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Short communication

A 3D mathematical model to predict spinal joint forces for a child with spina bifida

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ABSTRACT

Children with spina bifida (SB) can exhibit excessive arm swing, trunk sway, and pelvic tilt during walking. To understand the relationship between abnormal low back forces (LBF) and gait disorders in SB, we derived a mathematical model for evaluating LBF in this population. One unimpaired child and a child with SB were tested. A 3D motion analysis system and force plate were used to collect kinematic and ground reaction force data during walking. A mathematical model created using MATLAB software was used to calculate LBF for each child. The LBF for the child with SB was three times greater in the medio-lateral direction than for the unimpaired child. In the anterior–posterior direction, the LBF for the child with SB acted mostly towards the anterior trunk. In addition, the LBF of the child with SB increased by 24.5% of body weight at the fastest walking speed.

1. Introduction

Spina bifida (SB) is a common congenital condition and children with SB often have abnormal gait patterns due to the neurological deficit [1]. Fabry et al. [2] used motion analysis to measure joint kinematics in SB, including pelvic tilt, knee flexion/extension, and foot dorsi-flexion/plantar-flexion. They also quantified joint kinetics, including hip, knee, and ankle moments. 78% of patients with low lumbar-level myelomeningocele and 98% of patients with sacral-level myelomeningocele retained the ability to walk independently into adulthood.

Moore et al. [3] examined oxygen consumption in children with SB. Extensive weakness of the plantar-flexors in those who walked slowly was associated with altered kinematics in the trunk, pelvis, hip, and knee in all planes [4]. SB was also associated with increased motion of the centre of mass in the anterior direction [5] and increased knee extensor loading [6]. Abnormal motion patterns of the upper body were associated with the degree of muscle weakness in the lower limbs [7].

To reduce abnormal gait patterns in children with SB, dynamic assistive devices such as a carbon-fibre spring ankle-foot orthoses have been developed. These may increase energy return and simulate a more natural push-off action [8]. Despite studies reporting alterations in kinetics and kinematics and exploring new ankle-foot orthoses, little effort has been directed towards evaluating abnormalities in low back force (LBF) in children with SB. It is known that variations in LBF in children with SB are associated with lower back pain and irregular walking patterns [9]. The current study hypothesised that abnormal gait is associated with greater LBF in children with SB. To quantify LBF, a new mathematical model was needed since this force is difficult to measure in vivo. The main aims of this study were to develop a 3D mathematical model to calculate LBF and to apply the model to compare LBF in unimpaired children and those with SB.

2. Materials and methods

2.1. Subjects

Since a lot of computation was required to accurately validate the model, two subjects were recruited to undergo LBF analysis. One unimpaired child (male; 10 years old; 38 kg; 136 cm) and one child with SB (male; 10 years old; 28 kg; 124 cm) volunteered to participate. The lesion for the child with SB was located at the level of the L4 vertebral body. Gross function around the joint was assessed by standard manual muscle testing [10] and was characterised as grade 3–4 hip abduction and hip extension, grade 4 knee flexion, grade 0–2 dorsi-flexion, and grade 0 plantar-flexion. Two subjects provided written informed consent prior to participation in the study, which was approved by the Institutional Review Board of the Taipei Veterans General Hospital (#IRB970172A).

2.2. Motion analysis

Walking tasks were performed on a 5-m-long level walkway for both participants. The child with SB was tested in their own habitually worn shoes and separately with an ankle-foot orthosis, while the unimpaired child was only tested in their own shoes. Both participants walked at their preferred, self-selected

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speed for five trials for each condition. The walking speeds of the unimpaired child and the child with SB were 107 cm/s and 45 cm/s, respectively. To investigate the effects of different walking speeds on the LBF of the child with SB, this participant was also asked to walk at a faster speed, which 72 cm/s.

A mathematical model consisting of 15 segments and 20 nodal joints was developed to predict spinal joint force in SB (Fig. 1). This assumed that the body is composed of rigid links joined at articulation points. MATLAB software (Math Works Inc., MA, USA) was used to calculate the L5/S1 joint force. A total of 31 markers were attached to each participant to define the joint centre for each segment. Two multi-segment models were defined: the lower model, which included the feet, shanks, thighs, and pelvis, and the upper model, which included the hands, forearms, arms, head, and trunk. The lower model was used to calculate LBF on the L5/S1 joint from ground reaction forces, and the upper model was used to calculate LBF on the L5/S1 joint from hand joint forces.

The anthropometric data included the percentage distribution of total body weight (BW) and each the centre of mass for each segment. This followed the model used in Jensen's study [11], as shown in Fig. 1. A Vicon 370 motion analysis system (Oxford Metrics Ltd., UK) with six cameras was used to collect the 3D positions of the anatomical markers at a sampling frequency of 60 Hz. The ground reaction forces for each participant were measured using two force platforms (Bertec Co., OH, USA).

