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TECHNICAL NOTE

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Assessment of ground reaction force during scoliotic gait

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Abstract Although the causes and progression of adolescent idiopathic scoliosis (AIS) are still unclear, a recent extensive review has indicated a number of possible aetiological factors. Previous investigations, employing gait measurements, have indicated asymmetries in the ground reaction forces and suggest a relationship between these asymmetries, neurological dysfunction and spinal deformity. Using a strain-gauge force platform, the present study has examined the time-domain parameters of various components of the ground reaction force together with impulse. Symmetry indices (SI) between left and right sides have also been estimated. The results show that the patients with a left compensatory curve had a greater SI for a left-side impulse, whilst subjects with little or no compensation had a greater right-side impulse. This indicates that a possible gait compensation is occurring, so that the subjects compensate on the opposite pelvis/lower limb to that of the curve. While indicating the asymmetries between left and right, the results also serve to highlight the value of using kinetic parameters in developing the understanding of the pathogenesis and aetiology of scoliosis.

Keywords Ground reaction force · Impulse · Scoliosis · Spine

Introduction

Adolescent idiopathic scoliosis (AIS) frequently develops during the period of rapid growth, and the resulting deformity involves both translational and angular asymmetry of the vertebrae of the rib cage and back surface [18]. Scoliosis also affects the physical orientation of various body segments. Although the causes and progression of AIS are still not understood, recent reports have indicated a number of possible aetiological factors [3]. Most previous investigations involving movement analysis in scoliosis concentrated mainly on kinematic measurements. However, it would be useful to couple the movement data with force platform data. This is because scoliosis is a structural deformity affecting the normally symmetrical vertebral column, resulting in an alteration of the centre of mass position and the weight distribution down the lower limb. Thus, the examination of kinematic data in combination with kinetic data could establish any relationship between these two components and, in turn, lead to a better understanding of the aetiology of scoliosis.

Previous studies have indicated that ground reaction force (GRF) data has a role in indicating the developing gait patterns in growing children and additionally will highlight any gait abnormalities [1]. Other studies examining the harmonic analysis of ground-reaction-force measurement have indicated significant differences between scoliotic and healthy children [6]. The difference found was predominantly in the mediolateral direction and suggests that gait instability might affect the spine. Time and frequency domain analysis of ground reaction forces have also been found to be useful in the investigation of gait asymmetry [5]. However, in contrast, studies by Schizas [16] on the ground reaction forces indicated no relationship between gait asymmetry and a scoliotic curve. Schizas et al. did suggest an in-depth investigation of gait by combining kinematics and kinetics in order to understand the neurological dysfunction in scoliosis. Although not applied to scoliotic subjects, other research, studying the effects of backpack loads on peak forces in the lumbosacral spine during walking, has employed a combination of kinematics and kinetics [7].

The influence of an eccentric gravitational force on the spine with lateral deviation and the relationship between the axial rotation and gravitational force in the scoliotic spine has been reported [14]. Study of the symmetry of vertebral-body loading using biomechanical models indicates that spinal deformity progression is primarily biomechanical and is characterised by shear forces for asymmetric spinal loading and axial torque for rotational deformity [17]. Furthermore, a comprehensive review suggests that the lack of understanding in the pathomechanics of scoliosis progression deters the scientific treatment process [3].

Several reports have demonstrated that some selected measures derived from vertical ground reaction forces can be used as objective measures in assessing the pathomechanics of gait [15, 19]. Asymmetry of the loading rate was the most sensitive indicator of gait dysfunction [8]. Ground reaction force (GRF) is a direct representation of the acceleration of centre of mass (CoM) [12]. However, in clinical conditions that introduce physical deformity, CoM will be different from that of normal subjects. Consequently, the acceleration of CoM will be different, and this will be indicated by differences within the GRF.

It has been shown that, in normal subjects, asymmetries in the vertical ground-reaction forces, as well as the stance time, deviate by less than 4% [10]. This asymmetry (as indicated by symmetry index, SI) in the external kinetic parameters of the right and left legs can be identified using the formula:

$$SI = \frac{(X1 - X2)}{0.5 * (X1 + X2)} * 100 \qquad (1)$$

In clinical subjects, X1 is a measure on a normal limb, while X2 is that measure on the affected limb. In normal subjects the right and left legs are assigned randomly to be X1 and X2. A symmetry index of 0 indicates that the force parameter is equal on both legs.

