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Regression analysis of gait parameters with speed in normal children walking at self-selected speeds

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Abstract

Dimensionless analysis ensures that differences in sizes (e.g. height and weight) of children have a minimal influence on gait parameters. The results of changes in speed on gait parameters were examined using dimensionless analysis on data from a prospective 5-year study of 16 children. Linear regression analysis of peak and trough values of temporal distance parameters, ground reaction forces, joint angles, moments and powers provide a quantitative description of gait development with normalised speed. These linear relationships can be used to estimate gait parameters from speed measurements for normal subjects. However, caution is advised in using the data to attempt to predict an individual's gait parameters due to the wide spread of data about the regression lines and we do not recommend that the data be used to extrapolate the regression data to wider speed ranges.

Keywords: Walking; Children; Regression; Kinematics; Kinetics

1. Introduction

Gait in children is speed dependent [1–3] and evidence of changes with speed in temporal distance parameters [4–8], ground reaction forces [1,3,9–11], joint angles [7,10,12–14], joint moments and joint powers [15,16] have been presented previously. It is important to note that in many of these publications parameters were not normalised, thus introducing differences in data for subjects of different sizes (e.g. height and weight). This makes comparison of the results of one study with those of another difficult, where there was a difference in size of the subjects. It is possible to normalise gait parameters to dimensionless quantities, thus removing some of the size related variability in results [17,18]. To the authors' knowledge there is no published source of quantified data for relevant normalised parameters of gait covering the range of speeds achieved during self-selected walking in normal children.

For this study the results of gait analysis of a 5-year longitudinal study of 16 children between the ages of 7 and 12 years (previously reported by Stansfield et al. [1,2]) have been analysed quantitatively. The relationship between each of the gait parameters and normalised walking speed is presented to relate the speed of walking to temporal distance, kinematic and kinetic gait parameters. The suitability of using linear regression analysis to predict gait parameters from speed is also explored. The hypothesis tested was that 'speed can be used to predict gait parameters'.

2. Methods

Gait analysis was performed on 16 children between the ages of 7 and 12 years (eight boys and eight girls) each year for 5 consecutive years [1,2]. Children walked barefoot at

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self-selected normal velocities. Ground reaction forces (Kistler Instruments, AG Winterthur, Switzerland) and motion analysis data (five camera stystem—Vicon, Oxford Metrics Group, Oxford, UK) were collected at 50 Hz for approximately three sets of data for each leg for each child for each of the 5 consecutive years of the study (a total of 457 trials). Joint angles, moments and powers were calculated using Vicon Clinical Manager (Vicon, Oxford Metrics Group, Oxford, UK) and have been described previously [2].

Weight, height and leg length (greater trochanter to lateral malleolus) data were recorded.

2.1. Normalisation of gait data

Data was normalised to dimensionless quantities using the following formulae from Hof [17]:

$$\text{normalised time} = \text{time} \times \frac{1}{\sqrt{(H/g)}}$$

$$\text{normalised length} = \text{length} \times \frac{1}{H}$$

$$\text{normalised weight} = \text{weight} \times \frac{1}{M \times g}$$

This normalisation resulted in the following non-dimensional variables:

$$\text{normalised speed} = \text{speed} \times \frac{1}{\sqrt{(H \times g)}}$$

$$\text{normalised step length} = \text{step length} \times \frac{1}{H}$$

$$\text{normalised cadence} = \text{cadence} \times \sqrt{\frac{H}{g}}$$

$$\text{normalised force} = \text{force} \times \frac{1}{M \times g}$$

$$\text{normalised moment} = \text{moment} \times \frac{1}{M \times g \times H}$$

$$\text{normalised power} = \text{power} \times \frac{1}{M \times g^{3/2} \times H^{1/2}}$$

speed (m/s); step length (m); cadence (steps/s); force (N); moment (N m), power (W); H, height (m); M, mass (kg); g, acceleration due to gravity 9.81 m/s^2.

