ANALYSIS OF INTERFACE PRESSURE FOR DOUBLE CURVE IN IDIOPATHIC SCOLIOSIS PATIENT

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FACULTY OF ENGINEERING
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ABSTRACT

Scoliosis is a sideway curvature of the spine more than 10 degrees. Scoliosis is grouped into age groups where the children under the age of three, the disease is called "infantile scoliosis" and the ‘‘juvenile scoliosis’’ happen to children at the aged 3-10 years. “Idiopathic scoliosis" usually occurs in adolescent aged 10-15 years or who have not yet reached puberty. Scoliotic condition will get worse as the patient starts aging. This disease can be controlled if it can be detected early. However, if left untreated, the condition of the spine will get worse and will cause various health problems in the future including death. To date, the main cause of the disease is still unknown. However, there are several treatments available to control the progression.

The treatment of this disease is determined based on the degree of curvature of a patient. For curve angle between 10 to 25 degrees, the way of treatment is observation and appropriate exercises, while 20-45 degrees curve patients will be asked to use custom-made body braces. These special body braces are usually made up of plastic and need to be worn for more than 20 hours a day.Body brace has been proven to be effective in stopping the curve progression and delay the surgery. Chêneau brace is one of body brace types. Chêneau brace has proven its effectiveness in treating patients with idiopathic scoliosis for years. However, no studies have been reported on the analysis of interface pressure in patients with double curve idiopathic scoliosis.

This thesis focuses on measuring the interface pressure exerted by the Chêneau brace. A total of 72 (60 girls and 12 boys) patients aged 10 years and older participated in this study. Two sensors were placed on the inside of the brace wall so that it is in contact with patient’s body. The F-Socket Transducer (9811E) reading was used to assess the pressure on the right thoracolumbar and left thoracic curves between normal and maximum tension

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and the pressure variation of this interface with some basic daily activities. Each patient was asked to perform nine basic daily activities, and the interface pressure for each activity were recorded for normal and maximum tension.

The results showed that the mean peak pressure produced in adolescent idiopathic scoliosis curve was higher for right thoracic curve than left thoracolumbar curve in all tasks. Pressure increased significantly at the maximum inspiration task ($p < 0.0001$) for both indentation types for normal and maximum stresses. Patient were followed-up for six months and patients were asked to wear the brace in maximum tension at all times of possible. The levels of correction for thoracic and thoracolumbar indentations were 23.2% and 34.5%, respectively, after 6 months of brace use (23 hours per day). However, we could not find a large correlation between the mean peak pressure in the standing position and the degree of scoliosis correction for the two curves having values of $r = 0.158$, $p = 0.356$ and $r = -0.024$, $p = 0.889$.

Keywords: Adolescent idiopathic scoliosis, Chêneau brace, interface pressure, F-Socket

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ABSTRAK

Skoliosis adalah keadaan di mana tulang belakang membengkok lebih dari 10 darjah. Skoliosis dibahagikan kepada bahagian umur dimana kanak-kanak yang berumur bawah tiga tahun, penyakit ini digelar ‘’infantile scoliosis’’ manakala ’Juvenile scoliosis’ berlaku pada kanak-kanak yang berumur dalam lingkungan 3-10 tahun. ‘’Adolescent Idiopathic scoliosis’’ adalah kategori yang paling kerap ditemui dan kebiasaannya terjadi kepada remaja perempuan yang berumur 10-15 tahun yang masih belum mencapai akil baligh. Penyakit skoliosis ini akan dapat dikawal jika dapat dikenalpasti dari awal. Sebaliknya, jika dibiarkan tanpa rawatan, keadaan tulang belakang akan terus membengkok dan akan menyebabkan pelbagai masalah kesihatan lain di masa akan datang. Sehingga kini, penyebab utama penyakit ini masih belum diketahui.Walaubagaimanapun, terdapat beberapa rawatan untuk mengekang penyakit ini daripada berlarutan.

Rawatan penyakit ini ditentukan berdasarkan darjah kebengkokan badan seseorang. Untuk bengkok di antara 10 hingga 20 darjah cara rawatannya adalah melalui senaman yang bersesuaian. Manakala untuk 20-45 darjah pesakit akan diminta untuk memakai pendakap badan yang dibuat khas untuk setiap pesakit. Pendakap badan khas atau ‘’brace’’ ini kebiasaanya diperbuat dari plastik dan perlu dipakai lebih dari 20 jam sehari dan hanya dibuka untuk mandi dan tujuan senaman sahaja. Pendakap khas ini terbukti berkesan menghalang pertambahan bengkok badan pesakit dan memperlambatkan pembedahan.Secara teori, pendakap ini berfungsi untuk menahan badan daripada terus bengkok melalui plastik yang dibuat mengikut acuan badan. Kebiasaannya, tekanan diberikan kepada bahagian yang bengkok melalui plastik pendakap ini. Terdapat banyak rekaan jenis pendakap salah satunya pendakap Chêneau. Walau bagaimanapun, tiada

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kajian yang dilaporkan mengenai analisis tekanan antaramuka pada pesakit skoliosis idiopatik remaja bengkok dua.

Tesis ini memberi tumpuan untuk mengkaji tekanan yang diberikan kepada pendakap Chêneau skoliosis dan kaitan tekanan tersebut dengan aktiviti harian pesakit. Sebanyak 72 (60 kanak-kanak perempuan dan 12 kanak-kanak lelaki) pesakit berusia 10 tahun ke atas mengambil bahagian dalam kajian ini. Dua sensor diletakkan di bahagian dalam dinding pendakap supaya ia bersentuhan dengan kawasan paling bengkok badan pesakit. Bacaan Transduser F-Socket (9811E) digunakan untuk menilai tekanan pada lengkung toraks kanan dan kiri torakolumbar antara tegangan tali normal dan maksimum dan variasi tekanan antara muka ini dengan beberapa aktiviti asas harian. Setiap pesakit diminta untuk melakukan sembilan aktiviti asas harian, dan tekanan antara muka untuk setiap aktiviti dicatat untuk ketegangan normal dan maksimum. untuk setiap pesakit

Hasil kajian menunjukkan tekanan puncak min yang dihasilkan dalam skoliosis idiopatik remaja lengkung dua kali ganda lebih tinggi untuk lengkung toraks kanan daripada lengkung torakolumbar kiri dalam semua tugas. Tekanan meningkat dengan ketara pada tugas inspirasi maksimum ($p < 0.0001$) untuk kedua-dua jenis lekukan untuk tegangan normal dan maksimum. Perkembangan pesakit diikuti selama enam bulan. dan pesakit diminta untuk memakai pendakap semaksimum mungkin. Tahap pembetulan untuk lekuk toraks dan torakolumbar masing-masing adalah 23.2% dan 34.5%, selepas penggunaan pendakap selama 6 bulan (23 jam sehari). Walaubagaimanapun, kami tidak dapat menjumpai korelasi yang besar antara tekanan puncak rata-rata dalam kedudukan berdiri dan tahap pembetulan skoliosis untuk dua lengkung yang mempunyai nilai $r = 0.158$, $p = 0.356$ dan $r = –0.024$, $p = 0.889$

Kata kunci: Skoliosis idiopatik remaja, pendakap Chêneau, tekanan antara muka, F-Socket

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LIST OF SYMBOLS AND ABBREVIATIONS

AIS	:	Adolescent Idiopathic Scoliosis
SRS	:	Scoliosis Research Society
IS	:	Idiopathic scoliosis
AFBT	:	Adam Forward Bending Test

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LIST OF APPENDICES

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CHAPTER 1: INTRODUCTION

This chapter gives the information about the background of the human spine, scoliosis as well as the usage of braces in treating scoliosis.

1.1 Background

Human spine is a complex system with mechanism behaviors. It holds our bodies together, protect the structure and allows movement within our bodies. Normal human spine consists of 33 vertebrae and grouped according to the correspond regions: cervical, thoracic, lumbar, and sacral (**Figure 1.1**). The structure of each bone is unique and carry different functions to the spine.

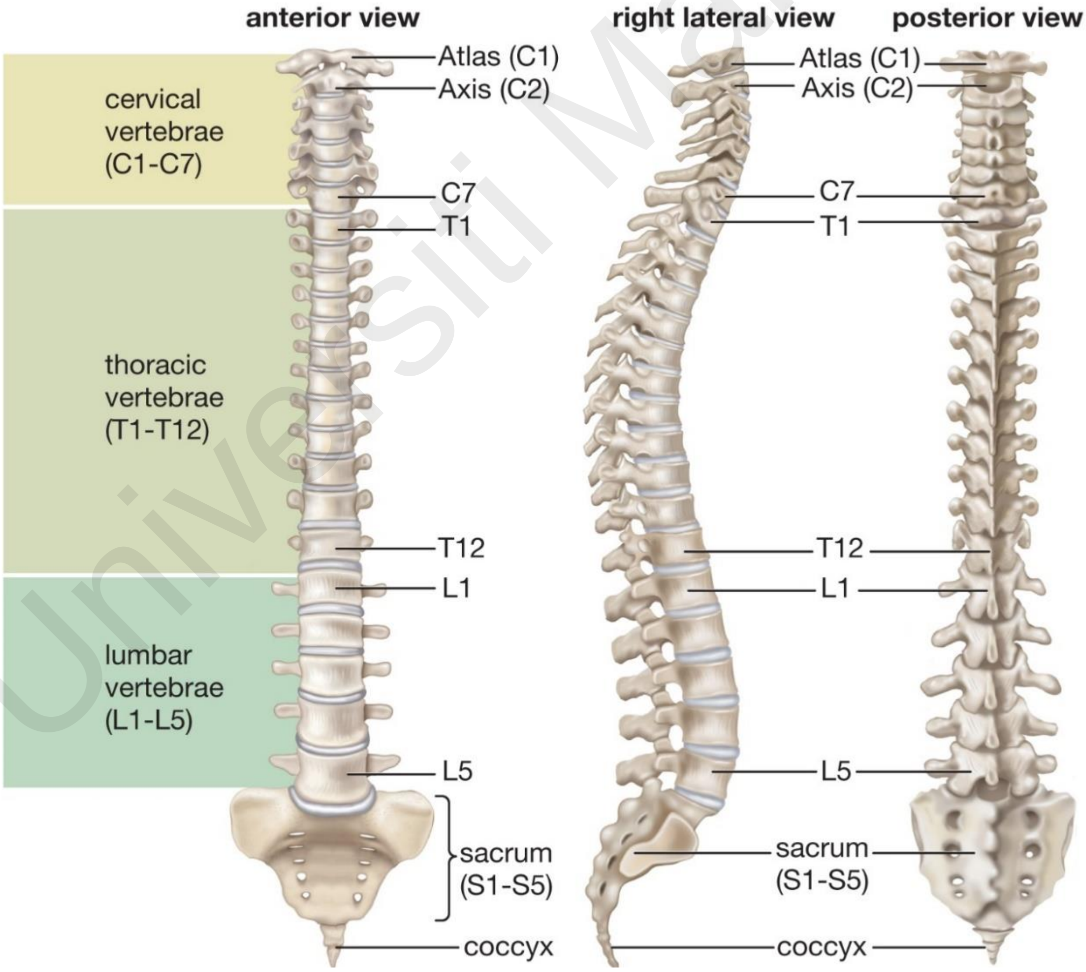

Figure 1.1: Bones in human spine

(https://www.britannica.com/science/vertebral-column)

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Laterally, there are also few curvatures in the spine named cervical, thoracic, lumbar, and pelvic (**Figure 1.2**). The main biomechanical function of the curvatures of the spine is to bear the load and absorb shock (Alison Middleditch & Jean Oliver, 2005).

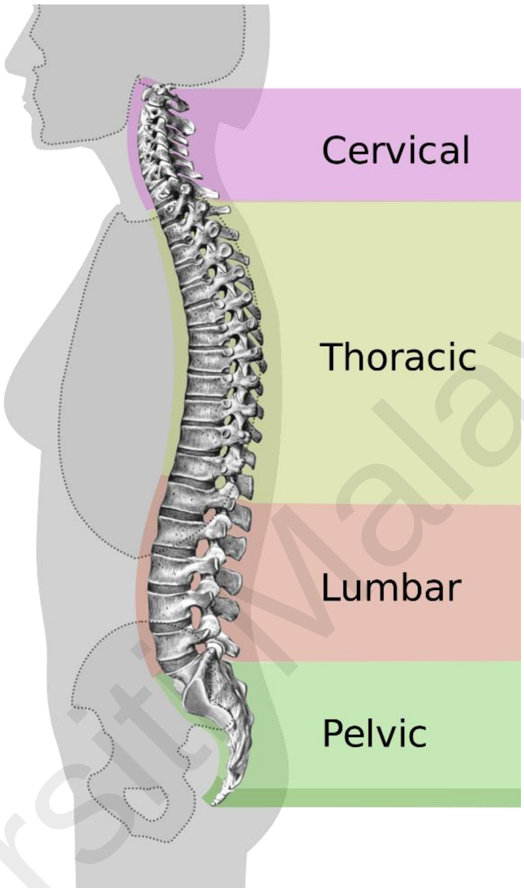

Figure 1.2: Lateral view showing different curvatures in normal human spine

https://en.wikipedia.org/wiki/Neutral_spine

The normal human spine is viewed straight in the frontal plane and has balanced curvatures in the vertical plane in the form of kyphosis (20 to 45 degrees in a normal paediatric population) and lordosis (35 to 60 degrees). However, these spinal curvatures are considered as deformity when they are exaggerated in an individual.

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1.2 Scoliosis

Scoliosis is one of the common spinal deformity, it can progresses to a complex three-dimensional disorder and affects healthy children and adult (Schlösser et al., 2017). The Scoliosis Research Society (SRS) (http://www.srs.org/) defines scoliosis as "a lateral structural curve with a Cobb angle greater than 10 degrees" **(Figure 1.3 and Figure 1.4)**. Scoliosis often classified as structural and non-structural. Structural curves are fixed, non-flexible, and fail to correct with bending where non-structural curves are not fixed but flexible and readily correct with bending. **Figure 1.5** shows example of scoliotic spine as seen on the X-rays.