One hypothesis of the causation of AIS suggests that the neuromuscular abnormalities may be secondary to the deformity [4]. If the central nervous system plays a significant role in the aetiology of AIS, any neurological dysfunction or the effects of the spinal deformity should be expressed in the patients' gait patterns. Previous studies have indicated this relationship [9, 13] and the present study has the objective of identifying asymmetries in kinetic gait parameters of patients with AIS. Results will serve to support or refute this hypothesis.

Methods

The present study has examined the time-domain parameters of various components of the ground reaction force, together with impulse, using a strain-gauge force platform sized 464×508 mm (Model OR 6–5, Advanced Mechanical Technology, MA, USA). The data was sampled at a rate of 1,000 Hz and appropriate associated software was used for data analysis. Sixteen scoliosis subjects took part in the study: 4 males and 12 females with an average age

Table 1 Subject information

Subject No.	Age at operation (years)	Cobb levels	Cobb angle/side (erect)	Compensatory curve	Aetiology
1	13	T4–T11	77 right	Yes: left lumbar	Idiopathic
2	14	T6–T12	75 right	Minimal: left lumbar	Idiopathic
3	13	T1–L3	52 left	No	Neurofibromatosis
4	11	T6–L1	52 right	Yes: left lumbar	Idiopathic
5	12	T6–T12	60 right	Yes: left lumbar	Idiopathic
6	13	T8–L1	85 left	Yes: right lumbar	Idiopathic
7	12	T5–T10	73 right	Minimal: left lumbar	Idiopathic
8	17	T6–L2	82 right	No	Idiopathic
9	16	T5–T11	57 right	Yes: left lumbar	Idiopathic
10	19	T4–T11	60 right	Minimal: left lumbar	Idiopathic
11	9	T4–T12	90 right	Yes: left lumbar	Early idiopathic
12	11	T11–L3	47 right	No	Idiopathic
13	15	C6–T6	44 right	Minimal: left thorocolumbar	Congenital
14	14	T6–T12	66 right	Yes: left lumbar	Idiopathic
15	17	T12–L4	81 left	No	Neurofibromatosis
16	14	T6–T12	85 right	Yes: left lumbar	Idiopathic

of 11 years (SD 2.82), weight of 46.27 kg (SD 7.28) and average height of 153.68 cm (SD 14.75). Demographic information on scoliotic subjects including the curve level, amplitude (average Cobb angle 68.37° (SD 14.53)) and the aetiology was recorded as given in Table 1.

Two subjects diagnosed as having neurofibromatosis and one subject classified as with congenital scoliosis was also included in the study. These subjects all presented with curve patterns similar to that of the idiopathic cases, and their inclusion in the survey was justified in order to examine whether they had any features of the condition that had biomechanical differences from the idiopathic group.

All subjects were assessed by an experienced clinician for anthropometric measurements, and the subjects had no known lower limb abnormalities, including leg-length discrepancies. Ground reaction-force measurements from the left and right foot were made from separate gait trials.

Each participant was then given time to become familiarised with the lab environment and was allowed a number of walking trials prior to data collection. Subjects performed three trials for each foot at the participant's normal walking speed. A valid trial consisted of the participant striking their heel on the force platform without altering their normal gait.

Following-force variables were measured from the vertical and the anteroposterior components of the ground reaction-force data. From the vertical component, first peak force (FZ1), second peak force (FZ2), loading rate (LR), unloading rate (UR) and impulse (IMP) were estimated (Fig. 1). From the anteroposterior component, positive peak (FY1), negative peak (FY2), negative impulse

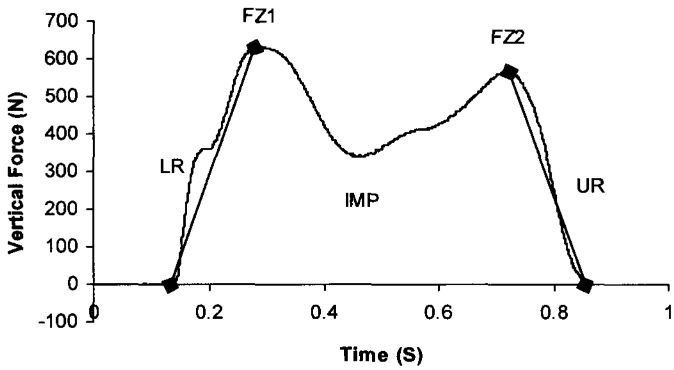

Fig. 1 Typical graph showing various parameters in the vertical ground reaction force (loading rate *LR* and unloading rate *UR* are estimated as the difference in force over difference in time; impulse *IMP* is the area under the force curve)

