THE DEVELOPMENT OF A THREE-DIMENSIONAL CERVICAL SPONDYLOTIC MYELOPATHY FINITE ELEMENT MODEL AND MEASUREMENTS OF ITS MECHANICAL AND FLUID DYNAMICS: PRE-TESTING

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BY

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2D	2-Dimensional
3D	3-Dimensional
AP	Anteroposterior
CD	Compact Disc
CFD	Computational Fluid Dynamics
CSF	Cerebrospinal Fluid
CSM	Cervical Spondylotic Myelopathy
CT	Computed Tomography
dMRI	Dynamic Magnetic Resonance Imaging
FE	Finite Element
FSI	Fluid-Solid Interaction
HU	Hounsfield Units
HUSM	Hospital Universiti Sains Malaysia
JEPeM	Jawatankuasa Etika Penyelidikan Manusia
MRI	Magnetic Resonance Imaging
ROI	Region of Interest
USM	Universiti Sains Malaysia
UTM	Universiti Teknologi Malaysia
WHO	World Health Organization

PEMBANGUNAN MODEL *FINITE ELEMENT* 3-DIMENSI *CERVICAL SPONDYLOTIC MYELOPATHY* SERTA UKURAN MEKANIKAL DAN DINAMIK BENDALIR: PRA-UJIAN

ABSTRAK

Pengenalan: *Cervical spondylotic myelopathy* (CSM) adalah disfungsi saraf tunjang yang disebabkan oleh perubahan degeneratif dalam kolum vertebra dan ia merupakan masalah yang biasa dalam populasi warga tua. Perubahan degeneratif ini menyebabkan adanya peningkatan tekanan dalam saluran vertebra dan tekanan pada saraf tunjang dalam kes CSM yang teruk. Matlamat kajian ini adalah untuk melihat perbezaan bagi tekanan dalam saluran vertebra dan aliran cecair serebrospinal (CSF) di antara tulang vertebra servikal normal dan tulang vertebra CSM.

Kaedah: Kajian kes perbandingan telah digunakan sebagai reka bentuk kajian. Dua model *finite element* (FE) 3-dimensi (3D) telah dibangunkan; satu model tulang vertebra servikal normal dan satu model tulang vertebra CSM. Model FE 3D, kemudiannya digunakan untuk melihat perbezaan tekanan pada saraf tunjang, tekanan cecair serebrospinal (CSF) serta aliran CSF antara tulang-tulang vertebra servikal normal dan tulang vertebra.CSM.

Keputusan: Pada 3D FE model CSM, telah dapat dikenalpasti bahawa pada vertebra C3 hingga C6, terdapat penurunan ketinggian badan vertebra, pertumbuhan tulang-tulang baru (*osteophyte)*, Oleh itu, telah berlaku penyempitan pada ruang *subarachnoid* dan tekanan saraf tunjang dapat dilihat. Disamping itu, tekanan purata pada saraf tunjang untuk tulang vertebra CSM adalah 3.89% lebih tinggi dan untuk tekanan CSF untuk tulang vertebra CSM adalah 4.29% lebih tinggi berbanding tulang vertebra normal. Seterusnya, bagi aliran CSF tulang vertebra CSM, ia menunjukkan 6.06% lebih perlahan halaju berbanding tulang belakang normal.

Kesimpulan: Dapatan kajian ini mengesahkan, tekanan dalam tulang vertebra CSM adalah lebih tinggi berbanding tulang vertebra servikal normal, dan tekanannya bertambah tinggi pada tahap terjejas iaitu pada C3 hingga C6.. Walau bagaimanapun, dapat juga dilihat bahawa perubahan dalam keadaan tulang vertebra CSM juga mempengaruhi vertebra di bahagian atas dan bawah. Selain itu, kaedah 3D *finite element* yang digunakan berfungsi sebagai alat kajian alternatif untuk kajian pada tulang vertebra.

THE DEVELOPMENT OF A THREE-DIMENSIONAL CERVICAL SPONDYLOTIC MYELOPATHY FINITE ELEMENT MODEL AND MEASUREMENTS OF ITS MECHANICAL AND FLUID DYNAMICS: PRE-TESTING

ABSTRACT

Background: Cervical spondylotic myelopathy (CSM) is a spinal cord dysfunction caused by degenerative changes in the vertebral column and it is the most common disorder in the elderly population. The degenerative changes may lead to increased pressure in the vertebral canal and spinal cord compression in severe cases. The aim of this study is to look for the observable difference of the pressure in the vertebral canal and the cerebrospinal fluid (CSF) flow between a normal cervical spine and CSM spine.