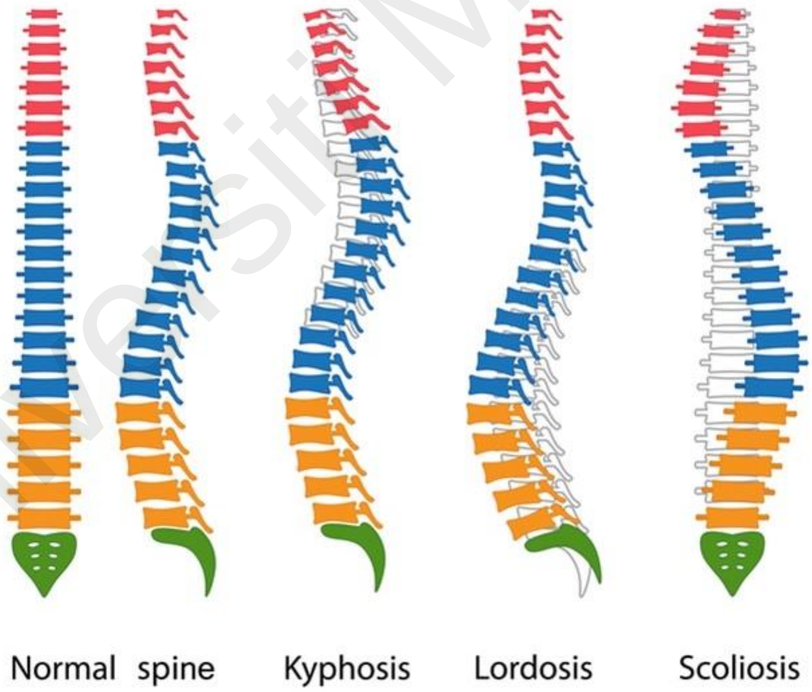

Figure 1.3: Normal human spine

(https://www.news-medical.net/health/Pediatric-Spinal-Deformities.aspx)

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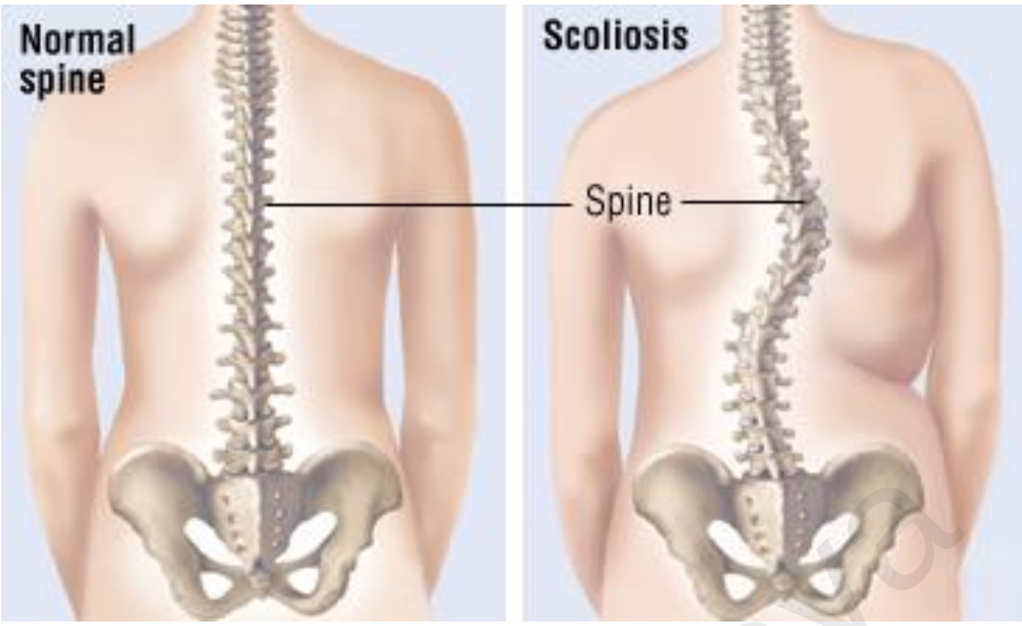

Figure 1.4: Normal spine versus scoliotic spine.

https://www.health.harvard.edu/a_to_z/scoliosis-a-to-z

Figure 1.5: Scoliotic spine as seen on Xray

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There are different types and multiple pathologies can lead to scoliosis. Idiopathic scoliosis is considered the most common types followed by congenital, neuromuscular, and adult scoliosis. "Idiopathic" means unknown; even though many research are ongoing including the gene regarding the AIS (Paria & Wise, 2015) . Congenital scoliosis is the condition develops in the mother's uterus and significantly affects the newborns. The condition gets worse as the children grows. Neuromuscular scoliosis (NMS) is a type of scoliosis that happen to children who have muscle, brain, and nerve problems. It may come at any age and the condition is severe and more progressive than other types (Murphy & Mooney, 2019). As the name suggest, adult scoliosis is a type of deformity that happen in adult life.

Scoliosis can occur at any age but typically it is common in children during growths spurts. Scoliosis can also be grouped based on the age of the patients when it first diagnosed as summarized in **Table 1.1**.

Table 1.1: Types of scoliosis based on age

Types	**Age (Years)**
Infantile idiopathic scoliosis	0-3
Juvenile idiopathic scoliosis	4-10
Adolescent idiopathic scoliosis (AIS)	>10

Infantile idiopathic scoliosis started in the mother's womb and the condition get worsen as the kids born and grow. Juvenile idiopathic scoliosis happens to children at the age of 4 to 10 years whereas idiopathic affects mostly children after 10 years age. Scoliosis is common in girls compared to boys because girls growth spurts are two times faster than boys (Altaf, Gibson, Dannawi, & Noordeen, 2013).

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This thesis will focus on the main type of scoliosis: Adolescent Idiopathic Scoliosis (AIS), which has unknown cause, and more specifically on the conservative treatment of this deformity.

1.3 Conservative Treatment

To date, Thoracolumbar Sacral Orthosis (TLSO) and physiotherapy are two types of conservative treatment for patient below 45 degree of scoliosis (Zaborowska-Sapeta, Kowalski, Kotwicki, Protasiewicz-Fałdowska, & Kiebzak, 2011). TLSO is defined as "the application of external corrective forces to the trunk, usually achieved through rigid supports and occasional use of elastic bands" (Colliard, Vachon, Circo, Beausejour, & Rivard, 2007). TLSO or hard bracing has been prescribed for patients with scoliosis with a Cobb angle ranging from 20 to 45. Positive results of the TLSO are shown in lot of cases with the Cobb's angle less than 45 degree (Goldberg, Moore, Fogarty, & Dowling, 2001) (Brox, Lange, Gunderson, & Steen, 2012). An example of TLSO is shown in **Figure 1.6**.

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Figure 1.6: Boston brace, a type of TLSO.

(https://www.choc.org/orthopaedics/spine-center/scoliosis/bracing/)

Many studies have shown the effectiveness of the different types of TLSO in treating scoliosis and some cases are proven to prevent the surgery if the braces are made correctly (Colliard et al., 2007; d'Amato, Griggs, & McCoy, 2001; De Giorgi et al., 2013). There are numerous designs of the TLSO brace available worldwide, all of which aim to stop curve progression until the patient reaches the skeletal maturity (Ahmad, Abu Osman, Mokhtar, Mehmood, & Kadri, 2019).

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Untreated scoliosis reduces the quality of life of a person (Danielsson, Hasserius, Ohlin, & Nachemson, 2010). According to Weiss et al. (Weiss, Karavidas, Moramarco, & Moramarco, 2016), this condition leads to severe long-term health consequences such as pulmonary problem , heart problem, and eventually death.

1.4 Problem Statement

TLSO or bracing is designed to stop progression of the deformity or at least maintains the scoliotic condition at initial stage. The current practice in scoliosis brace treatment; during the fitting process, the modification is made to the brace and eventually affect the corrective force designed. However, brace treatment may get fail in achieving the required goals owing to the certain reasons. The main reason is inappropriate correctional force designed on the scoliosis brace. To date, the magnitude of the corrective forces for maximal curve correction is still not found (Ioannis Loukos, Constantinos Zachariou, Christos Nicolopoulos, Dimitrios Korres, & Nicolaos Efstathopoulos, 2011). The author sought to measure the corrective forces exerted by the Chêneau brace; a type of TLSO to help in achieving the optimal brace correction in the treatment of double curve AIS patients.

1.5 Aim and Objectives

Improving scoliosis brace treatment required quantitative data to evaluate proper brace fabrication. This data will be helpful to practitioner in achieving optimum curve in-brace correction for AIS patient. The study aims to study the F-socket Tekscan sensor system in measuring interface pressures exerted by Chêneau brace in double curve AIS patient.

The objectives of this study are:

1) To analyses the variations of interface pressure in left thoracolumbar and right thoracic curve in a patient before and after strap tightening

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2) To study the correlation between the MPP values in the standing position and the degree of curve correction after 6 months of brace usage.

1.6 Thesis Organization

This thesis has five chapters. The thesis organization is as follow:

Chapter 1 gives the background information about human spine, scoliosis as well as the usage of scoliosis braces to control the scoliotic curve in Adolescent Idiopathic Scoliosis (AIS).

Chapter 2 contains the existing and current knowledge about the current scoliosis braces that are used in the world and their mechanism of actions. It also explains the usage of scoliosis braces to stop the curve progression in Adolescent Idiopathic Scoliosis (AIS).

Chapter 3 consists of the methodology of the research in which sensors were added in the brace fabrication process. This chapter comprise of the participant recruitment, ethical approval form, and fabrication details about the experimental study that has been carried out by all the participants. Data analysis is also present in this section.

Chapter 4 provides a detail explanation about the results and discussion where a comparative study is analyzed and portrayed in graphs. The sensor values have been recorded before and after straps adjustment which is presented in linear graph and coefficient of Pearson correlation. The values have also been analyzed using SPSS software.

Chapter 5 includes the conclusion derived from the thesis findings as well as future work to be done to improve or extend the presented work in this thesis.

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CHAPTER 2: LITERATURE REVIEW

This chapter explains the AIS in depth and the existing and current knowledge about the scoliosis braces that commonly used and their mechanism of actions. It also explains the usage of scoliosis braces to stop the curve progression in Adolescent Idiopathic Scoliosis (AIS).

2.1 Adolescent Idiopathic Scoliosis

Adolescent Idiopathic Scoliosis (AIS) is a structural, lateral, and rotated curvature of the spine that arises in healthy children at or around puberty (Ahmad et al., 2019). The diagnosis of AIS is made when other causes of scoliosis, such as vertebral malformation, neuromuscular disorder, and syndromic disorders have been ruled out (Stuart L. Weinstein, Dolan, Cheng, Danielsson, & Morcuende, 2008). Scoliosis Research Society (SRS) defined AIS is as the "scoliosis which happens after ten years of age and whose cause is not yet known". AIS is usually asymptomatic, however the physical look of AIS adversely affects young children and adults (Vasiliadis & Grivas, 2008).

Global statistics shown 1–3% children of those aged in the range of 10–16 are susceptible to AIS (Stuart L. Weinstein et al., 2008). In Asian countries, this value varies between 0.4% - 7%. In Malaysia, the prevalence of scoliosis is 2.55%, affecting mostly female adolescents, and the male-to-female ratio is approximately 1:3 (Deepak et al., 2017). To diagnose scoliosis, there are several signs that may indicate the possibilities such as sideways curvature of the spine, sideways body posture, uneven hips, and one shoulder raised higher than the other.

Figure 2.1 shows the example of possible signs of scoliosis in children. Further examination is needed upon the presence of these signs in a child.

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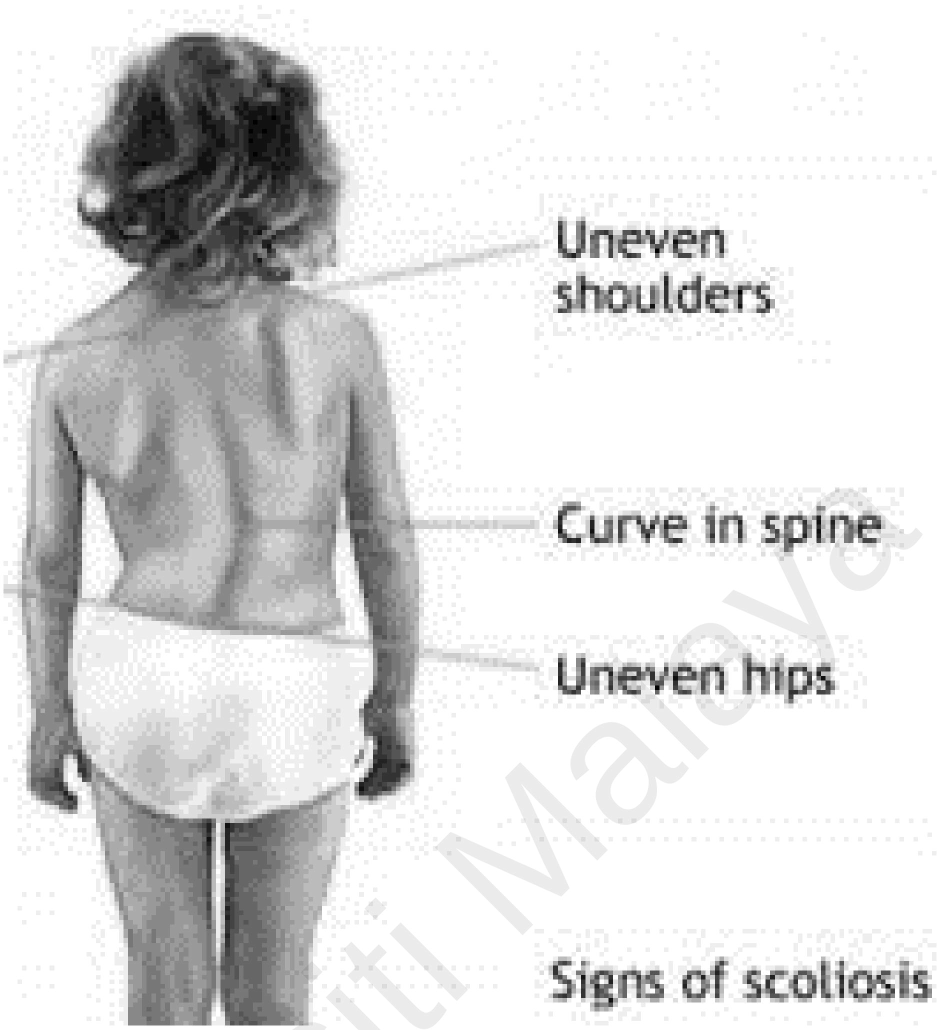

Figure 2.1: Signs of scoliosis in children

(https://www.physio-pedia.com/Scoliosis)

The initial examination to detect scoliosis condition in a patient is called Adams' Forward Bend Test (AFBT). AFBT is done by examining the spine in a standing position, The patient is asked to put their palms together, head down and bend forward by flexing at the hips **(Figure 2.2)** (Gordon & Dhokia, 2021). Noticeable hump and ribs prominence indicate the sign of thoracic abnormal curvature which is caused by spinal rotation (Reamy & Slakey, 2001)

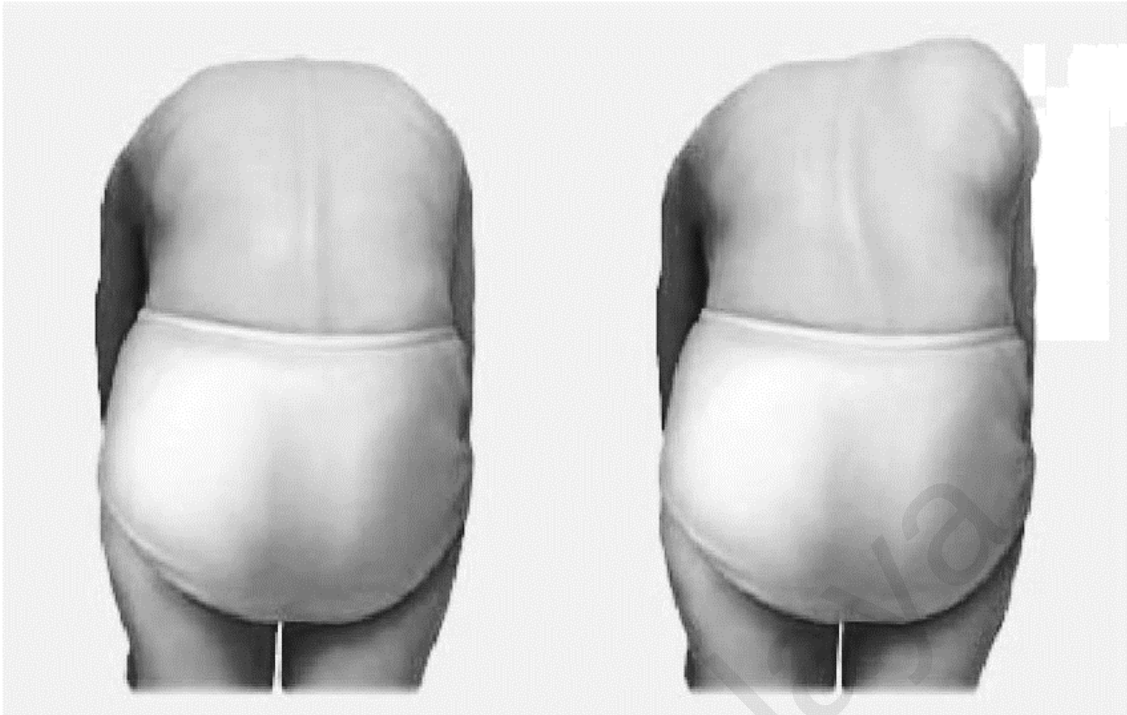

Figure 2.2: The Adam's forward bend test performed by (left) a patient without scoliosis, and (right) a patient with scoliosis showing a rib hump.