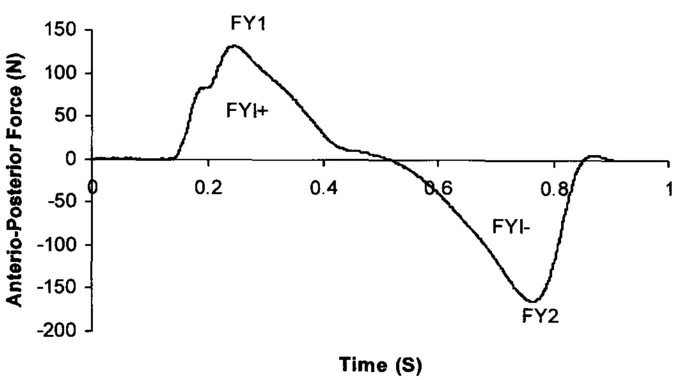

Fig. 2 Typical graph showing various parameters in the anteroposterior ground reaction force

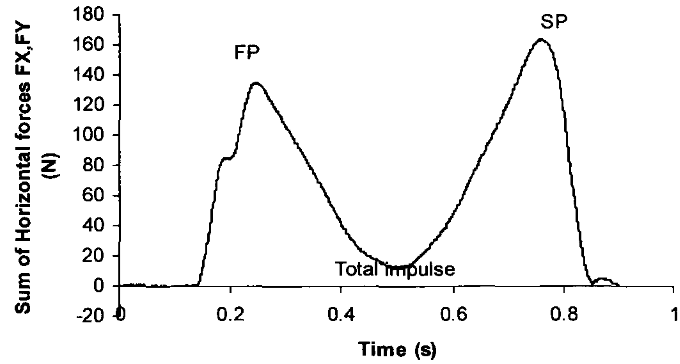

Fig. 3 Typical graph showing various parameters in the resultant horizontal ground reaction force

(FYI–) and positive impulse (FYI+) were recorded (Fig. 2). Symmetry indices (SI) between the left and right sides were calculated. The upper and lower limits of symmetry indices were estimated as reported in the literature [10].

$$SI_{UL} = 0 \pm t_{df(0.05)} * SD \quad (2)$$

Where $t_{df(0.05)}$ is the critical value of a t-distribution with df degrees of freedom, and a significance of 0.05. SD is the standard deviation of the symmetry indices for a given variable.

Although some studies have used a mediolateral component of the ground reaction force for analysis [4], it is also indicated that this force component is variable and has no consistent pattern from individual to individual [7]. Furthermore, the magnitude of this component is very small (ranges from 0.01 BW in walking to 0.1 BW in running). So to detect differences in shear forces, the sum of horizontal components (anteroposterior and mediolateral) was estimated. From this sum (Fig. 3), first peak (FP), second peak (SP) and the total impulse were estimated. Symmetry indices were classified into left dominant or right dominant for comparison with the major side of the scoliotic curve. Fisher's exact test was used to test whether there was a significant association between any gait asymmetry and left and right patterns of scoliotic curve.

Results

The average force values and average loading rates do not indicate a major difference between left and right sides. However, the symmetry index for loading and unloading