Method: Comparative case-control study design was used.Two 3-dimensional (3D) patient-specific finite element (FE) models were developed; one for a normal spine and one for CSM spine. The 3D FE models were then used to determine and observe the changes in pressure on the spinal cord, pressure of the cerebrospinal fluid (CSF) and the CSF flow between the normal cervical spine and CSM spine.

Results: From the developed 3D FE model, it was observed in the 3D FE CSM model, at the level of C3 until C6 vertebra the height of the vertebral body decreases, there are presence of osteophytes, thus narrowing of the subarachnoid space and spinal cord compression were also visualised. In addition, the average pressure on the spinal cord for CSM spine is 3.89% higher and for the pressure of the CSF for CSM spine is 4.29% higher compared to normal spine. Besides that, for the CSF flow of the CSM spine, it showed 6.06% slower in the velocity compared to the normal spine.

Conclusion: This study confirms the higher pressure in a CSM spine compared to a normal spine, in which the pressure was worsen at the affected level C3 to C6; however, it is also noted that the changes in CSM condition also influenced the upper and lower-level vertebra. Besides that, the 3D finite element method used serves as an alternative research tool in spine study.

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Cervical spondylotic myelopathy (CSM) is a spinal cord dysfunction caused by degenerative changes in the vertebral column. In most cases, this process is caused by degenerative changes in the cervical spine, with the most severe cases resulting in spinal cord compression. The dynamic mechanisms in excessive movement of the spine with spinal cord compression will result in traumatic spine injury. The clinical symptoms of cervical spondylotic myelopathy range from mild axial neck pain, sensory loss, motor weakness, spastic gait, fine motor dysfunction, and loss of sphincter control (Tracy & Bartleson, 2010; Heary *et al.*, 2018).

Furthermore, when the spine's discs age, they lose height, bulge, dry up, lose water content, and become stiffer (Zileli *et al.*, 2019). This condition causes the disc spaces to settle or collapse, resulting in a loss of disc space height. The vertebrae move closer together as the discs lose their height. The body strengthens the disc by producing additional bony spurs around it in response to the deflated disc. The whole spine structure stiffens, and the vertebral canal narrows because of these bone spurs. As a result, the spinal cord will be compressed or squeezed.

The vertebral disc will herniate when the jelly-like centre inside the vertebral disc, which is the nucleus pulposus, pushes against the outer ring, which is known as annulus fibrosus. The nucleus pulposus may press through when the annulus fibrosus has been worn or damaged. A herniated disc can impose pressure on the spinal cord or the nerve roots when it bulges out towards the spinal cord.

Tingling sensation or numbness in the arms, fingers, or hands and weaknesses in the shoulders or hand muscles indicate cervical spondylotic myelopathy. Patients may have trouble grasping or holding objects in their hands. They will become unstable and have other coordination concerns, such as finding it difficult to walk or falling over. In myelopathy, there is no sense of spinning. Instead, their head and eyes are steady, but their bodies cannot complete the task at hand.

Fine motor skills such as handwriting, buttoning clothes, picking up money, and feeding themselves may be problematic for certain people. Nonsurgical therapies such as a soft cervical collar, physical therapy, or medications like nonsteroidal anti-inflammatory drugs or oral corticosteroids may be utilised in milder cases of CSM. The goal is to reduce pain and improve the patient's capacity to do daily tasks.

1.2 Problem Statement

According to the World Health Organization (2018), the life expectancy of the human population is getting longer, where the percentage of older people is higher than the younger children. A well-documented problem or disease associated with the global ageing factor among the adult population is cervical spondylotic myelopathy (CSM) (Badhiwala *et al.*, 2018; Nouri *et al.*, 2020). Kalsi-Ryan, Karadimas and Fehlings (2013) share that a nontraumatic, degenerative form of cervical spondylotic myelopathy is the commonest cause of spinal cord impairment in the elderly population. As the population ages, the incidence of CSM will continue to rise. The authors also share that a patient's quality of life is affected, and this is due to the limited range of motion of the neck and sensational loss due to the compression of the spinal cord. Because of the limited range of motion, the vertebral canal is also said to be under increased pressure.