(Reproduced from: Adolescent idiopathic scoliosis - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/The-Adams-forward-bend-test-performed-by-left-a-patient-without-scoliosis-and right_fig1_236599695 [accessed 13 April, 2020]).

Other than AFBT, the patients will be inspected by using scoliometer; a device used to get the early detection of scoliosis by measuring the Angle of Trunk Rotation (Negrini et al.) **(Figure 2.3)**. There is a possibility of scoliosis in the patient if the angle of trunk rotation is more than 10 degree on scoliometer which is further confirmed through the Cobb angle measurement using X-ray machine (Murrell, Coonrad, Moorman 3rd, & Fitch, 1993).

Patient who scored less than 10 degrees in AFBT and scoliometer measurement requires further check-up at the hospital to confirm the condition. This examination is the common screening process worldwide to detect the AIS among school children (Horne, Flannery, & Usman, 2014). The screening process helps to detect patients at early stage,

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thus enable the conservative treatment to start timely and prevents the risks of progression (Deurloo & Verkerk, 2015).

Figure 2.3: A scoliometer; device used to get the early detection of scoliosis by measuring Angle of Trunk Rotation (Negrini et al.).

(https://scoliosis3dc.com/2011/01/26/evaluating-scoliosis-scoliometer/).

The amplitude of the scoliosis condition is measured by Cobb angle, which is derived from a posterior- anterior standing X-ray of the scoliotic spine. The Cobb angle is the angle formed from perpendicular line drawn at most tilted vertebrae above and below the apex of the curve of the scoliotic spine **(Figure 2.4 and Figure 2.5)** (Horne et al., 2014).

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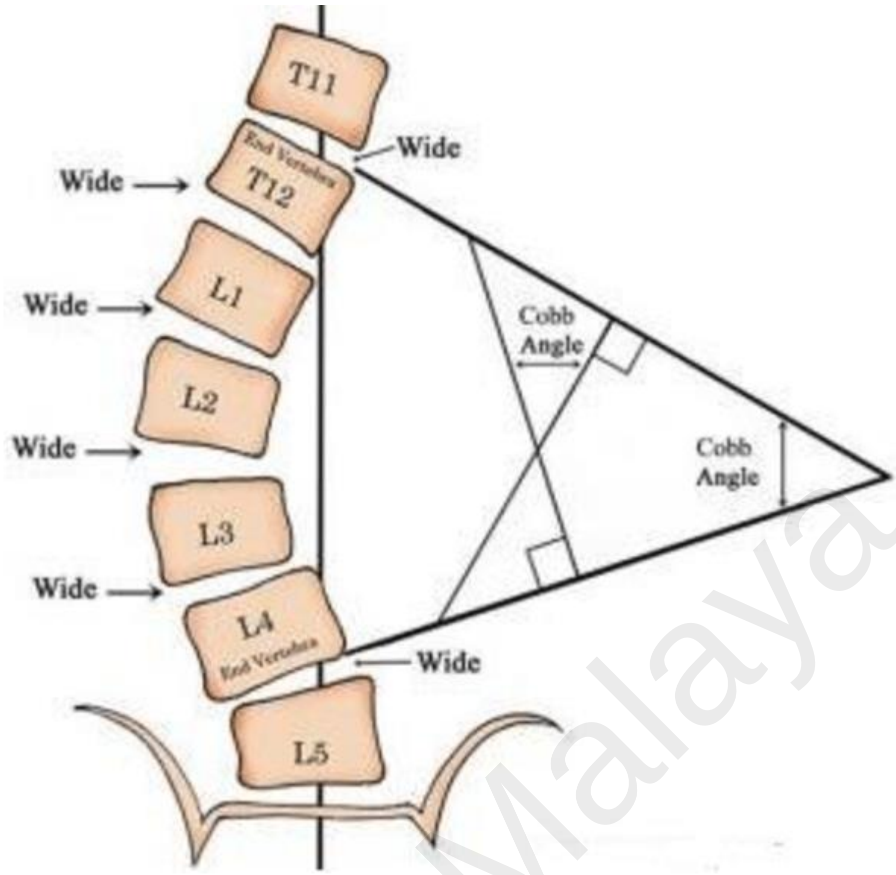

Figure 2.4: Manual method for measuring the Cobb-angle.

(http://incolors. club/collectionsdwn-scoliosis-x-ray-cobbangle.htm.).

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Figure 2.5: Cobb angle measurement (Here, 62 degrees).

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2.2 Types of curves in scoliosis

Scoliosis is often described in relation to its location. The Scoliosis Research Society Classification for Adult Deformity defined thoracic curve as an “apex between the second thoracic vertebral body and the 11th and 12th thoracic disc” and thoracolumbar curve has “an apex between the first and second thoracolumbar disc and the fourth thoracolumbar vertebral disc” (Ahmad et al., 2019). The ideal scoliotic conditions for orthotic management are single curve and double curve which can happens at any region (thoracolumbar, thoracic or lumbar).

Before further understanding the types of curves, it is important to classify the curve according to the group. The classification system of curve patterns is crucial for the practitioner to plan the proper treatment for scoliosis patient. In all types of classification of scoliosis patterns, the evaluation of the scoliotic curve is always observed from dorsal aspect of the coronal plane X-ray.

In 1950, Ponseti and Friedman attempted to classify idiopathic curves, they tried to divide the cases according to the curve pattern; single, double, and triple curve patterns (Ponseti & Friedman, 1950). These patterns were named according to the location of the apex such that the apex of the thoracolumbar curves was at T12 to L1, above T12 for thoracic curves above and below L1 for lumbar curves below. However, this classification system could not reveal the true complexity of the deformity with curve type and location alone.

Later in 1983, King and Moe introduced an ordinal classification system which characterized scoliosis into five different curve types that incorporated curve pattern, magnitude and flexibility to establish the limits of the fusion in surgical procedures **(Figure 2.6)** (Lowe, Berven, Schwab, & Bridwell, 2006).

However, the King system did not consider scoliosis with double or triple major curves and did not recognize curve in vertical plane which is considered weakness in this system.

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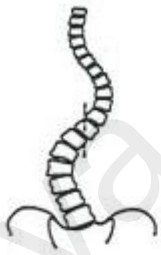
King type I: A S-shaped curve in which both the thoracic and lumbar curves cross the midline. The magnitude of the Cobb angle of the lumbar curve is larger than that of the thoracic curve on standing roentgenogram. Both curves are structural, with nearly equal flexibility.	
King type II: A S-shaped curve in which both the thoracic and lumbar curves cross the midline. The magnitude of the Cobb angle of the thoracic curve is larger than that of the lumbar curve on standing roentgenogram. The lumbar curve is more flexible.	
King type III: A thoracic curve in which the lumbar curve does not cross the midline (so-called overhang).	
King type IV: A long thoracic curve in which L5 is centered over the sacrum, but L4 tilts into the long thoracic curve.	
King type V: A double thoracic curve with T1 tilted into concavity of upper curve. The upper curve is structural on side bending.	

Figure 2.6: King-Moe classification system of thoracic curve patterns in idiopathic scoliosis (King et al., 1983).

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In 2001, Lenke classification was developed by members of the Harms Study Group with the aim to be comprehensive and encompass all curve types, to be based on objective criteria for each curve type, to emphasize sagittal plane alignment, and to be easily understood and applied (Lowe et al., 2006). To date, Lenke et al., system is considered good, efficient and reproducible because of the complex classification style and helps clinician to communicate better (Lenke et al., 2002).

The term structural and non-structural refers to the flexibility of the spine. Lenke et al. defined 'structural' as a curve which remains greater than 25° on flexibility test (Lenke et al., 2002). Occasionally, the term primary or major curve refers to the curve with the largest Cobb angle. Quite often, the primary curve is coupling with the secondary curve which is derived to give the balance to the spine (Lenke et al., 2002).

Types 1 and 2 refer to structural thoracic scoliosis; Type 5 refers to structural thoracolumbar/lumbar scoliosis; Types 3, 4, and 6 include structural thoracic and thoracolumbar/lumbar curves. The classification relies on measurements taken from both front and side and is reliable to clinicians for deciding the treatment plan for the patient. **(Figure 2.7)** (Lenke et al., 2002).

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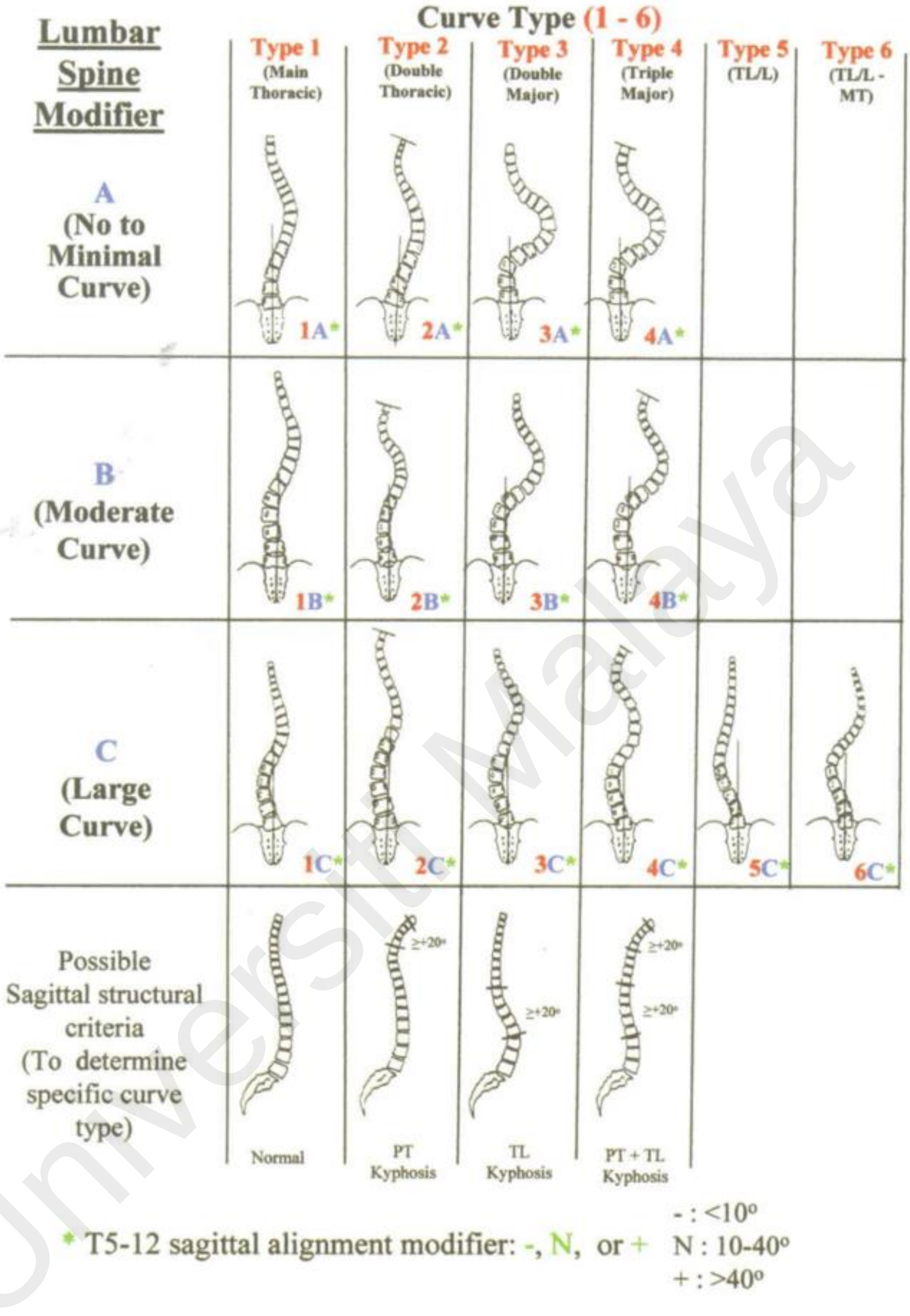

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Figure 2.7: Lenke classification system. Reproduced from (Hadagali, 2014).

2.3 Curve Progression

Curve progression in AIS is highly related to the pattern. It is believed that double curves progress is more than single curves. Study by Bunnel et al. found out that lumbar curves progress was the slowest among all types of curves (Bunnell, 1986). Larger curves (30 to 40 degree) progressed more than small curves between 20-29 degree and deformity continued even after skeletal maturity has been reached (Picault, Mouilleseaux, & Diana, 1986).

Curve below 30 degree is considered moderate whereas above 30 degree is in high risk to progress. **Table 2.1** summarizes the risk of progression based on the degree of curve.

Table 2.1: Summarization on the risk of curve progression based on the degree of curve (Reamy & Slakey, 2001).