A Newtonian equation was used to estimate the L5/S1 joint resultant intersegmental forces:

$$\vec{F}_{L5/S1} = -\sum_{r=1}^{n}\vec{F}_r - \sum_{i=1}^{k} m_i\vec{g} + \sum_{i=1}^{k} m_i\vec{a}_i$$

$\vec{F}_{L5/S1}$: resultant force of the joint L_5/S_1; $\vec{F}_r$: external force; m_i: mass of segment i; $\vec{a}_i$: acceleration of centre of mass; $\vec{g}_i$: acceleration of gravity.

The resultant forces were estimated using the weight of the body segment and the external load values. A global coordinate system with the x-axis in the medio-lateral (ML) plane, the y-axis in the anterior–posterior (AP) plane, and the z-axis pointing upward was chosen [12].

To validate the mathematical model, the LBF values calculated for the upper and lower models were compared using the correlation coefficient (CC) r and the root mean square (RMS). Descriptions of the CC and RMS are given below:

$$r = \frac{\sum(U_i - \bar{U})(L_i - \bar{L})}{\sqrt{\sum(U_i - \bar{U})^2}\sqrt{\sum(L_i - \bar{L})^2}}$$

$$\text{R.M.S.} = \frac{\sum\sqrt{(U_i - L_i)^2}}{t}$$

Ui: force of upper model in each frame; $\bar{U}$: mean force of upper model; Li: force of lower model in each frame; $\bar{L}$: mean force of lower model; t: total number of frames.

The criterion for model validation was defined such that the CC had to be greater than 0.95 and the R.M.S. had to be less than 0.5 N.

3. Results

The CC for the unimpaired child and the child with SB ranged from 0.95 to 0.99, while the RMS value ranged from 0.016 to 0.036 N, as indicated in Table 1. The LBF estimated for the upper model was consistent with the lower model in the vertical, ML, and AP directions.

Table 1
Mathematical model validation using the correlation coefficient (CC) and root mean square (RMS).

		CC (Unitless)	R.M.S. (Newtons)
Unimpaired child	X	0.95	0.024
	Y	0.98	0.016
	Z	0.99	0.036
Child with SB	X	0.99	0.018
	Y	0.99	0.020
	Z	0.99	0.028

In the ML direction, the LBF for the child with SB was approximately three times greater than for the unimpaired child (Fig. 2A) and demonstrated an oscillating pattern ranging from −0.3 to 0.28 times BW. The unimpaired child's LBF ranged from −0.1 to 0.09 times BW. In the AP direction, the LBF for the child with SB ranged from 0.073 to 0.205 times BW and mainly acted in the anterior direction. However, the unimpaired child's LBF exhibited reciprocal oscillation in the AP direction that ranged from 0.05 to −0.157 times BW (Fig. 2B). In the vertical direction, the LBF of the unimpaired child was slightly greater than that of the child with SB and oscillated more markedly, as shown in Fig. 2C. In the ML direction, the LBF for the child with SB only varied slightly between the preferred and the fast speeds (Fig. 2A). In the AP and vertical directions, the maximum LBF increased by 24% of BW when the walking pace was increased from preferred speed to fast walking.

4. Discussion

For the gait cycle ranging from 10 to 30% and again from 70 to 90%, LBF in the ML direction was found to be higher in the child with SB than an unimpaired child. In general, the unimpaired child's LBF remained consistent during walking and differed from the child with SB. The child with SB swung both hands and tilted the shoulders to increase inertial force while walking forward, causing greater movement of the trunk in the ML direction. This induced an increase in LBF in the ML direction. The child's LBF was