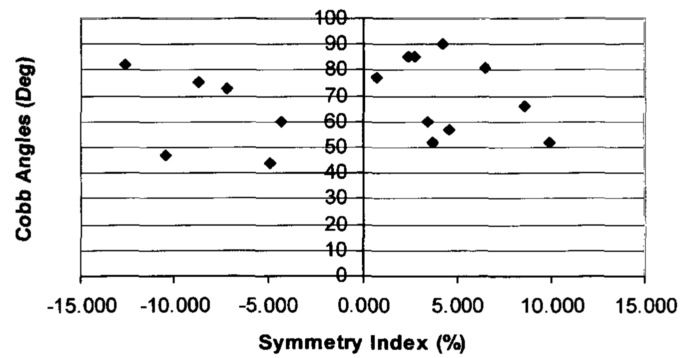

Fig. 4 Scatter plot between impulse symmetry indices *SI* and Cobb angles

rates differ for individual subjects. These values do not follow a specific pattern but do indicate some asymmetry. While the results indicate that the subjects with a left curve or a left compensation curve had a greater SI for left-side impulse and subjects with a right curve with very little or no compensation had a greater right-side impulse, the examination of a scatter plot (Fig. 4) indicates there is no specific relationship between the magnitude of the curve and SI for impulse.

Discussion

When considering the vertical component of the ground reaction force, differences in the symmetry indices within various reported parameters were noted between the groups. Although these symmetry indices did not exceed the range reported in previous studies [10], there is a marked difference between the left and right side impulses.

As indicated in the results, patients with a left curve or a left compensation curve had a greater SI for a left-side impulse and subjects with very little or no compensation had a greater right-side impulse. This is considered to be due to the compensation in gait, where the subjects compensate on the opposite pelvis/lower limb. Although a previous investigation has indicated that there is no difference in the peak force values in the time domain, the results represent differences in the frequency domain [6]. There are no results reported for impulse [5, 6, 10]. Since impulse is the rate of change of momentum and represented by the product of force and time, if either of the values is higher, the estimated impulse will be higher. Results indicate that the average peak force values are not that different between the left and right sides. This means that the subjects have a higher stance time on the side of the major curve in the lumbar or lower thoracic region. Fisher's exact test performed between the side of the curve and the side with higher impulse indicated a significant correlation. Although, for all other variables this kind of relationship is not evident, the loading and unloading rates also indicate asymmetries. These values are again time dependant.

Various time domain parameters in the anteroposterior force also have marked differences in SI. However these do not correlate to the patients' physiological curves. Similar results were observed for the total shear forces, which included anteroposterior and mediolateral forces.

One of the recent investigations [13] looking into the temporal parameters of gait in stroke patients showed asymmetries with swing-phase time. However, this investigation did not consider gait speed or the timing of various phases. From the descriptive statistics it appears that the standard deviations for the vertical force peaks and the peaks of sums of shear forces were small, indicating that the variability of the gait parameters was relatively low. The parameters showing highest deviation were the loading and unloading rates. Previous studies indicate higher symmetry for vertical forces and lower symmetry for mediolateral forces [10, 13].

Taking this into consideration, and since differences between left and right side impulses have been found, this method could be extended to detect the severity of the curve and gait compensation in scoliotic subjects. Furthermore, this relationship between the impulse and the side of the curvature is evident not only in idiopathic cases but in other aetiologies. However, one of the limitations of this study is that the reported data is not from successive steps, which might lead to variability, as indicated by Kim and Eng (2003).

Further studies are needed to investigate if the findings are due to the structural deformity or a consequence of the progression of the torsional deformity. Furthermore, previous studies on torsion in lower limb bones, indicate that the curve progression is determined by the eccentric loading created by the gravitational forces in the presence of muscle imbalance in the trunk [4]. This leads to the conclusion that scoliosis affects the gait pattern and, in turn, asymmetries, as indicated in the results of this study.

The total walking pattern itself may be influenced by mechanical factors, such as the presence of an asymmetrical rotation of the lumbar spine and trunk during ambulation. The magnitude of the asymmetry of loading of vertebrae in scoliosis has not been measured, since it depends on the magnitude of muscle forces. There is very little quantitative information about how scoliosis affects the loads acting on the spine and on the sensitivity of growth to asymmetric loading. The combination of knowledge on spinal loading asymmetry and on the sensitivity of spinal growth to load would allow quantification of how mechanical factors determine scoliosis progression during growth. It is already established that mechanical forces influence vertebral growth [18] and, hence, spinal shape, in a potentially vicious cycle.

The results of this study, therefore, indicate the presence of asymmetries in kinetic gait parameters amongst scoliotic subjects. In particular, this study has highlighted the relationship between the side of the scoliotic curve and impulse. The results also serve to highlight the value of using kinetic parameters in developing further understanding of the pathogenesis and aetiology of scoliosis and similar conditions.

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