Curve (degree)	Growth Potential (Riser grade)	Risk*
10 to 19	Limited (2 to 4)	Low
10 to 19	High (0 to 1)	Moderate
20 to 29	Limited (2 to 4)	Low/moderate
20 to 29	High (0 to 1)	High
>29	Limited (2 to 4)	High
>29	High (0 to 1)	Very high

*Low risk=5 to 15%, moderate risk=15 to 40%, high risk=40 to 70%, very high risk=70 to 90%.

Curve progression is main concerns in AIS. Even though, the risk of progression is considered uncertain in AIS but other factors such as remaining skeletal growth, magnitude, curve type, and gender influence the scoliosis curve progression (Lenz et al., 2021). There is evidence in the relationship between rapid adolescent growth and curve progression in AIS patients and growth spurt make the scoliotic curve worsen (Busscher,

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Wapstra, & Veldhuizen, 2010). Therefore, skeletal growth is a key factor in the progression of the scoliotic curve.

On the other hand, a review by Rowe et al. explain that in untreated female patients who had thoracic scoliosis, the risk of progression increases with the magnitude of the curve at the time of detection and decreases with increased age at the time of detection (Rowe et al., 1997). **Table 2.2** summarizes the risk of progression increases with the magnitude of the curve at the time of detection and decreases with increased age at the time of detection for thoracic curve.

Table 2.2: summarize the risk of progression increases with the magnitude of the curve at the time of detection and decreases with increased age at the time of detection for thoracic curve (Rowe et al., 1997).

Magnitude of Curve at Detection *(Degrees)*	**Risk of Progression *(Per cent)***		
	10, 11, or 12 Yrs.*	13, 14, or 15 Yrs.*	≥16 Yrs.*
<19	25	10	0
20–29	60	40	10
30–59	90	70	30
≥60	100	90	70

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Considering all these possibilities throughout the treatment, all bracing patients will be monitored through observation and postero-anterior (PA) standing X-rays at regular intervals (typically 3-6 months apart) until they reach the skeletal maturity. This process is crucial to determine whether any clinically significant Cobb angle changes (>5°) have occurred since their previous presentation and further treatment is required.

In adolescent patients, the amount of residual skeletal growth is clinically assessed using radiologic methods such as the Risser sign and the elbow Olecranon method. The Risser sign is a progressive measure of ossification in the iliac apophysis (pelvis) **(Figure 2.8)** and the Olecranon method is a progressive measure of ossification in the elbow (Little & Sussman, 1994).

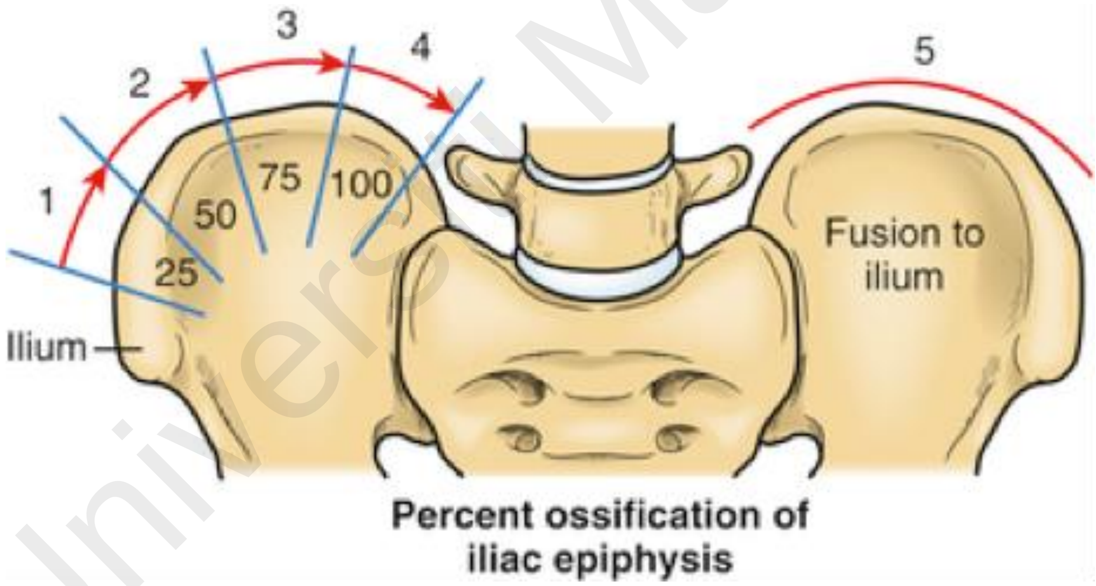

Figure 2.8: Risser sign scale in scoliosis treatment.

(https://vsrc.com.au/wp-content/uploads/2016/03/Risser.png)

Male and female have different range of skeletal maturity. The ossification of iliac apophysis starts around 14 years in females and 15 years in male. However, the complete process of ossification from stage 1 to stage 4 takes around 12-18 months (Hacquebord & Leopold, 2012).

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2.4 Types of Treatment

Scoliosis treatment in AIS is categorized by magnitude of the curve. For Cobb angle below 20-25 degree, only observation is needed whereas if it is more than 20-25 and below 45 degrees, the patient is asked to use custom molded scoliosis brace to stop the curve progression. However, for more than 45 degrees, the only treatment is the surgery in which the spinal rod is added to correct the spinal curvature of a patient. **Table 2.3** summarizes the treatment available for scoliosis patient based on Cobb angle and Risser scale (Reamy & Slakey, 2001).

Table 2.3: Treatment and Referral guidelines for patients of Scoliosis

Cobb angle	**Risser grade**	**Radiography/referral**	**Treatment**
10 to 19	0 to 1	Radiography every six months, no referral	Observe
10 to 19	2 to 4	Radiography every six months, no referral	Observe
20 to 29	0 to 1	Radiography every six months, referral	Brace after 25 degrees
20 to 29	2 to 4	Radiography every six months, referral	Observe or Brace*
29 to 40	0 to 1	referral	Brace
29 to 40	2 to 4	referral	Brace
>40	0 to 4	referral	Surgery†

*Risser grade 4 probably warrants only observation

†Surgery can be delayed with Risser grade 4

Most brace types are prescribed to be worn 20-23 hours a day for a period of two to four years, until the end of skeletal growth, as determined by Risser sign or skeletal maturity by bone age. The key factors in assessing the likelihood of curve progression include the initial size of the curve as measured through the Cobb Angle and the amount of growth remaining (Negrini et al., 2018). Treatment effectiveness is measured by looking at the reduction of risk of requiring surgery and medical standards considering a curvature progression of less than 5% as successfully treated curve (Nachemson et al., 1995).

The goal of brace treatment for AIS is to stop the curve progression and to improve the appearance by aligning the whole body and balance. After skeletal growth completed, the curve progression is likely to be slow but can continue throughout the lifetime. Curve more than 30 degrees by the end of growth has been observed in 0.2% of the population that increases the risk of health problems in adulthood significantly (Negrini et al., 2018).

The most frequent long-term consequences of untreated scoliosis are curve progression, back pain, cardiopulmonary problems, and psycho-social concerns. The severity of the effects varies from patient to patient. Additionally, severe deformity can displace internal organs, leading to multisystem organ problems (S. L. Weinstein et al., 2003). If this non-surgical treatment is not successful, the spinal surgery is performed later. Surgery involves fusing vertebra and placing metal rods along the spine to decrease the curvature and stabilize the vertebral column (Weiss & Werkmann, 2012).

2.5 Types of scoliosis brace

Scoliosis braces are well known as thoracic-lumbar-sacral orthoses (TLSO). There are various types of braces that have been designated for scoliosis treatment; each type is designed slightly different and is made up of different materials, targets different areas of the spinal column, and demands different treatment protocols. They can be rigid, flexible, or composite and can utilize passive or active correction mechanisms. Prescription of a brace depends on severity of the deformity and flexibility of the spine, clinician professional opinion and preference. **Figure 2.9** and **Figure 2.10** show the top view of the correction given to all the scoliosis braces. The curve correction for the thoracic curve

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is given anterior-laterally, whereas for the lumbar curve, the correction is given posterior-laterally (Ahmad et al., 2019).

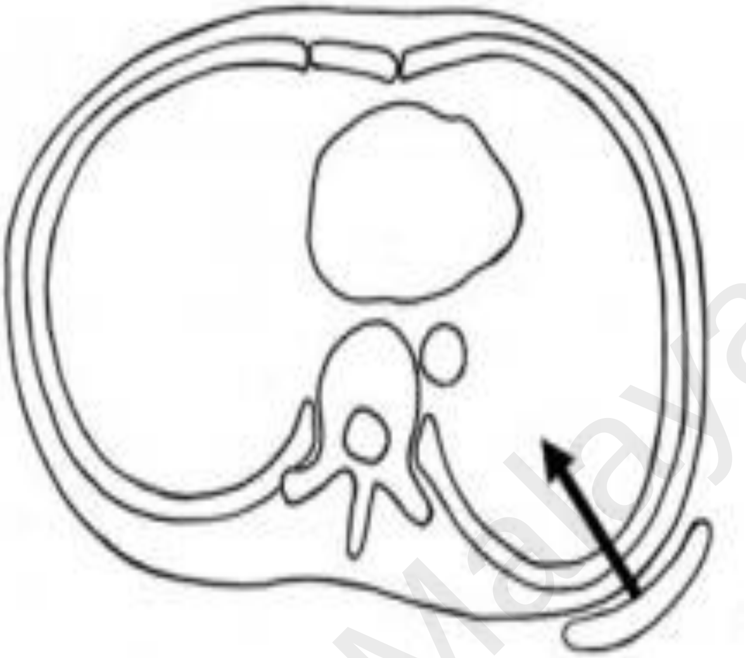

Figure 2.9: Area of correction given to thoracic curve.

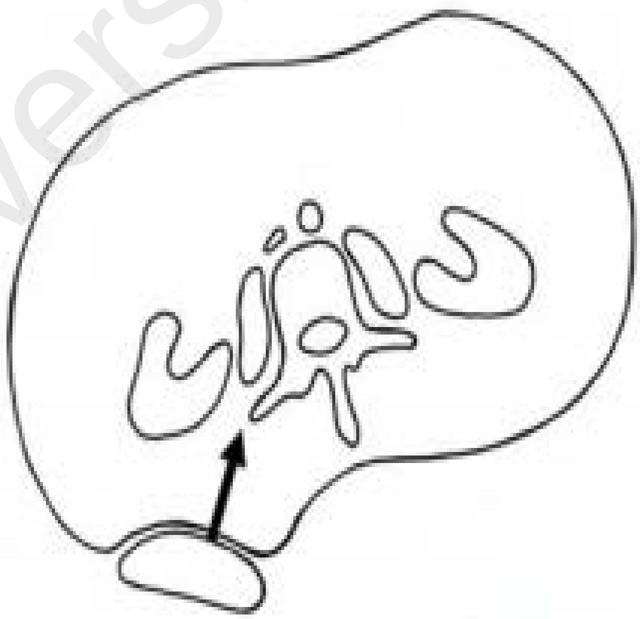

Figure 2.10: Area of correction given to the lumbar curve.

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1) Milwaukee brace

The Milwaukee brace developed in the 1940s, is a orthosis designed as an auto-elongation brace and has shown significant success in halt curve progression (Lonstein & Winter, 1994). It is the first removable brace for the treatment of Scoliosis. The brace is symmetric with a posterior opening, and it consists of multiple parts. The pelvic girdle, made up of leather or thermoplastic materials, wraps around the waist. The superstructure is a combination of an aluminum anterior bar, stainless steel posterior bars, and a neck ring with a non-contact throat mold **(Figure 2.11)**. Passive and active mechanisms can be utilized for curve correction, depending on the addition of different design features.

Figure 2.12 shows a successful outcome after 5 years of treatment with a Milwaukee brace.