2.2. Regression analysis

The data from this study demonstrated trends with changes in normalised speed. To present a quantification of these trends, specified peak and trough values of each parameter were calculated and linear regression analyses performed on these data. All the children's data from all 5 years were used to calculate a linear regression line for each of the 40 parameters against normalised speed. The significance of the gradient (m) and intercept (c) of the line were tested for difference from zero. Forty tests were performed and a Bonferroni correction was applied as multiple tests were made. A significance level of $p < 0.05$ was set with the Bonferroni correction incorporated. To illustrate the reasonableness of fit, standard error values and R^2 values were calculated. A significant result for the gradient and intercept values implied that the values of these parameters were significantly different from zero.

Statistical analysis was performed using SPSS (SPSS Inc., Chicago, USA).

3. Results

All children's data from all 5 years of the study and all trials within these years have been included in this analysis. The average age of the children was 9.55 years (S.D. ± 1.41 years), with a height of 1.38 m (S.D. ± 0.11 m), leg length of 0.66 m (S.D. ± 0.06 m) and mass of 32.64 kg (S.D. ± 8.07 kg). The speed of the children spread across a normalised range of 0.20–0.45. Only seven trials were performed in the 0.20–0.25 band. There were 70 trials from 0.25 to 0.30, 208 trials from 0.30 to 0.35, 142 trials from 0.35 to 0.40 and 30 trials in the normalised speed band 0.40–0.45. The children walked at their self-selected speed at all times.

Average curves for ground reaction forces (Fig. 1A and B), joint kinematics (Fig. 1C–F), joint moments (Fig. 1G and I) and joint powers (Fig. 1J–L) are presented. These were used to identify characteristic peak and trough values. FZ1 and FZ2 were defined as peak values for the vertical component of ground reaction forces and FZ0 as the trough value in mid stance. FX1 was defined as the largest posteriorly directed force and FX2 as the largest anteriorly directed force.

Specific features of the joint angles, moments and powers as well as the results of the regression analysis are presented in Table 1. Table 1 shows gradient (m) and intercept (c) for the best-fit linear regression line relating the relevant parameter to normalised speed. The standard error and R^2 values are given. Fig. 2 presents selected normalised parameters from all trials against normalised speed with superimposed best-fit linear regression lines. These figures provide typical examples of the distribution of points about the best-fit lines.

Visual examination of the distribution of results provided information on the suitability of the choice of linear regression lines for best-fit purposes. None of the plots provided evidence to suggest that any other form of line was more suitable than a linear fit. A number of parameters demonstrated either an increase or decrease with increasing normalised speed. Upon testing of the best-fit regression line a linear fit line with a gradient significantly different from zero existed for all measured parameters except age, leg length/height, FZ2, maximum hip extension (0–100%), maximum knee extension (20–60%), maximum knee flexion (50–100%), minimum dorsiflexion (50–80%), maximum

