Development and Evaluation of Synthetic Paediatric Mid-Thoracic Spine Model for Scoliosis Assessment

by

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LIST OF ABBREVIATIONS

ROM	Range of Motion
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Modelling
LF	Ligamentum Flavum
ISL	Interspinous Ligament
TL	Intertransverse Ligament
ALL	Anterior Longitudinal Ligament
PLL	Posterior Longitudinal Ligament
SSL	Supraspinous Ligament
CL	Capsulary Ligament
PVC	Polyvinyl Chloride
PU	Polyurethane
ASTM	American Standard for Testing & Materials
NZ	Neutral Zone
PZ	Plastic Zone
FSU	Functional Spinal unit
EZ	Elastic Zone
CT	Computed Tomography
DOF	Degree of Freedom
SEM	Scanning Electron Microscope
AID	Artificial Intervertebral Disc
SLS	Selective Laser Sintering
AD	Age Density

LIST OF SYMBOLS

C	Cervical spine region
T	Thoracic spine region
L	Lumbar spine region
S1	Slope 1
S2	Slope 2
L_L	Length of cell
N_L	Number of cell
ρ_c	Density of the composite
ρ_m	Density of the matrix
ρ_f	Density of the fibre
ρ_{c1}	Density of the fabricated composite

Pembangunan dan Penilaian Model Tulang Belakang Pertengahan Toraks Pediatrik Sintetik untuk Pentaksiran Skoliosis

ABSTRAK

Skoliosis adalah kelengkungan melintang tulang belakang yang tidak normal, walaupun semua peringkat usia boleh mengalami skoliosis, penyakit ini biasanya dihidapi oleh kanak-kanak. Sebilangan besar kajian yang mengkaji kes skoliosis menggunakan tulang belakang haiwan dan dewasa, yang sebenarnya tidak mewakili tulang belakang pediatrik kerana pediatrik bukan miniatur tulang belakang dewasa. Oleh itu, tujuan kajian ini adalah untuk membangunkan model tulang belakang pediatrik sintetik dan menilai tingkah laku mekanikal berbanding dengan tulang belakang dewasa dan haiwan. Bahagian tulang belakang yang dipilih untuk penyelidikan ini adalah kawasan pertengahan toraks dari T4-T8. Oleh kerana tulang belakang adalah struktur yang kompleks, proses fabrikasi model sintetik dipermudah dengan memfokuskan pada tiga komponen utama, iaitu vertebra, cakera intervertebral dan ligamen. Span PU yang boleh dikembangkan dipilih untuk menggantikan tulang trabekular. Manakala untuk cakera intervertebral bahan dipilih adalah silikon bagi menggantikan nukleus pulposus dan monothane® sebagai annulus fibrosus. Bahan komposit yang terdiri daripada pita serat dan silikon plastik digunakan untuk mewakili ligamen. Tulang belakang pediatrik sintetik dibuat dengan membesarkan saiz model tulang belakang pediatrik sebanyak 200%. Ujian biomekanik dilakukan untuk mengukur julat pergerakan dan ketidaklurusan lengkung sigmoidal pada enam darjah kebebasan dengan momen antara ± 1 hingga ± 4 Nm. Hasilnya dibandingkan dengan tulang belakang khinzir dan tulang belakang dewasa analog (Sawbones®). Perbezaan yang terdapat pada pergerakan melintang dan putaran paksi tulang belakang pediatrik sintetik berbanding khinzir adalah 18% dan 3% sementara pergerakan fleksi tegangan berbeza sebanyak 45% tetapi masih berada dalam julat. Lengkung sigmoidal serupa diperhatikan untuk keenam-enam darjah kebebasan jika dibandingkan dengan tulang belakang lumbar dewasa analog, di mana fleksi tegangan dan putaran paksi cenderung lebih lurus. Julat pergerakan pediatrik diukur menggunakan model unsur terhingga (FE) pediatrik yang disahkan pada momen ± 0.5 Nm (beban pediatrik) untuk menentukan momen yang diperlukan oleh tulang belakang pediatrik sintetik bagi mendapatkan julat pergerakan pediatrik. Hasil kajian menunjukkan bahawa dalam fleksi tegangan,julat pergerakan pediatrik mendekati momen ± 3 Nm, sementara pada pergerakan melintang dan putaran paksi, ROM pediatrik lebih dekat dengan momen ± 2 Nm. Pergerakan tulang belakang pediatrik sintetik didapati lebih lentur dalam fleksi tegangan dan lebih fleksibel dalam lenturan melintang berbanding dengan model FE pediatrik. Ini berkemungkinan disebabkan reka bentuk cakera intervertebral yang dipermudah dan ikatan yang lemah antara cakera dan tulang belakang. Walaupun begitu, model yang difabrikasi menunjukkan hasil yang positif dan menunjukkan bahawa tulang belakang pediatrik sintetik berpotensi untuk digunakan sebagai alternatif model tulang belakang pediatrik dan dalam jangka panjang dapat menggantikan tulang belakang haiwan dan dewasa untuk kajian patologi tulang belakang pediatrik seperti skoliosis.