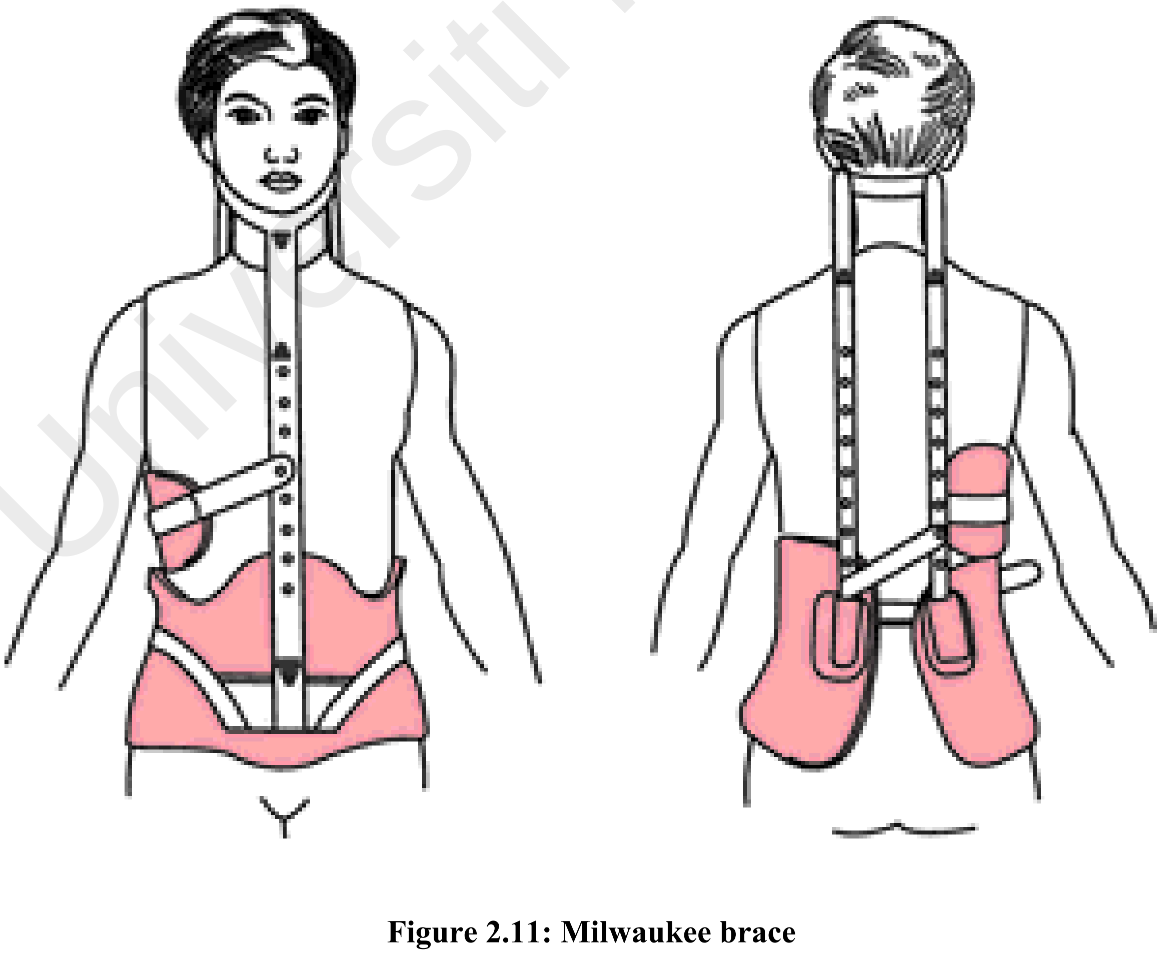

Figure 2.11: Milwaukee brace

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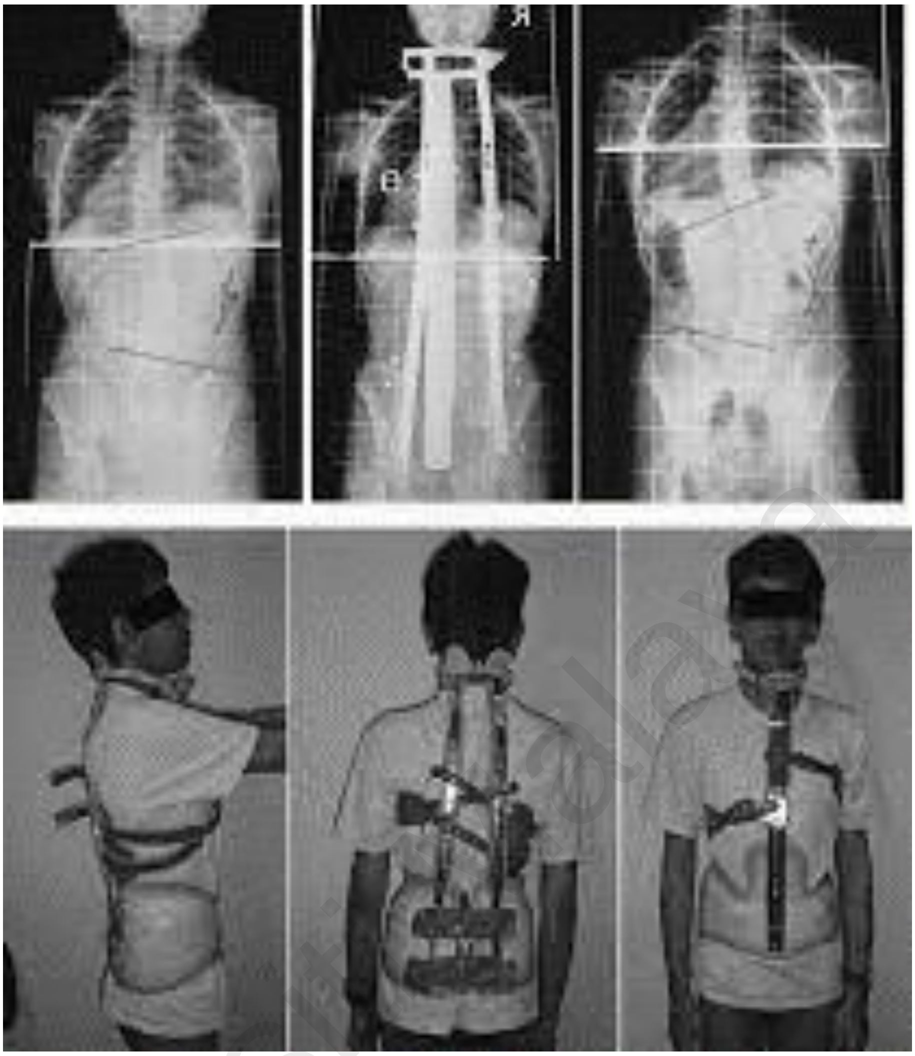

Figure 2.12: Successful outcome after 5 years of treatment with a Milwaukee brace. (Above) Standing radiograph at the beginning (left), during (center), and at the cessation of treatment (right). (Below) Clinical photographs Reproduced from (Garg, Ahuja, & Basu, 2020).

However, poor cosmesis is due to the bulky design results in non-compliance and limited prescription of the Milwaukee brace.

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2) **Boston Brace**

Figure 2.13: Boston brace.

(https://www.bostonoandp.com/products/scoliosis-and-spine/boston-brace/.)

The most popular TLSO Scoliosis brace in North America is the Boston Brace (**Figure 2.13**). The brace was originated in 1972 at Boston Children's Hospital as a modified Milwaukee brace. The brace design included a pelvic girdle modified with thoracolumbar and thoracic extensions and overall superstructure replaced with low profile plastic axillary extensions. Compared to the custom-molded predecessors, the fabrication time and cost was greatly reduced through computer aided design-computer aided manufacturing (CAD-CAM) construction methods. The final device is symmetrical with a posterior opening. Within the brace, apical pads are placed to passively load the scoliotic

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curve. A section of material can be removed from the brace opposite the apex of the curve for creating a window of relief to allow and improved truncal shift and ventilation **(Figure 2.14)**.

Figure 2.14: Anterior and posterior view of the Boston brace.

The Boston brace works by applying corrective pressure on the convex (outer) side of the curve and cutting out corresponding areas of relief on the concave (inner) side of the curve so the spine can migrate in that direction. The brace opens in the back, so patient may need help getting into and out of it.

3) Dynamic Spine-Cor brace

The Dynamic Spine-Cor brace is comparatively new and is commercially available since 1992. This brace is considered the most recent non-rigid brace **(Figure 2.15)**. Postural disorganization, muscular dysfunction, and unsynchronized spinal growth that can lead to spinal deformation are the main three factors that contribute to the development of the scoliosis braces (Garg et al., 2020).

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Figure 2.15: Dynamic Spine-Cor brace.

(http://www.spinecor.com/ForPatients/ScoliosisTreatments.aspx).

The Dynamic Spine-Cor is a full-time brace that works on the principle of neuromuscular integration through active biofeedback **(Figure 2.16)**.

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Figure 2.16: A patient is wearing non rigid Dynamic Spine-Cor brace. Reproduced from (Rivard & Coillard, 2002).

4) The Providence brace

The Providence brace was designed for counteracting the forces of the spine and holding the patient up to or even past the midline of the body **(Figure 2.17)**. It is made up of stronger material like acrylic and can treat all single and double curves. Overnight braces were designed specifically to reduce the psychological impact on the patient, however, they are less effective due to the decreased exposure time (Donzelli, Zaina, & Negrini, 2015)

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Figure 2.17: The Providence brace

(https://www.researchgate.net/figure/The-Providence-nighttime-brace-works-through-a-combination-of-forces-laterally-applied_fig6_24446297).

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5) Chêneau brace

Chêneau brace is commonly used in Europe. It is proven in reducing the risk of progression and lowering the rate of surgery of AIS patients (De Giorgi et al., 2013; Weiss & Werkmann, 2012). The Chêneau brace uses the principle of three-dimensional over correction on the scoliotic curve and creating the expansion chambers on the opposite sides **(Figure 2.18)**.

Figure 2.18: Chêneau brace (Reproduced from;(Zaborowska-Sapeta et al., 2011).

The passive mechanism of correction for Chêneau brace is the tissue transfer in three dimensions, elongation effect, rib cage derogation, and bending (Kotwicki & Cheneau, 2008). Meanwhile, the active mechanism happens in the applied pressure areas are shifting the body away to the expansion chambers (Wynarsky & Schultz, 1991). **Figure 2.19** show the in-brace correction of a patient after wearing Chêneau brace.

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Figure 2.19: In- brace correction with Chêneau brace.

2.6 Interface Pressure Assessment in Scoliosis Brace

Adequate corrective force is the main determinants for good brace in scoliosis patient. Recognizing this important, various studies have been conducted to identify the corrective force on the different brace design (Babaee, Kamyab, Ahmadi, Sanjari, & Ganjavian, 2017). Some studies also tried to analyze the pressure distribution throughout the daily activities of the scoliosis patients (Joon-Hyuk, Stegall, & Agrawal, 2015). However, even though the magnitude of the corrective forces is still not determined, the information and data from all the studies provide insight to the force system acting on the scoliosis brace which could be useful in designing the fitting tool in the future (Babaee et al., 2017; Kotwicki & Cheneau, 2008).

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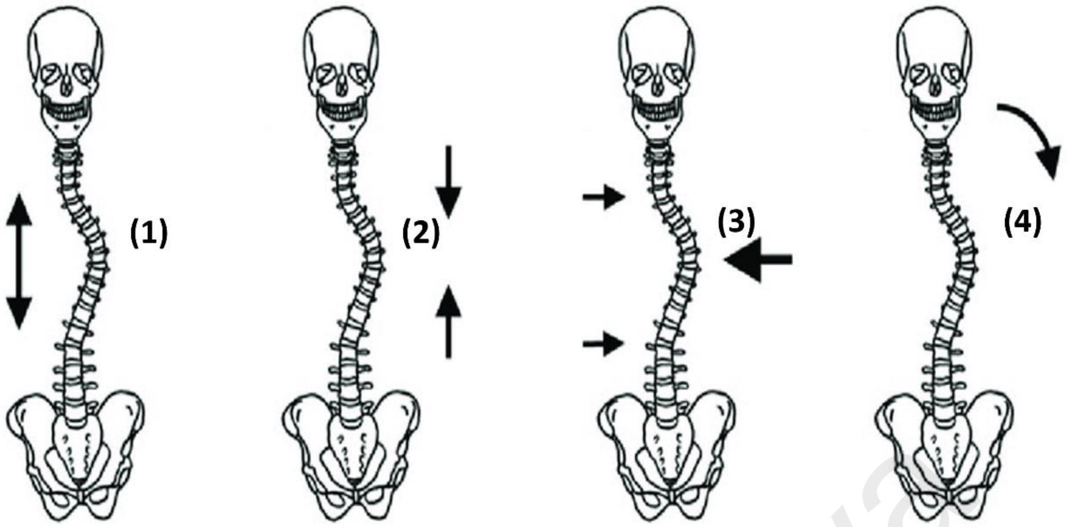

Figure 2.20: Types of forces used to correct the spinal deformity (1) Distraction force; (2) compression force; (3) transverse force; and (4) bending force. Reproduced from (Lou, Hill, & Raso, 2008).

The corrective forces used to correct the spinal deformity is known as distraction forces on the concave side, compression forces on the convex side, transverse forces from both sides, and side bending for the convex side (**Figure 2.21**). Out of all these forces, the commonly used in AIS brace treatment is transverse force because it is more efficient in correcting a Cobb Angle that is in the range of 20-45 degree (WHITE III, 1989). A recent study by Karimi et al. suggest that the combination both transverse and vertical forces are better in correcting the spinal deformity (Karimi, Rabczuk, & Pourabbas, 2020). However, in real practice, the application of all these forces is depending on types, severity of the angle, and experience of the brace maker.

These transverse or corrective force can be measured by using interface pressure measurement system. The material used to sense these corrective forces is recognize as intelligent material because it can respond to the stimuli given and translate into the numerical values. Intelligent materials can be found in several forms such as piezoelectric materials, magnetochemically fluid and shape memory alloy which are used in industrial,

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medical, and surgical applications (Dragašius et al., 2021). The ability for this material to respond to the stimuli making it useful for the biomedical application (Sferruzza, Birer, Matias, Theillère, & Cathignol, 2001).

Study by Van de Hout et al. in 2002 measured these direct forces exerted by the pads in a Boston brace in 16 patients with idiopathic adolescent scoliosis, using the electronic PEDAR measuring device (van den Hout, van Rhijn, van den Munckhof, & van Ooy, 2002). However, this study only incoporated lumbar and thoracic curve acting on different bodies. The other data for type of curves is still unknown.

A study by Mac-Thiong et al. used a mat made of force-sensing transducers, tried to determine the strap tension associated with optimal Boston brace interface forces. Single curve and double curve were studied and standardized tension were put to the straps at the same time. Eventhough the results were still unclear, they managed to conclude the amount of tension required for both types of curve in Boston brace.

F-Socket 9811E is one of the piezoelectric transducers available in the market and has been used for in situ interface pressure measurement over the past years **(Figure 2.21)**. Ali et al. reported the usage of the F-Socket Pressure Measurement System in analysing the interface pressure of the transtibial prosthetic foot (Ali et al., 2012). El- Sayed et al. also reported the use of this piezoelectric material in transfemoral prosthesis experiment for interface pressure (El-Sayed, Hamzaid, & Abu Osman, 2014). Both studies reported that this sensor can measures wide range of movement of the lower limb prosthesis activity.

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Figure 2.21: Application of piezoelectric transducer to measure interface pressure of the transtibial prosthesis. Reproduced from : (Ali et al., 2012).

This system enables quantitative analysis to be done from detailed pressure profiles and graphical displays. The high-resolution sensor embedded in a paper-thin film can be trimmed into freely floating fingers to closely approximate the curvature of the interface, enabling it to be a useful tool in measuring the interface pressure due to the different curvature of the spinal surfaces. Based on the available resources and studies from previous experiment, the author sought to study the F-Socket 9811E pressure sensor to measure the interface pressures in patients with double-curve AIS. The measurement will consider the tension between normal and maximum strap and variation of these interface pressure with other tasks and analysing the variation with position and activity

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CHAPTER 3: METHODOLOGY

This chapter presents the methods used to conduct the experiment. It describes the details about the material and sensor configuration and placement utilized in the experiment. Also, it explains the data collection methods, experimental setup, and experimental protocol.

3.1 Introduction

The study is designed to evaluate the interface pressure of the Chêneau brace action in double curve AIS patient treatment. The Tekscan system used in the study measures the forces applied to the patient's body by the Chêneau brace in double-curve scoliosis pattern. This study also determines whether these pressure measurement devices are useful to evaluate the proper brace fabrication and helps in achieving optimum curve in-brace correction for patient with double curve AIS. There are 72 double curve AIS patients recruited in this study.

All patients had been asked to do nine different tasks according to every day's assigned tasks such as standing, maximal inspiration, maximal exhalation, walking, sitting knee 90°, supine, lying right side and left side, and prone after the sensor positioned onto the designated place. The readings were obtained at a time of 15 s and at a frequency of 13 Hz. After tightening the straps, patients were asked to do the same nine different postures again. Interface pressures exerted was recorded and analysed by using Tekscan software version of 6.51. This comparison helps us know about the deviation occurs in the interface pressure of double curve AIS patients before and after tightening the straps.

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3.2 Participants

A total of 72 participants (60 girls and 12 boys) aged 10 years and above participated in the study. Written informed consent was obtained from the parents and assent from the patients to participate in the study prior to enrolment. This experimental study involved participants from the Outpatient Scoliosis Clinic, Universiti Malaya Medical Centre (UMMC), Kuala Lumpur, Malaysia. Ethical approval was obtained from the UMMC Medical Ethics Review Committee. We conducted a convenient sampling on patients in the scoliosis clinic in UMMC.