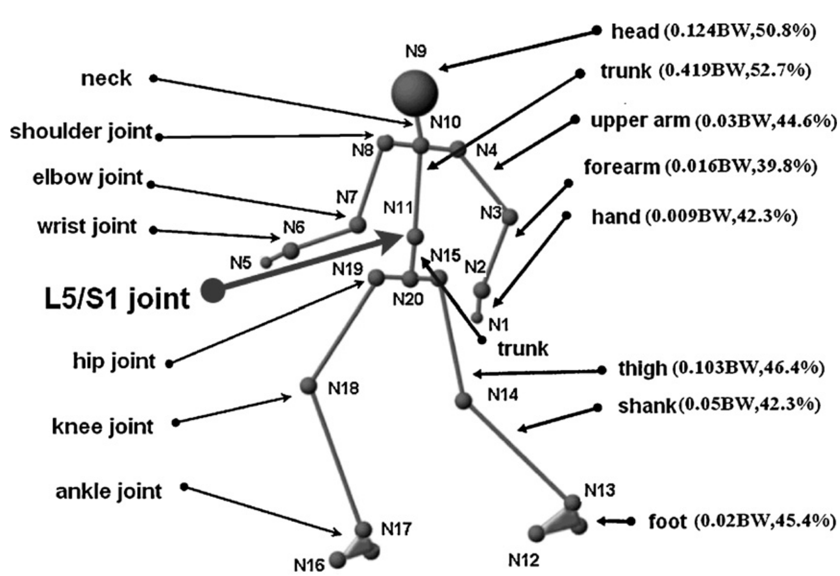

Fig. 1. A mathematical model comprised of 14 joints and 15 segments using 20 nodal joints from N1 to N20. A total of 31 markers were attached to the child with SB. The parentheses indicate the ratio of body weight (BW) and location of centre of mass proximal to the joint in each segment.

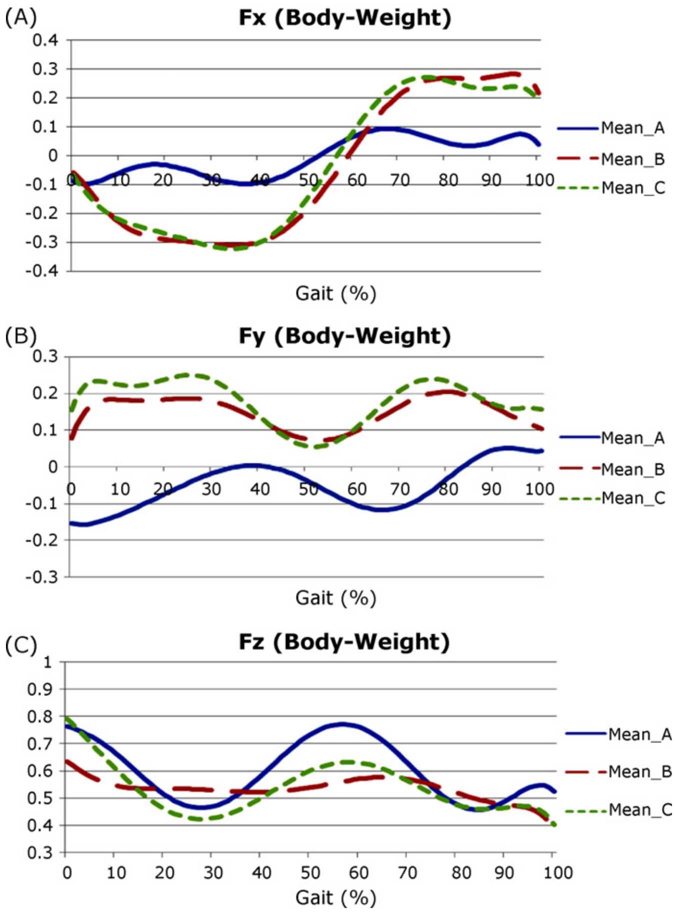

Fig. 2. Comparison of LBF calculation for the unimpaired child and the child with SB. (A) ML direction, (B) AP direction and (C) vertical direction (unit: body weight). Note: Mean_A represents the mean LBF of the unimpaired child at a preferred speed; Mean_B represents the mean LBF of the child with SB at a preferred speed; Mean_C represents the mean LBF of the child with SB at a fast speed.

not strongly influenced by different walking speeds since increasing trunk swing does not increase forward propulsion.

In the AP direction, LBF for the child with SB was directed forwards, apparently due to weakness of the lower extremities. The unimpaired child's LBF generally acted in the backward direction. The child with SB exhibited weakness in the dorsi- and plantar-flexors, which appeared to be related to greater movement of the trunk, pelvis, and shoulders in the frontal and transverse planes [7]. Moreover, the child's centre of gravity was positioned more in the posterior direction than usual, apparently due to compensatory trunk extension for increasing forward propulsion. As a result, the maximum LBF of the child with SB was about 25% greater when walking at lower speeds.

Concerning validation of this mathematical model using the upper and lower models, the CC ranged from 0.95 to 0.99 which was consistent with a previous report [12]. A limitation of this study was that each segment in the mathematical model was simulated using a rigid body. In addition, anthropometric data were adopted from studies of Western children. Although the mathematical model was successfully validated, further studies of a larger sample of children with SB with varying muscle strengths should be conducted.

5. Conclusion

This study successfully generated a 3D mathematical model for evaluating LBF in a child with SB. LBF in the child with SB was three times greater in the ML direction than for an unimpaired child. In the AP direction, the LBF of the child with SB mainly acted towards the anterior trunk. Additionally, at the fast walking speed, the LBF of the child with SB increased by 24% BW, accentuating the gait disorder.

Conflict of interest

Originality: Each author warrants that the work is original. *Financial disclosure*: Each author warrants that they have no commercial associations (e.g., consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.). No funds were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

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