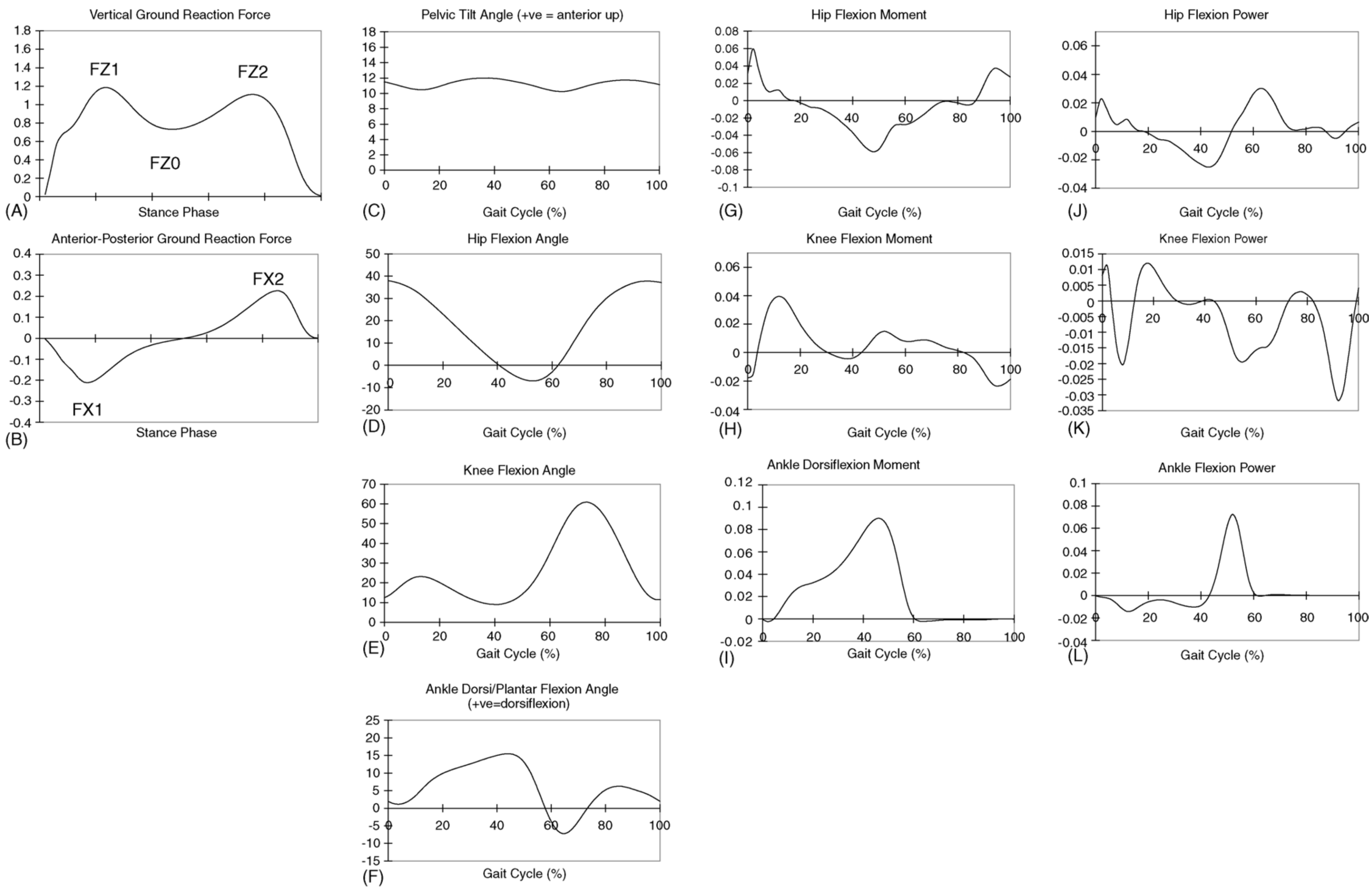

Fig. 1. (A–L) Average traces of gait characteristics based on all data from all children over all years of the study. (A) vertical ground reaction force (N/body weight) for the stance phase of gait, (B) anterior–posterior ground reaction force (N/body weight) for the stance phase of gait (positive, anteriorly directed on the foot), (C) pelvic tilt angle (positive, anterior, up), (D) hip flexion angle, (E) knee flexion angle, (F) ankle dorsi/plantar flexion angle (positive, dorsiflexion), (G) hip flexion moment, (H) knee flexion moment, (I) ankle dorsiflexion moment, (J) hip flexion power, (K) knee flexion power, (L) ankle flexion power. Joint moments (N m/(mass × g × height)) and powers (Watts/(mass × $g^{3/2}$ × height$^{1/2}$)) are presented over the gait cycle from heel strike to next heel strike.