Based on the doctors' (orthopaedic spine surgeons) notes and patients' X-ray results, those who fulfilled the inclusion criteria were approached. The inclusion criteria are as follows: (i) diagnosed as IS with double-curve pattern type, (ii) age must be 10 years and above, (iii) Cobb angle ranges 20° to 45°, (iv) Risser sign should be 0, 1 or 2 at the start of treatment, (iv) prescribed Chêneau brace, and (v) latest postero-anterior and lateral standing thoracolumbar spine radiographs with or without brace. Aim and procedure of the study were explained to patients and parents verbally. They were also provided the patient information sheet. The patients were examined again after 6 months of brace wearing.

3.3 Experimental procedure

In the fabrication process, the same brace maker fabricated the same brace design to all patients. **Figure 3.1** show the casting procedure to make the negative cast out of a patient body. **Figure 3.2** show the modification that has been done to the positive cast of a patient body. The modification is done according to Chêneau brace principle.

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Figure 3.1: Casting procedure.

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Figure 3.2: Modification

After modification, the next process is draping the plastic onto the positive cast. Thermoplastic is melted in the infrared oven and draped onto the cast. The cast then is cut and shaped according to Chêneau brace principle. **Figure 3.3** shows the fitting process of the Chêneau brace. Before the fitting session, the sensors were calibrated before the placement according to the mean weight of five healthy individuals. **Figure 3.4** show the sensor is cut and placed against apex of the hump**. Figure 3.5** is the top view of the sensor's placement. **Figure 3.6** illustrates the position of sensors and transducers during the experiment.

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Figure 3.3: Fitting

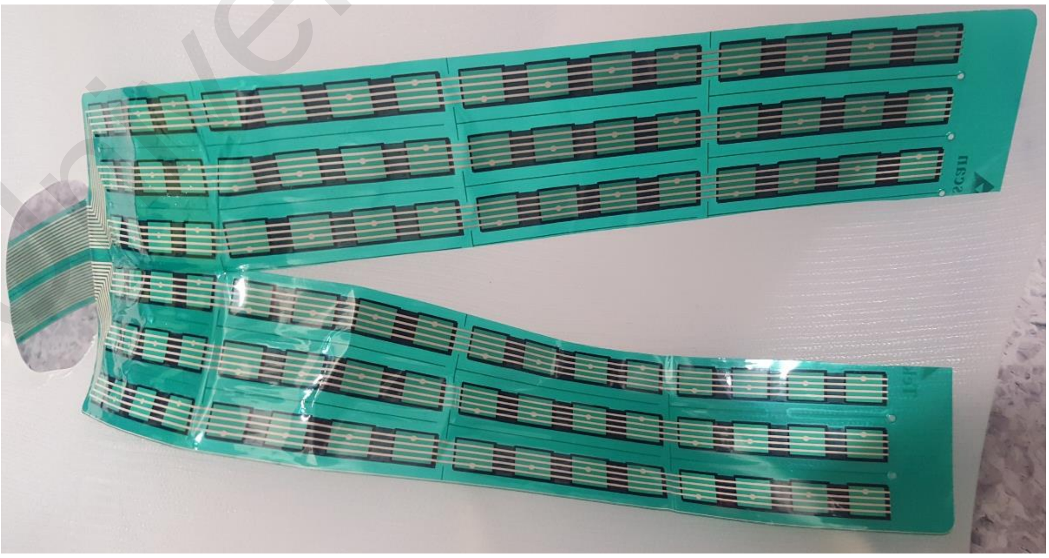

Figure 3.4: Sensor is cut and placed against apex of the hump

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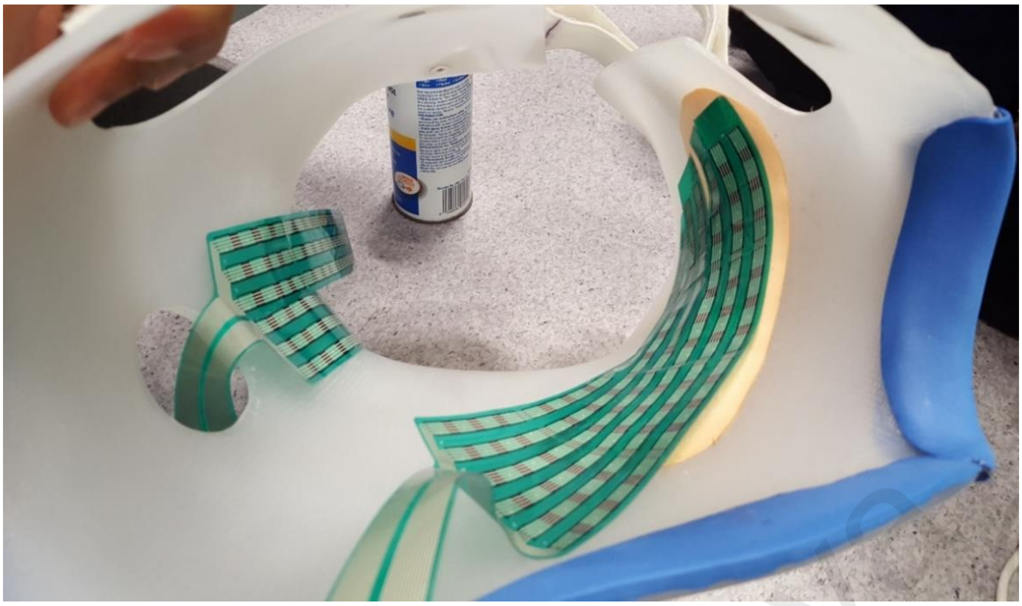

Figure 3.5: Top view of the sensors placement on the scoliosis brace.

Figure 3.6: Position of sensors and transducers during experiment.

All participants were asked to do the nine different tasks according to every day's assigned task. These tasks were standing whilst breathing normally, with maximum inspiration and expiration, walking, sitting at 90° knee flexion, lying supine and prone, and lying on the left and right side.

The readings were obtained at a time of 15 s and at a frequency of 13 Hz. After tightening the straps, patients were asked to do the same nine different tasks again. The interface pressure was acquired using the F-Socket 9811E pressure sensor connected to the Evolution Handle Sensor attached with a USB cable (Tekscan, USA). The sensor had 0.178 mm thickness and 96 cells. The sensors were placed in between the brace and patient back.

The placement of sensors was against apex of the hump, and it varied amongst patients, depending on the position of the humps. The pressure is given laterally for the thoracic curve, and for the thoracolumbar curve, the pressure is given posterior lateral. The key role of this sensor was to exert the maximum force on the scoliotic curve. The same processes were repeated for 72 patients. Interface pressure exerted was recorded and analysed by using Tekscan software version 6.51.

3.4 Ethical Approval

This research is conducted with the approval of permission by National Medical Research Register Secretariat 33628. The patient was aware with the consent from the research; Refer to Appendix C.

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3.5 Data Analysis

SPSS software version 25.0 (SPSS Inc., Chicago IL, USA) was used to perform statistical analysis. Paired sample t-test and Pearson's and Spearman's correlation coefficients were used in this analysis. Paired sample t-test was accomplished to analyse and compare the interface force from the nine different tasks against mean interface force in a standing position. The correlation between the mean force value and radiographic degree obtained after scoliosis correction after 6 months brace wearing was analysed using Pearson and Spearman's correlation coefficients. The significance threshold was set at a value of 0.05 **(Figure 3.7)**.

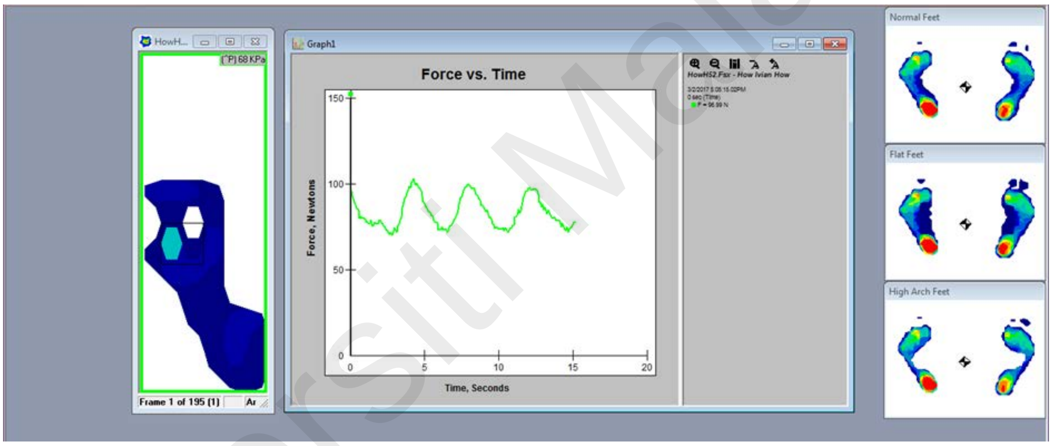

Figure 3.7: Forces at the areas of the graph.

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CHAPTER 4: RESULTS AND DISCUSSIONS

This chapter gives an explanation about the results and discussion of the data collected from the interface pressure measurement for double curve AIS patients. Paired sample t-test was accomplished to analyse and compare the interface force from the nine different tasks against mean interface force in a standing position.

4.1 Subject profile

The total number of patients were 72 out of them 60 were females and 12 were males. 80% of the patients were in normal weight whereas 20% were overweight. As for the Risser scale classification, 7 patients were still in the stage where there was no ossification at the level of iliac crest apophysis, 14 patients were at stage 1: apophysis under 25% of the iliac crest and 51 patients were in stage 2 where apophysis over 25-50% of the iliac crest. The demographic details are shown in the frequency distribution **Table 4.1**.

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Table 4.1: Frequency distribution

Variable	Level	n	Mean / %
Age		72	11.99
Gender	Female	60	83.3%
	Male	12	16.7%
BMI	Underweight (< 18.5)	0	0%
	Normal weight (18.5–24.9)	56	80%
	Overweight/Obese (≥ 25.0)	14	20%
Risser	no ossification	7	9.7%
	Apophysis under 25%	14	19.4%
	Apophysis over 25-50%	51	70.8%

In this study, recruited patients were double curve AIS patients that were followed-up for 6 months to check the effectiveness of the Chêneau brace in treating the double curve

AIS patients. The mean for the initial thoracic angle was 28.96 degree whereas the final thoracic angle was 21.87 degree. The mean for the initial thoracolumbar angle was 32.85 degree whereas the final thoracolumbar angle was 22.28 degree. The details of the angle are shown in the Cobb's Angle **Table 4.2**.

Table 4.2: Cobb's Angle

	N	Mean	Minimum	Maximum
Initial Thoracic angle	72	28.96	21	37
Final Thoracic angle	72	21.87	8	32
Initial Thoracolumbar	72	32.85	25	42
Final Thoracolumbar	72	22.28	11	38

4.2 Interface pressure

Pressure data were extracted from 72 patients for both types of curves. The mean interface forces for both types of curves are presented in **Tables 4.3 and Table 4.4**. In the standing position, normal and maximum strap tension were 71.6 ± 16.9 and 82.5 ± 17.1 kPa for right thoracic curve and 68.8 ± 14.9 and 85.1 ± 16.5 kPa for the left thoracolumbar curve, respectively.

Table 4.3: Mean interface force of daily tasks for thoracic curve for normal and maximum tension

	Mean Force (N)	
	Normal Tension	Maximum Tension
	Mean	Mean
Standing	71.6 ±16.9	82.5 ±17.1
Maximal Inspiration	85.8 ±20.3	111.71±24.50
Maximal exhalation	79.1 ±19.9	91.8 ±28.6
Walking	69.5 ±28.7	81.9 ±15.9
Sitting knee 90°	70.6 ±27.0	88.2 ±19.7

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Supine	77.7 ±18.5	90.2 ±22.5
Lying Right Side	80.6 ±16.8	99.6 ±20.3
Lying Left Side	37.8 ±19.4	56.8 ±20.7
Prone	54.3 ±19.4	76.3 ±20.4

Table 4.4: Mean interface force of daily tasks for lumbar curve for normal and maximum tension.

	Mean Force (N)	
	Normal Tension	Maximum Tension
	Mean	Mean
Standing	68.8 ±14.9	85.1 ±16.5
Maximal Inspiration	76.4 ±18.6	104.5 ±38.3
Maximal exhalation	66.5 ±24.5	90.4 ±26.5
Walking	65.0 ±25.7	81.6 ±17.7
Sitting knee 90°	67.8 ±21.6	86.5 ±14.0
Supine	65.0 ±16.3	92.7 ±15.3
Lying Right Side	69.2 ±15.0	95.7 ±19.6
Lying Left Side	37.6 ±19.1	46.2 ±13.5
Prone	61.8 ±20.7	79.7 ±20.2

The force significantly increased at the task of maximal inspiration ($p < 0.0001$) for both types of curves for normal and maximum tension. The mean force of both types of curves clearly increased after the maximum tension was applied to the straps. The values changed from one activity to the other, but all the values positively increased after maximum strap tension adjustment

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The mean interface forces for both types of curves also presented in **Figure 4.1 and Figure 4.2.**

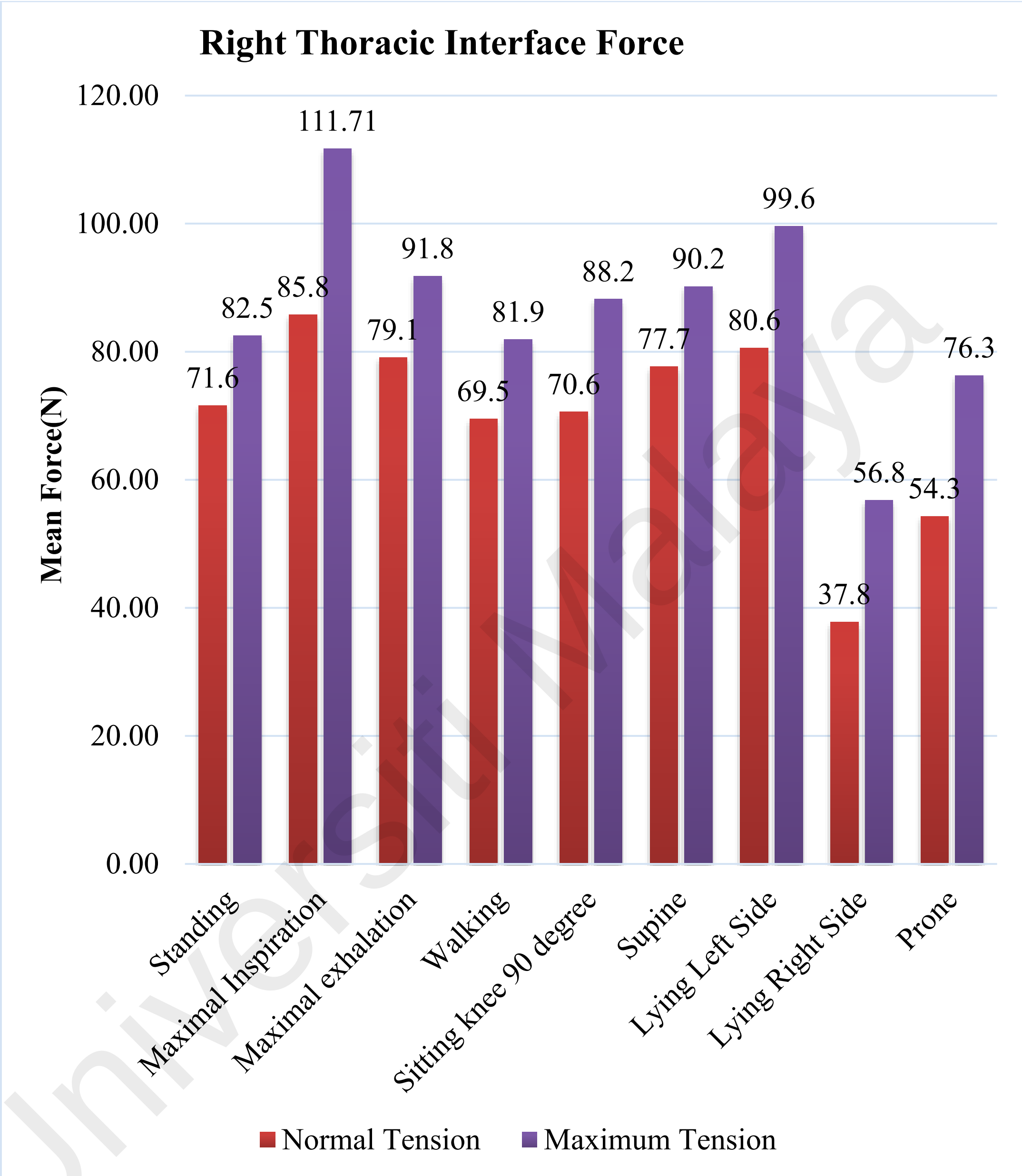

Figure 4.1: Mean interface force of daily tasks for thoracic curve for normal and maximum tension.

