. Dev Med Child Neurol 2001;43:16–21.
[10] Eames M, Baker R, Duffy CM, Cosgrove AP. The gait of patients with lower lumbar level myelomeningocele: how to abduct without abductors [Abstract]. Gait Posture 1999;10:76–7.
[11] Eames M, Cosgrove AP, Baker R. Centre of mass excursion in children with myelomeningocele [Abstract]. Gait Posture 1998;8:70.
[12] Iida H, Yamamuro T. Kinetic analysis of the center of gravity of the human body in normal and pathological gaits. J Biomech 1987;20:987–95.
[13] Engsberg JR, Tedford KG, Harder JA. Center of mass location and segment angular orientation of below-knee- amputee and able-bodied children during walking. Arch Phys Med Rehabil 1992;73:1163–8.
[14] Tesio L, Lanzi D, Detrembleur C. The 3-D motion of the centre of gravity of the human body during level walking. I. Normal

subjects at low and intermediate walking speeds. Clin Biomech 1991;13:77–82.
[15] Dierick F, Domicent C, Detrembleur C. Relationship between antagonistic leg muscles co-contractions and body centre of gravity mechanics in different level gait disorders. J Electromyogr Kinesiol 2002;12:59–66.
[16] Tesio L, Civaschi P, Tessari L. Motion of the center of gravity of the body in clinical evaluation of gait. Am J Phys Med 1985;64:57–70.
[17] Detrembleur C, van den HA, Dierick F. Motion of the body centre of gravity as a summary indicator of the mechanics of human pathological gait. Gait Posture 2000;12:243–50.
[18] Simon SR, Knirk JK, Mansour JM, Koskinen MF. The dynamics of the center of mass during walking and its clinical applicability [proceedings]. Bull Hosp Joint Dis 1977;38:112–6.
[19] Cavagna GA, Tesio L, Fuchimoto T, Heglund NC. Ergometric evaluation of pathological gait. J Appl Physiol 1983;55:607–13.
[20] Perry, J.: Gait analysis. Thorofare, NJ: SLACK Inc., 1992.
[21] Gage JR. Gait analysis in cerebral palsy. London: Mac Keith Press, 1991.
[22] Stark GD, Baker GCW. The neurological involvement of the lower limbs in myelomeningocele. Dev Med Child Neurol 1967;9:732–44.
[23] Bartonek Å, Saraste H. Factors influencing ambulation in myelomeningocele: a cross-sectional study. Dev Med Child Neurol 2001;43:253–60.
[24] Bartonek Å, Saraste H, Knutson LM. Comparison of different systems to classify the neurological level of lesion in patients with myelomeningocele. Dev Med Child Neurol 1999;41:796–805.
[25] Hislop HJ. Daniel's and Worthingham's muscle testing: techniques of manual examination. Philadelphia: Saunders Company, 1995.
[26] Bartonek Å, Saraste H, Eriksson M, Knutson LM, Cresswell AG. Upper body movements during walking in children with lumbosacral myelomeningocele. Gait Posture 2002;15:120–9.
[27] Vankoski SJ, Sarwick JF, Moore C, Dias L. Characteristic pelvic, hip, and knee kinematic patterns in children with lumbosacral myelomeningocele. Gait Posture 1995;3:51–7.
[28] Duffy CM, Hill AE, Cosgrove AP, Corry IS, Mollan RAB, Graham HK. Three-dimensional gait analysis in spina bifida. J Pediatr Orthop 1996;16:786–91.
[29] Duffy CM, Hill AE, Cosgrove AP, Corry IS, Graham HK. The influence of abductor weakness on gait in spina bifida. Gait Posture 1996;4:34–8.
[30] Thomson JD, Ounpuu S, Davis RB, DeLuca PA. The effects of ankle-foot orthoses on the ankle and knee in persons with myelomeningocele: an evaluation using three-dimensional gait analysis. J Pediatr Orthop 1999;19:27–33.
[31] Fabry G, Molenaers G, Desloovere K, Eyssen M. Gait analysis in myelomeningocele: possibilities and applications. J Pediatr Orthop 2000;9:170–9.
[32] Gutierrez EM, Bartonek Å, Haglund-Åkerlind Y, Saraste H. Gait with successive muscle paresis: characteristic kinematics in myelomeningocele [abstract]. Gait Posture 2002;16:136–7.
[33] Whittle MW. Three-dimensional motion of the center of gravity of the body during walking. Hum Mov Sci 1997;16:347–55.
[34] Duff-Raffaele M, Kerrigan DC, Corcoran PJ, Saini M. The proportional work of lifting the center of mass during walking. Am J Phys Med Rehabil 1996;75:375–9.
[35] Eames MHA, Cosgrove A, Baker R. Comparing methods of estimating the total body centre of mass in three-dimensions in normal and pathological gaits. Hum Mov Sci 1999;18:637–46.
[36] Saini M, Kerrigan DC, Thirunarayan MA, Duff-Raffaele M. The vertical displacement of the center of mass during walking: a comparison of four measurement methods. J Biomech Eng 1998;120:133–9.
[37] Kadaba MP, Ramakrishnan HK, Wooten ME. Measurement of lower extremity kinematics during level walking. J Orthop Res 1990;8:383–92.
[38] Gutierrez EM, Saraste H. Measuring center of mass displacement during gait: Whole-body kinematic model vs. ground reaction force calculation [Abstract]. Conference Proceedings, 4th World Congress of Biomechanics, 2002.
[39] Jensen RK. Changes in segment inertial proportions between 4 and 20 years. J Biomech 1989;22:529–36.
[40] Davis RB, Ounpuu S, Tyburski D, Gage JR. A gait analysis data collection and reduction technique. Hum Mov Sci 1991;10:575–87.