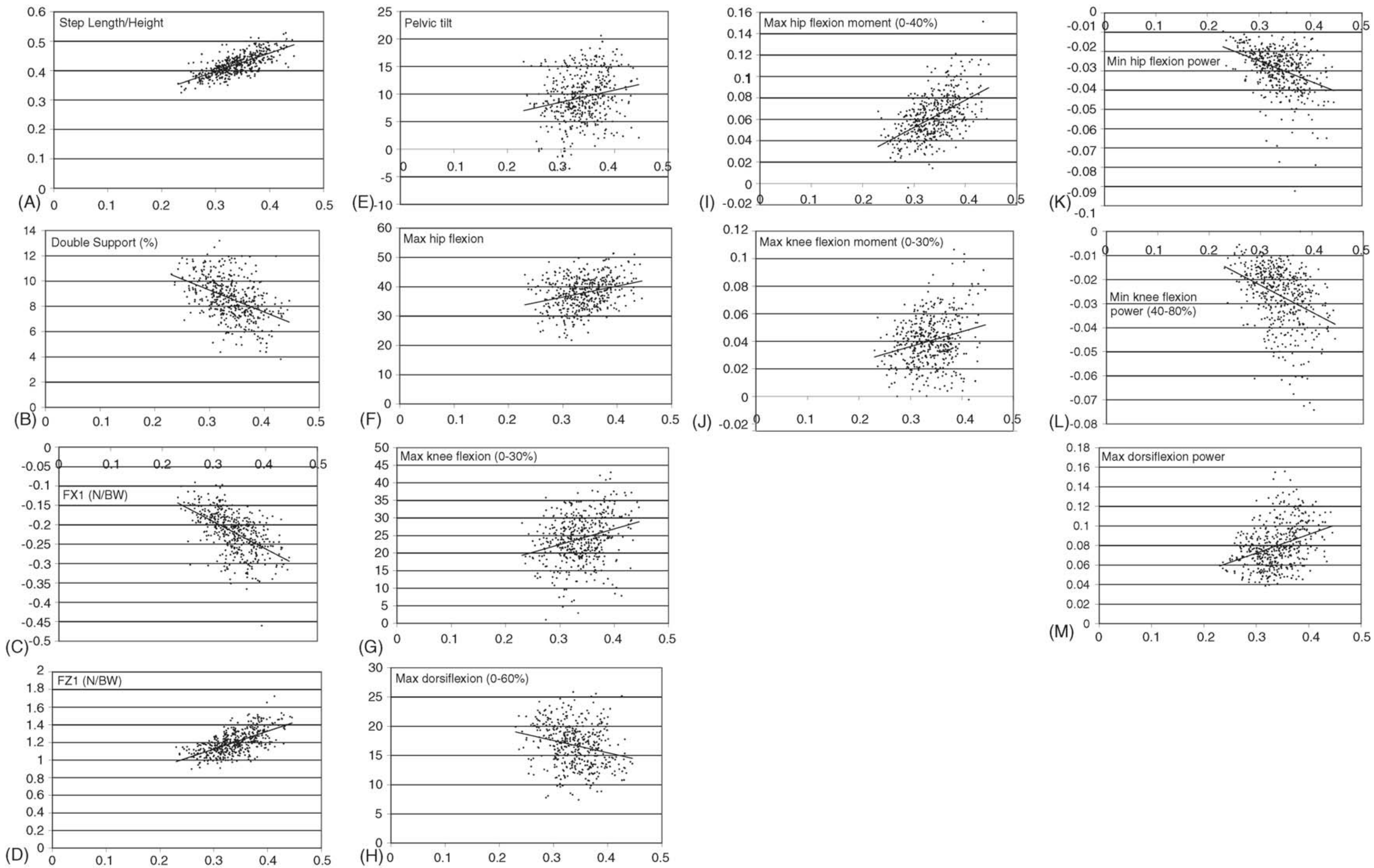

Fig. 2. (A–M) Scatter plots of subject characteristics, temporal distance parameters and joint kinetics and kinematics for all results from all children from all years against normalised speed (m/s $\times$ (1/(height $\times$ g)$^{1/2}$). Best-fit linear regression lines are superimposed on the data. (A) step length/height, (B) double support (% gait cycle), (C) FX1 (N/body weight), (D) FZ1 (N/body weight), (E) pelvic tilt (degrees), (F) maximum hip flexion angle (0–100% of the gait cycle), (G) maximum knee flexion angle (0–30% of the gait cycle), (H) maximum dorsiflexion angle (0–60% of the gait cycle), (I) maximum hip flexion moment (0–40% of the gait cycle), (J) maximum knee flexion moment (0–30% of the gait cycle), (K) minimum hip flexion power (0–100% of the gait cycle), (L) minimum knee flexion power (40–80% of the gait cycle), (M) maximum dorsiflexion power (0–100% of the gait cycle). Joint moments (N m/(mass $\times$ g $\times$ height)) and powers (Watts/(mass $\times$ $g^{3/2}$ $\times$ height$^{1/2}$)) are presented over the gait cycle from heel strike to next heel strike.