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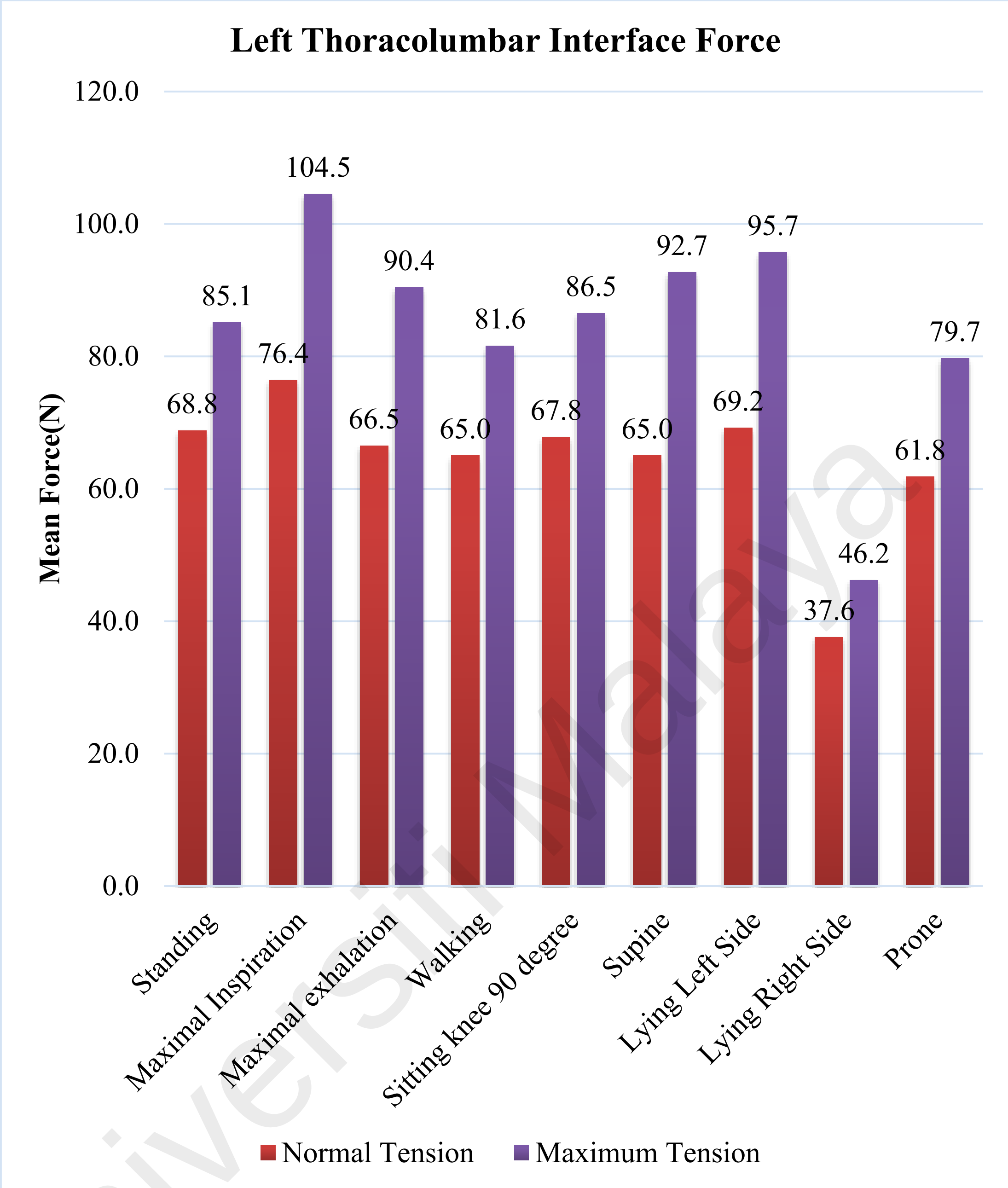

Figure 4.2: Mean interface force of daily tasks for thoracolumbar curve for normal and maximum tension.

The mean resultant interface force exerted on the patient body was higher after the strap adjustment (maximum tension) for all activities, indicating that the strap tension had a greater impact on the magnitude of the exerted force, Joon-Hyuk et al. (Joon-Hyuk, Stegall, & Agrawal, 2015) and Loukos et al (I. Loukos, C. Zachariou, C. Nicolopoulos, D. Korres, & N. Efstathopoulos, 2011) obtained the same result after strap adjustment. Aubin et al. (Aubin et al., 1999) studied the variability of the strap tension and suggested that regular strap tension adjustment is needed throughout the brace treatment due to the stretching of the straps that occur after some time due to voluntary and involuntary movements of the patient's body within the brace. Thus, for our brace design, we suggest patients to change the strap after every 4 months or whenever it is worn out.

The results also showed the mean interface force was higher for the right thoracic curve than left thoracolumbar curve in all positions except for the prone position. The interface forces are lower in prone position due of the action of gravity and position of the sensors. The results obtained are comparable with those of previous studies done by (Kotwicki & Cheneau, 2008; I. Loukos et al., 2011; van den Hout, van Rhijn, van den Munckhof, & van Ooy, 2002).

However, after 6 months of brace wearing, thoracolumbar curve acquired better correction compared with the thoracic curve. This is due to the fact that thoracolumbar curves are generally assumed to give better result in the brace treatment than thoracic curve. (Picault et al., 1986). Curves with thoracic apex tend to progress with prevalence of 58-100% progression (Bunnell, 1986; Picault et al., 1986; S. Weinstein & Ponseti, 1983; S. L. Weinstein et al., 2003).

The mean interface force during everyday tasks compared with that in the standing position for right thoracic curves are presented in **Table 4.5** and mean interface force of

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daily tasks in the standing position for left thoracolumbar curves are presented in **Table 4.6.**

Table 4.5: Mean interface force of daily tasks in the standing position for right thoracic curves.

	Mean Force (N)					
	Normal Tension			Maximum Tension		
	Mean	Mean Difference	*p*	Mean	Mean Difference	*p*
Standing	71.6 ± 16.9			82.5 ± 17.1		
Maximal Inspiration	85.8 ± 20.3	14.29	<0.001*	111.71 ± 24.5	29.16	<0.001 *
Maximal exhalation	79.1 ± 19.9	7.51	0.030*	91.8 ± 28.6	9.22	0.061
Walking	69.5 ± 28.7	-2.09	0.665	81.9 ± 15.9	-0.64	0.812
Sitting knee 90°	70.6 ± 27	-0.96	0.833	88.2 ± 19.7	5.67	0.092*
Supine	77.7 ± 18.5	6.16	0.054	90.2 ± 22.5	7.67	0.049*
Lying Right Side	80.6 ± 16.8	9.08	0.003*	99.6 ± 20.3	17.05	<0.001 *
Lying Left Side	37.8 ± 19.4	-33.78	<0.001*	56.8 ± 20.7	-25.72	<0.001 *
Prone	54.3 ± 19.4	-17.25	<0.001*	76.3 ± 20.4	-6.24	0.074

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Table 4.6: Mean interface force of daily tasks in the standing position for left thoracolumbar curves.

	Mean Force (N)					
	Normal Tension			Maximum Tension		
	Mean	Mean Difference	p	Mean	Mean Difference	p
Standing	68.8 ± 14.9			85.1 ± 16.5		
Maximal Inspiration	76.4 ± 18.6	7.64	0.019*	104.5 ± 38.3	7.64	0.004*
Maximal exhalation	66.5 ± 24.5	-2.25	0.585	90.4 ± 26.5	-2.25	0.233
Walking	65 ± 25.7	-3.82	0.378	81.6 ± 17.7	-3.82	0.246
Sitting knee 90°	67.8 ± 21.6	-0.96	0.791	86.5 ± 14	-0.96	0.533
Supine	65 ± 16.3	-3.77	0.174	92.7 ± 15.3	-3.77	0.005*
Lying Right Side	69.2 ± 15.0	0.47	0.854	95.7 ± 19.6	0.47	0.003*
Lying Left Side	37.6 ± 19.1	-31.2	<0.001*	46.2 ± 13.5	-31.2	<0.001*
Prone	61.8 ± 20.7	-7.02	0.049*	79.7 ± 20.2	-7.02	0.119

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We observed significant pressure increment during the maximal inspiration ($p < 0.001$) for thoracic and thoracolumbar curves ($p = 0.019$) compared with that in the standing position for both curve and strap tensions. Loukos et al. (I. Loukos et al., 2011) measured the pressure exerted by Dynamic Derotational Brace by using the F-Socket obtained the same results during the maximal inspiration for both curves. No significant difference was observed for the moment of maximal exhalation for the thoracolumbar curve with strap tension. However, the right thoracic curve was significantly different compared to maximal exhalation with normal tension, but the value changed at maximum tension. This finding could be different from other studies (Pham et al., 2008), because we measured the right thoracic and left thoracolumbar curves together simultaneously in a single body.

The values changed because the double-curve pattern possessed active mechanism of action between the two curves at the same time. In sitting and supine position, the value was not significant, except after maximum tension was applied for both types of the curve. The mean force value in the sitting position was lower than in the standing position with normal tension for both types of curves. However, these values exceeded the standing position value at maximum tension. Our results are also comparable with the study done by Babaee et al. (Babaee et al., 2017) who investigated the action of the Milwaukee brace. This happened when the knee and hip are flexed in the sitting position, pelvic is shifted backward and thoracolumbar lordosis reduced, thus interface pressure values also reduced.

In lying postures, the values for the moment of lying to the right and left were significant (p = 0.003) and (p < 0.001) during the normal and maximum tension for the thoracic curve. For thoracolumbar curve, both values only became significant (p = 0.003) and (p < 0.001) during maximum tension but not in the prone position. Our findings are similar with some reported studies by Pham et al. (Pham et al., 2008) and Wong & Evans (Wong & Evans, 1998). They studied the same pressure on Chêneau and Milwaukee braces in different positions such as supine, lying to left and right side, and prone. Prone position generated less pressure compared to other positions. However, the value increased during the maximum strap tension. In our study, the left curve was thoracolumbar curve, whereas the right curve was the thoracic curve. The thoracic curve had higher brace pressure than the thoracolumbar curve. This is because the action of the force in the thoracic area is opposed by the rib cage, but in the left thoracolumbar area, it is just the muscle and soft tissue. Also, there is a need to tighten the brace during lying position to maximize the brace pressure.

In this study, we were unable to observe any substantial correlation between mean force in standing position and curve correction degree for right thoracic and left thoracolumbar curves (*r = 0.158, p = 0.356 and – 0.024, p = 889*, respectively). The correlation between the mean interface force values in the standing position and the degree of curve correction are presented in **Table 4.7**.

Table 4.7: Correlation between the MPP values in the standing position and the degree of curve correction.

Curve Patterns	Mean Pressure in Standing Position	% Correction	Correlation Coefficient	*p*
Thoracolumbar	68.78	34.5	.158	.356
Thoracic	71.56	23.2	-.024	.889

Based on the literature studied, there are many factors which improve the outcome of the successful brace treatment such as optimal degree of the exerted force, suitable strap tension, good fit of brace, proper fabrication of brace and type of curve. In our study, the F-Socket sensor was found to be useful in studying the pressure distribution on the main force areas in double curve AIS patients. The value obtained could indicate the optimal brace fitting, which will improve the brace efficacy. According to best of our knowledge after thorough study of the reported literature, no work has been done so far on the analysis of degree of in-brace corrective force for AIS having double curves.

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CHAPTER 5: CONCLUSIONS

This chapter presents a summary derived from the thesis findings as well as future work to be done to improve or extend the presented work in this thesis.

5.1 Summary

In this study, the goal was to measure the interface pressure exerted by Chêneau brace in double-curve scoliosis pattern by using F-socket sensor and The Tekscan system. The quantitative data obtained from the study will help to evaluate the proper brace fabrication thus achieving optimum curve in-brace correction. These data will also provide insight in designing pressure measurement tool for scoliosis brace for double curve AIS patient in the future.

It is also found out that several positions altered the magnitude of forces exerted from the brace. Keeping the forces system intact to the body is important to prevent further deformity of the scoliotic curve. Tightening of brace straps always provided higher exerted pressure in all positions. Higher pressure was observed for right thoracic and left thoracolumbar curves during maximum inspiration. Interestingly, even though the exerted pressure in the thoracic area obtained a higher reading than in the thoracolumbar area, the degree of correction for the thoracolumbar area was higher than that for the thoracic area.

5.2 Limitation of the study

The limitation of our study is that we only measured the pressure for right thoracic and left thoracolumbar curve even though many of other curves are presents on different patients.

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5.3 Recommendation for future works

It is proven that the TLSO brace able to stop the curve progression by using corrective force. However, the magnitude and direction of these corrective forces remain unknown. The study has provided promising results. Nonetheless, it is recommended that further studies should be done to other curves pattern with more variation of sensors to further verify the result.

The pressure measurement can be designated practically to be used as brace fitting tools. This can provide an insight tool for the scoliosis treatment because the current practice in treating scoliosis brace patient, the fitting process involves making alterations to the brace that affect its corrective force capacity.