Development and Evaluation of Synthetic Paediatric Mid-Thoracic Spine Model For Scoliosis Assessment

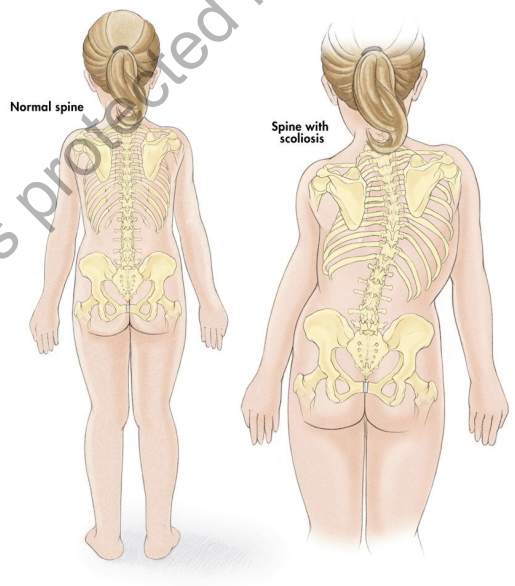
ABSTRACT

Scoliosis is a condition with abnormal spine lateral curvature that is affecting people of all ages but is the most common in children. Most of the studies that had investigated scoliosis-related subjects were using animal and adult spines; thus, in reality, they may not be representing the paediatric spine, as the paediatric spine is not the same and should not be treated as a miniature version of an adult spine. Therefore, the aim of this study is to develop a synthetic paediatric spine model and to evaluate the mechanical behaviour of the paediatric spine in comparison with adult and animal spines. The section of the spine selected for this research was the T4 to T8 mid-thoracic region. As the spine is such a complex structure, the fabrication process of the synthetic model was simplified by focusing on three main components; vertebra, intervertebral disc and spinal ligaments. The expandable PU foam was selected to replicate the trabecular bone. Meanwhile, the lightweight silicone materials were selected to model the intervertebral disc by replicating the nucleus pulposus, while the monothane® materials were used to model the annulus fibrosus. Additionally, the composite materials consisting of fibre tape and plastic silicone were used to represent the spinal ligaments. The synthetic paediatric spine was fabricated as a scaled-up model of the paediatric spine by 200%. Biomechanical tests were conducted to measure the range of motion (ROM) and non-linearity of the sigmoidal curves at six DOF, with moments ranging from between ±1 to ±4 Nm. The results were compared with the data reported on porcine spines (retrieved from prior literature) and an analogue adult lumbar spine (Sawbones®). The differences of 18% and 3%, respectively, were found in lateral bending and axial rotation of the synthetic paediatric spine, as compared to the porcine spine. Moreover, the flexion extension was observed to differ by 45%, but the ROM was still within the range. Similar sigmoidal curves were observed for all six DOF when compared to the analogue adult lumbar spine, where the flexion extension and axial rotation tended to be more linear. The paediatric ROM was measured using a validated paediatric FE model at ±0.5 Nm moment (i.e. paediatric loading) to determine the moment required by the synthetic paediatric spine to obtain the paediatric ROM. The results showed that in flexion extension, the paediatric ROM was closer to ±3 Nm moment, while in the lateral bending and axial rotation, the paediatric ROM was closer to ±2 Nm moment. The movements of the synthetic paediatric spine were found to be stiffer in the flexion extension but were more flexible in the lateral bending in comparison to the paediatric FE model. This was potentially due to the simplified design of the intervertebral disc, as well as the poor bonding between the disc and vertebrae. Despite that, the developed model showed promising results, hence suggested that the synthetic paediatric spine has the potential application as an alternative paediatric spine model. In the long term, this model could replace the animal and adult spines to investigate pathologies of the paediatric spine, such as scoliosis.

CHAPTER 1 : INTRODUCTION

1.1 Research Background

This present study is evolved from original research that measures spinal curvature, better known as scoliosis. Scoliosis can be characterised by a side-to-side deviation from the normal body axis and is caused by the lateral displacement of the spine (Ali Baaj, 2017), as illustrated in Figure 1.1. People of all ages can develop scoliosis, but this issue is more prevalent in children. Depending on the severity of curvature and the age of a person, scoliosis treatment is typically divided into three major phases, which are observation, bracing, and surgery for very severe cases.



(a) (b)

Figure 1.1 Illustration of spinal shape for (a) normal spine and (b) spine with scoliosis. (Erika, 2017)

In Malaysia, 55.8 % of students from a sample size of 9000 from the ages of between 13 to 15 years old were positively diagnosed to have suffered from scoliosis, based on a school screening programme conducted by Deepak et al. (2017), while around 2.6% of these students were severely affected, with the Cobb angle of more than 40 degree recorded. In Asian countries, adolescent idiopathic scoliosis had a prevalence of about 0.4% to 7% (Deepak et al., 2017; Du et al., 2016; Suh et al., 2011). These data revealed the common prevalence of scoliosis among children. Most importantly, surgical treatments that are costly and risky for a child's development are required to treat severe scoliosis cases.

The cost of spinal surgery treatments is very high and often prohibitive. The study by Yawn & Yawn (2000) calculated the estimated scoliosis surgical costs in the United States and revealed that an average cost of $120,000 was needed per operation, based on the data collected from approximately 20,000 Harrington rod implantation surgeries that were performed on the patients with scoliosis annually. Another issue is that approximately 8,000 peoples have been legally defined as permanently disabled for the rest of their lives after they had undergone scoliosis corrective surgeries in their youth.

1.2 Problem Statements and Research Motivation

Scoliosis surgical treatment is expensive and has a high failure risk during the surgery due to the usage of screws and rods. Although numerous studies (Janssen et al., 2011; Lavell et al., 2016; Nowak, 2019; Patel et al., 2011; Schwab et al., 2009) have been performed to investigate these associated problems of scoliosis surgical