Table 1
Linear regression analysis on results for all trials of all children from all years

	$y = mx$ (normalised speed) + c				
	m	S.E.	c	S.E.	R^2
Subject parameters					
Age (years)	−1.8448	1.596	10.178*	0.544	0.003
Height (m)	−0.5563*	0.118	1.5719*	0.040	0.046
Leg length (m)	−0.309*	0.065	0.768*	0.022	0.047
Weight (N)	−361.5*	87.850	442.46*	29.930	0.036
Step length/height (statures)	0.6245*	0.028	0.2098*	0.009	0.529
Cadence × sqrt (height/g)	1.2009*	0.053	0.3967*	0.018	0.531
Leg length/height	−0.0295	0.010	0.489*	0.004	0.018
Double support as % cycle	−17.412*	1.609	14.501*	0.548	0.205
Single support as % cycle time	17.412*	1.609	35.499*	0.548	0.205
Ground reaction forces (N/BW)					
Fx1	−0.6982*	0.500	0.0171	0.017	0.303
Fx2	0.689*	0.350	0.0011	0.012	0.458
Fz1	2.0322*	0.117	0.5139*	0.040	0.397
Fz0	−1.529*	0.710	1.239*	0.024	0.504
Fz2	0.2149	0.930	1.0557*	0.032	0.012
Sagittal plane joint angles (degrees)					
Average pelvic tilt (0–100%)	21.872*	4.806	1.9649	1.637	0.044
Maximum hip extension (0–100%)	−8.0536	6.467	−6.5754	2.203	0.003
Maximum hip flexion (0–100%)	37.614*	5.768	25.184*	1.965	0.086
Maximum knee flexion (0–30%)	44.424*	7.192	9.1163*	2.450	0.077
Maximum knee extension (20–60%)	−10.459	5.960	11.907*	2.031	0.007
Maximum knee flexion (50–100%)	24.255	6.986	54.234*	2.380	0.026
Maximum dorsiflexion (0–60%)	−20.953*	3.896	23.836*	1.327	0.060
Minimum dorsiflexion (50–80%)	−17.681	7.268	−2.2893	2.476	0.013
Maximum dorsiflexion (60–100%)	−4.0448	3.842	8.4859*	1.309	0.002
Sagittal plane joint moments (dimensionless)					
Maximum hip flexion moment (0–40%)	0.2555*	0.019	−0.0243*	0.007	0.281
Maximum hip flexion moment (70–100%)	0.116*	0.012	0.0029	0.004	0.175
Minimum hip flexion moment (0–100%)	−0.1039*	0.016	−0.0273*	0.005	0.084
Maximum knee flexion moment (0–30%)	0.1081*	0.019	0.0037	0.007	0.064
Maximum knee flexion moment (40–60%)	0.0431*	0.011	0.0033	0.004	0.035
Minimum knee flexion moment (30–50%)	−0.049*	0.013	0.0093	0.004	0.030
Maximum dorsiflexion moment (0–100%)	0.0106	0.015	0.0873*	0.005	0.001
Sagittal plane joint powers (dimensionless)					
Maximum hip flexion power (0–30%)	0.1773*	0.015	−0.0322*	0.005	0.241
Maximum hip flexion power (50–80%)	0.1621*	0.012	−0.0197*	0.004	0.293
Minimum hip flexion power (0–100%)	−0.1054*	0.011	0.0067	0.004	0.161
Maximum knee flexion power (10–30%)	0.0713*	0.010	−0.0102	0.003	0.106
Minimum knee flexion power (0–20%)	−0.158*	0.016	0.032	0.005	0.179
Minimum knee flexion power (40–80%)	−0.1116*	0.013	0.0111	0.004	0.144
Minimum knee flexion power (80–100%)	−0.1272*	0.011	0.0069	0.004	0.220
Maximum dorsiflexion power (0–100%)	0.1904*	0.023	0.015	0.008	0.128
Minimum dorsiflexion power (0–25%)	−0.1127*	0.012	0.0219*	0.004	0.159
Maximum dorsiflexion power (25–50%)	0.0656*	0.013	−0.0389*	0.004	0.057

Ground reaction forces are defined at specific maximum magnitude points (see Fig. 1A and B). Angles, moments and powers are either defined for a specific period of the gait cycle (e.g. 0–30% means between 0 and 30% of the gait cycle from initial foot contact) or for maximum or minimum points over the whole gait cycle (0–100%). Fig. 1C–L provide a visual illustration of these points. Regression lines of the form $y = m \times$ (normalised speed) + c with standard error of coefficients are given.