Furthermore, this measurement system can develop confident for the patient, thus increasing compliant. As a conclusion, the result of this work provides quantitative data for pressure measuring system and it is believed the Tekscan system can be used as one of the pressure measurement system in the scoliosis brace treatment in the future.

Future studies should rule out all other possible indications.

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REFERENCES

Ahmad, A., Abu Osman, N. A., Mokhtar, H., Mehmood, W., & Kadri, N. A. (2019). Analysis of the interface pressure exerted by the Chêneau brace in patients with double-curve adolescent idiopathic scoliosis. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 233*(9), 901-908.

Ali, S., Osman, N. A. A., Mortaza, N., Eshraghi, A., Gholizadeh, H., & Wan Abas, W. A. B. B. (2012). Clinical investigation of the interface pressure in the trans-tibial socket with Dermo and Seal-In X5 liner during walking and their effect on patient satisfaction. *Clinical Biomechanics, 27*(9), 943-948. doi: https://doi.org/10.1016/j.clinbiomech.2012.06.004

Alison Middleditch, M., & Jean Oliver, M. (2005). *Functional anatomy of the spine*: Elsevier Health Sciences.

Altaf, F., Gibson, A., Dannawi, Z., & Noordeen, H. (2013). Adolescent idiopathic scoliosis. *Bmj, 346*.

Aubin, C.-É., Labelle, H., Ruszkowski, A., Petit, Y., Gignac, D., Joncas, J., & Dansereau, J. (1999). Variability of Strap Tension in Brace Treatment for Adolescent Idiopathic Scoliosis. *Spine, 24*(4), 349-354.

Babaee, T., Kamyab, M., Ahmadi, A., Sanjari, M. A., & Ganjavian, M. S. (2017). Measurement of Milwaukee Brace Pad Pressure in Adolescent Round Back Deformity Treatment. *Asian Spine Journal, 11*(4), 627-633. doi: 10.4184/asj.2017.11.4.627

Brox, J. I., Lange, J. E., Gunderson, R. B., & Steen, H. (2012). Good brace compliance reduced curve progression and surgical rates in patients with idiopathic scoliosis. *European Spine Journal, 21*(10), 1957-1963.

Bunnell, W. P. (1986). The natural history of idiopathic scoliosis before skeletal maturity. *Spine, 11*. doi: 10.1097/00007632-198610000-00003

Busscher, I., Wapstra, F. H., & Veldhuizen, A. G. (2010). Predicting growth and curve progression in the individual patient with adolescent idiopathic scoliosis: design of a prospective longitudinal cohort study. *BMC musculoskeletal disorders, 11*(1), 1-9.

Colliard, C., Vachon, V., Circo, A. B., Beausejour, M., & Rivard, C. H. (2007). Effectiveness of the SpineCor brace based on the new standardized criteria proposed by the Scoliosis Research Society for adolescent idiopathic scoliosis. *J Pediatr Orthop, 27*. doi: 10.1097/01.bpb.0000271330.64234.db

d'Amato, C. R., Griggs, S., & McCoy, B. (2001). Nighttime bracing with the Providence brace in adolescent girls with idiopathic scoliosis. *Spine, 26*(18), 2006-2012.

Universiti Malaya

Danielsson, A. J., Hasserius, R., Ohlin, A., & Nachemson, A. L. (2010). Health-related quality of life in untreated versus brace-treated patients with adolescent idiopathic scoliosis: a long-term follow-up. *Spine, 35*(2), 199-205.

De Giorgi, S., Piazzolla, A., Tafuri, S., Borracci, C., Martucci, A., & De Giorgi, G. (2013). Chêneau brace for adolescent idiopathic scoliosis: long-term results. Can it prevent surgery? *European Spine Journal, 22*(6), 815-822. doi: 10.1007/s00586-013-3020-1

Deepak, A., Ong, J., Choon, D., Lee, C., Chiu, C., Chan, C., & Kwan, M. (2017). The Clinical Effectiveness of School Screening Programme for Idiopathic Scoliosis in Malaysia. *Malaysian orthopaedic journal, 11*(1), 41.

Deurloo, J. A., & Verkerk, P. H. (2015). To screen or not to screen for adolescent idiopathic scoliosis? A review of the literature. *Public Health, 129*(9), 1267-1272. doi: https://doi.org/10.1016/j.puhe.2015.07.021

Donzelli, S., Zaina, F., & Negrini, S. (2015). Compliance monitor for scoliosis braces in clinical practice. *Journal of children's orthopaedics, 9*(6), 507-508.

Dragašius, E., Eidukynas, D., Jūrėnas, V., Mažeika, D., Galdikas, M., Mystkowski, A., & Mystkowska, J. (2021). Piezoelectric Transducer-Based Diagnostic System for Composite Structure Health Monitoring. *Sensors, 21*(1), 253.

El-Sayed, A. M., Hamzaid, N. A., & Abu Osman, N. A. (2014). Piezoelectric bimorphs' characteristics as in-socket sensors for transfemoral amputees. *Sensors, 14*(12), 23724-23741.

Garg, B., Ahuja, K., & Basu, S. (2020). Bracing in adolescent idiopathic scoliosis. *Indian Spine Journal, 3*(2), 151.

Goldberg, C., Moore, D., Fogarty, E., & Dowling, F. (2001). Adolescent idiopathic scoliosis: the effect of brace treatment on the incidence of surgery. *Spine, 26*(1), 42-47.

Gordon, R. I., & Dhokia, R. (2021). Clinical examination of the spine. *Surgery (Oxford)*.

Hacquebord, J. H., & Leopold, S. S. (2012). In brief: The Risser classification: a classic tool for the clinician treating adolescent idiopathic scoliosis. *Clinical orthopaedics and related research, 470*(8), 2335-2338.

Hadagali, P. (2014). *Subject-specific Finite Element Modeling of the Adolescent Thoracic Spine for Scoliosis Research.*

Horne, J. P., Flannery, R., & Usman, S. (2014). Adolescent idiopathic scoliosis: diagnosis and management. *American family physician, 89*(3), 193-198.

Joon-Hyuk, P., Stegall, P., & Agrawal, S. K. (2015, 26-30 May 2015). *Dynamic brace for correction of abnormal postures of the human spine.* Paper presented at the 2015 IEEE International Conference on Robotics and Automation (ICRA).

Universiti Malaya

Karimi, M. T., Rabczuk, T., & Pourabbas, B. (2020). Evaluation of the efficiency of various force configurations on scoliotic, lordotic and kyphotic curves in the subjects with scoliosis. *Spine deformity*.

Kotwicki, T., & Cheneau, J. (2008). Biomechanical action of a corrective brace on thoracic idiopathic scoliosis: Cheneau 2000 orthosis. *Disabil Rehabil Assist Technol, 3*(3), 146-153. doi: 10.1080/17483100801905744

Lenke, L. G., Betz, R. R., Clements, D., Merola, A., Haher, T., Lowe, T., . . . Blanke, K. (2002). Curve prevalence of a new classification of operative adolescent idiopathic scoliosis: does classification correlate with treatment? *Spine, 27*(6), 604-611.

Lenz, M., Oikonomidis, S., Harland, A., Fürnstahl, P., Farshad, M., Bredow, J., . . . Scheyerer, M. J. (2021). Scoliosis and Prognosis—a systematic review regarding patient-specific and radiological predictive factors for curve progression. *European Spine Journal*, 1-10.

Little, D. G., & Sussman, M. D. (1994). The Risser sign: a critical analysis. *Journal of pediatric orthopedics, 14*(5), 569-575.

Lonstein, J. E., & Winter, R. B. (1994). The Milwaukee brace for the treatment of adolescent idiopathic scoliosis. A review of one thousand and twenty patients. *The Journal of bone and joint surgery. American volume, 76*(8), 1207-1221.

Lou, E., Hill, D., & Raso, J. (2008). Brace treatment for adolescent idiopathic scoliosis. *Studies in health technology and informatics, 135*, 265.

Loukos, I., Zachariou, C., Nicolopoulos, C., Korres, D., & Efstathopoulos, N. (2011). Analysis of the corrective forces exerted by a dynamic derotation brace (DDB). *Prosthetics and orthotics international, 35*(4), 365-372.

Loukos, I., Zachariou, C., Nicolopoulos, C., Korres, D., & Efstathopoulos, N. (2011). Analysis of the corrective forces exerted by a dynamic derotation brace (DDB). *Prosthet Orthot Int, 35*(4), 365-372. doi: 10.1177/0309364611420477

Lowe, T., Berven, S. H., Schwab, F. J., & Bridwell, K. H. (2006). The SRS classification for adult spinal deformity: building on the King/Moe and Lenke classification systems. *Spine, 31*(19S), S119-S125.

Murphy, R. F., & Mooney, J. F. (2019). Current concepts in neuromuscular scoliosis. *Current reviews in musculoskeletal medicine, 12*(2), 220-227.

Murrell, G., Coonrad, R. W., Moorman 3rd, C., & Fitch, R. D. (1993). An assessment of the reliability of the Scoliometer. *Spine, 18*(6), 709-712.

Nachemson, A. L., Peterson, L.-E., Bradford, D., Burwell, R., Duhaime, M., Edgar, M., . . . Lidstrom, J. (1995). Effectiveness of treatment with a brace in girls who have adolescent idiopathic scoliosis. A prospective, controlled study based on data from the Brace Study of the Scoliosis Research Society. *Journal of Bone and Joint Surgery-Series A, 77*(6), 815-822.

Universiti Malaya

Negrini, S., Donzelli, S., Aulisa, A. G., Czaprowski, D., Schreiber, S., de Mauroy, J. C., . . . Kotwicki, T. (2018). 2016 SOSORT guidelines: orthopaedic and rehabilitation treatment of idiopathic scoliosis during growth. *Scoliosis and spinal disorders, 13*(1), 1-48.

Paria, N., & Wise, C. A. (2015). *Genetics of adolescent idiopathic scoliosis.* Paper presented at the Seminars in Spine Surgery.

Pham, V. M., Houilliez, A., Schill, A., Carpentier, A., Herbaux, B., & Thevenon, A. (2008). Study of the pressures applied by a Cheneau brace for correction of adolescent idiopathic scoliosis. *Prosthetics and Orthotics International, 32*(3), 345-355. doi: 10.1080/03093640802016092

Picault, C., Mouilleseaux, B., & Diana, G. (1986). Natural history of idiopathic scoliosis in girls and boys. *Spine, 11*(8), 777-778.

Ponseti, I. V., & Friedman, B. (1950). Prognosis in idiopathic scoliosis. *J Bone Joint Surg Am, 32*(2), 381-395.

Reamy, B. V., & Slakey, J. (2001). Adolescent idiopathic scoliosis: review and current concepts. *American family physician, 64*(1), 111.

Rivard, C. H., & Coillard, C. (2002). SpineCor System. *Scoliosis Research Society*.

Rowe, D. E., Bernstein, S. M., Riddick, M. F., Adler, F., Emans, J. B., & Gardner-Bonneau, D. (1997). A meta-analysis of the efficacy of non-operative treatments for idiopathic scoliosis. *JBJS, 79*(5), 664-674.

Schlösser, T. P., Semple, T., Carr, S. B., Padley, S., Loebinger, M. R., Hogg, C., & Castelein, R. M. (2017). Scoliosis convexity and organ anatomy are related. *European Spine Journal, 26*(6), 1595-1599.

Sferruzza, J.-P., Birer, A., Matias, A., Theillère, Y., & Cathignol, D. (2001). Experimental identification of a piezoelectric material for high impulse pressure wave applications. *Sensors and Actuators A: Physical, 88*(2), 146-155.

van den Hout, J. A. A. M., van Rhijn, L. W., van den Munckhof, R. J. H., & van Ooy, A. (2002). Interface corrective force measurements in Boston brace treatment. *European Spine Journal, 11*(4), 332-335. doi: 10.1007/s00586-001-0379-1

Vasiliadis, E., & Grivas, T. B. (2008). Quality of life after conservative treatment of adolescent idiopathic scoliosis. *Studies in health technology and informatics, 135*, 409.

Weinstein, S., & Ponseti, I. (1983). Curve progression in idiopathic scoliosis. *The Journal of bone and joint surgery. American volume, 65*(4), 447-455.

Weinstein, S. L., Dolan, L. A., Cheng, J. C. Y., Danielsson, A., & Morcuende, J. A. (2008). Adolescent idiopathic scoliosis. *The Lancet, 371*(9623), 1527-1537. doi: https://doi.org/10.1016/S0140-6736(08)60658-3

University Malaya

Weinstein, S. L., Dolan, L. A., Spratt, K. F., Peterson, K. K., Spoonamore, M. J., & Ponseti, I. V. (2003). Health and function of patients with untreated idiopathic scoliosis: A 50-year natural history study. *JAMA, 289*(5), 559-567. doi: 10.1001/jama.289.5.559

Weiss, H.-R., Karavidas, N., Moramarco, M., & Moramarco, K. (2016). Long-term effects of untreated adolescent idiopathic scoliosis: a review of the literature. *Asian spine journal, 10*(6), 1163.

Weiss, H.-R., & Werkmann, M. (2012). Rate of surgery in a sample of patients fulfilling the SRS inclusion criteria treated with a Chêneau brace of actual standard. *Stud Health Technol Inform, 176*, 407-410.

WHITE III, A. A. (1989). Clinical biomechanics of cervical spine implants. *Spine, 14*(10), 1040-1045.

Wong, M., & Evans, J. (1998). Biomechanical evaluation of the Milwaukee brace. *Prosthetics and orthotics international, 22*(1), 54-67.

Wynarsky, G. T., & Schultz, A. B. (1991). Optimization of skeletal configuration: Studies of scoliosis correction biomechanics. *Journal of Biomechanics, 24*(8), 721-732. doi: 10.1016/0021-9290(91)90336-L

Zaborowska-Sapeta, K., Kowalski, I. M., Kotwicki, T., Protasiewicz-Fałdowska, H., & Kiebzak, W. (2011). Effectiveness of Cheneau brace treatment for idiopathic scoliosis: prospective study in 79 patients followed to skeletal maturity. *Scoliosis, 6*(1), 1-5.

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LIST OF PUBLICATIONS AND PAPERS PRESENTED

Conference

1. **Ahmad, A.,** Abu Osman, N. A., Mokhtar, H., Mehmood, W., & Kadri, N. A. (2019). Analysis of the interface pressure exerted by the Chêneau brace in patients with double-curve adolescent idiopathic scoliosis. Conference for International Conference on Orthotics and Prosthetics.Accepted for oral presentation.

Journal paper

1. **Ahmad, A.,** Abu Osman, N. A., Mokhtar, H., Mehmood, W., & Kadri, N. A. (2019). Analysis of the interface pressure exerted by the Chêneau brace in patients with double-curve adolescent idiopathic scoliosis. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 233(9), 901-908. **(Published)**
2. Fuss, F. K., **Ahmad, A**., Tan, A. M., Razman, R., & Weizman, Y. (2021). Pressure Sensor System for Customized Scoliosis Braces. Sensors, 21(4), 1153 **(Published)**

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