* $p < 5.05$.

dorsiflexion (60–100%) and maximum dorsiflexion moment (0–100%).

Variables with best-fit lines with gradients significantly different from zero are listed in Table 1. Several of the best-fit lines had intercepts ('c' in Table 1) significantly different from zero.

4. Discussion

Two previous studies [1,2] have demonstrated that changes in gait parameters in children's gait between the ages of 7 and 12 years when non-dimensional normalisation techniques were used for analysis were predominantly determined by speed of progression and not age. It was therefore considered reasonable to combine all of the children's data for the regression analysis in the present study. The non-significant relationship of age with normalised speed confirmed the appropriateness of using all data from all children from all years together in the analysis.

By including all of the walking trials in the analysis, no averaging effect was imposed on the results. The treatment of all trials as examples of children's walking ensured a broader range of speeds and parameters to be analysed. All trials with complete data were included in the analysis. The number of children taking part in this study was limited by practical considerations. Only children who returned for 5 consecutive years of gait analysis were included in this study.

The data presented only relates to the self-selected speed range of the children taking part in this study. It is possible that had the children walked at prescribed speeds other than their preferred walking speed, the relationships between the measured parameters and speed would have been different. The self-selected speeds used by the children did not cover the entire range of speeds seen in neuromuscular disorders where a large proportion of subjects would walk at reduced speeds [3]. It is possible that the relationship between the parameters studied and normalised speed would follow a different pattern over an extended range of speed conditions. Other authors have advocated the use of more complex relationships, although they have not used normalised parameters in their analyses. For example Lelas et al. [16] used linear, square or cubic relations with speed in an adult population. For the self-selected speeds chosen in the present study it was not possible to justify using a more complex form of analysis.

The relationship between leg length/height and normalised speed demonstrated a non-significant gradient. By using height in the normalisation rather than leg length, the results of the study may, however, have been biased although the effect on the results would have been minor compared to the differences of using normalised as compared to non-normalised analysis [18].

Ground reaction force relationships with speed have been documented by a number of authors [1,3,9,10]. The results of this study demonstrate that there were clear relationships for FX1, FX2, FZ1 and FZ0, but not FZ2. This may suggest that the second peak of vertical ground reaction force is more directly associated with the body's control of stability than with the maintenance of speed.

The significance of changes with normalised speed for joint angles, moments and powers have been demonstrated previously for these data [2], but not quantified. The previous analysis [2] of these data was grouped into speed bands. The results of the previous analysis and those from the present regression analysis on all data provide identical evidence of significant trends with normalised speed apart from maximum knee extension (20–60%). Stansfield et al. [2] demonstrated a significant decrease in maximum knee extension angle (20–60%), which was not demonstrated in this study. The differences in significance of trends highlight the need to be aware of the effect of different analysis techniques on results.

The data shown in Fig. 2 demonstrate a wide spread about the best-fit linear regression lines. This indicates that it would be difficult to use the calculated regression lines to predict gait parameters for an individual moving at a given normalised speed. Therefore, the quoted best-fit lines can only be used as indications of the trends in the parameters and not to predict precise values. This study does not provide evidence to suggest that these trends can be extrapolated outside the range of self-selected speeds exhibited by these children. Indeed, observations over an extended range of speed may indicate that the data presented here are part of a more generalised non-linear trend. Therefore, we do not recommend that these linear regression fit lines be used to predict gait parameters for children walking at self-selected speeds outside the non-dimensional speed bands presented in this study.

5. Conclusion

Linear regression analysis of the relationships between speed of walking and related kinetic and kinematic parameters has been presented. Significant trends in gait parameters with normalised speed have been quantified.

These linear relationships can be used to estimate gait parameters from speed measurements for normal subjects. However, caution is advised in using the data to attempt to predict an individual's gait parameters due to the wide spread of data about the regression lines and we do not recommend that the data be used to extrapolate the regression data to wider speed ranges.

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