Since the damage to the cervical spinal cord is often irreversible, previous authors have recommended early diagnosis and decompression surgery even in cases of mild myelopathy to prevent further neurological deterioration (Badhiwala *et al.*, 2018; Joaquim *et al.*, 2016). A diagnostic MRI is required if myelopathy is suspected to establish the cause, to confirm the diagnosis, and to evaluate the spinal cord compression and dysfunction symptoms.

According to Kolcun *et al.* (2017), MRI is said to be a gold standard in diagnosing CSM as the MRI is best in visualizing soft tissue. Both static and dynamic MRI are useful tools in diagnosing CSM; however, there are still some drawbacks observed from this method , for example, patients that cannot undergo the MRI procedure due to the MRI contraindication. Regarding decompression surgery in CSM treatment, the most common approach is laminoplasty (Hirano et al., 2018; Weinberg and Rhee, 2020; Lin et al., 2019). However, the surgical approaches may also vary according to the severity of the CSM and the patient's condition. There are reported complication rates depending on the surgical approach (Shiban and Meyer, 2014; Farrokhi et al., 2016; Bakhsheshian, Mehta and Liu, 2017). Additionally, previous studies have demonstrated that the risk of complications increases significantly with advancing age (Bakhsheshian, Mehta and Liu, 2017). The elderly appears to have a significantly higher risk of complications than younger adults, including the risk of longer length of stay and the mortality rate after surgery ((Passias et al., 2017; Badhiwala *et al.*, 2020).

Integration with the engineering method of analysis has been the advancement in medical research, mainly in the biomechanics field. The finite element (FE) analysis is a standard tool used in the engineering field to assess the stability and stress-strain distribution of a complex geometry structure (Cattaneo, Dalstra & Frich, 2015). The human spine is known to be a complex structure; therefore, it is said that the FE analysis may help in giving better visualisation of the spine structures such as the vertebral body and the spinal cord (Kim *et al.*, 2018) and by using this finite element method, a patient-specific spine can be created and analysed.

Consequently, it is believed that there is a presence of a knowledge gap in some areas of research on CSM. For instance, the precise aetiology and history of the CSM remain undefined (Tetreault *et al.*, 2017). Similarly, some authors did some studies on the recovery plan for the patient with CSM (Badran *et al.*, 2018; Fehlings *et al.*, 2013). Additionally, a study by Mowforth *et al.* (2019) finds that only limited research is being conducted on some research themes, such as the epidemiology of CSM. Most studies focus more on the management and treatment plan of CSM instead of understanding its mechanism. Not to mention, Bakhsheshian, Mehta and Liu, (2017) also point out that it is important to understand more about the CSM to make a more informed diagnosis and treatment plan. On that account, having a 3D patient-specific FE model spine helps to appreciate the problems causing the CSM.

1.3 Justification of Study

Mowforth *et al.* (2019) shares that although the amount of research and research areas on CSM has been increasing annually, there is little diversity. A 3D FE model can help to visualise and understand the anatomical structure; so, the dynamic mechanism of the cervical spondylotic myelopathy can be seen better (Kim *et al.*, 2018; Manickam & Roy, 2021). In addition, the 3D FE model is a patient-specific model, and it can be a good tool as a part of advancement in teaching and learning gross anatomy. Therefore, explaining the multitude of clinical presentations of cervical myelopathy in a developed 3D FE model is essential. The vertebral body and spinal cord condition can be compared using this 3D FE model for the normal cervical spine and a CSM spine.

With the findings from this study, better visualisation of the CSM spine conditions were obtained; hence, we could see in the CSM 3D FE model whether it only influences the specific affected area/level or does it influence the whole cervical vertebra structure. Furthermore, using the finite element analysis, the detailed view of the position of osteophytes and their sizes and the impingement it caused in CSM can aid the surgeon in manipulating and managing the case in decompression surgery. Moreover, the finite element can be a new technological advancement in spine surgery that can benefit pre-operative planning, surgical simulations, patient-clinician communication, education, intraoperative assistance, and even implantable devices.

This study opens the opportunity for future research to explore the CSM spine's behaviour and improve the surgical procedure in CSM and other spine surgery using finite element analysis. Having the 3D FE model may improve patient safety, and it may assist surgeons in performing more intricate procedures in spine surgery. However, more research is needed to maximise its potential and understand the spinal structures and the different approaches in spine surgery where it can be used safely. This study may provide a new platform or guideline to help improve surgical techniques, such as choosing the best approach for decompression surgery. This is because there are also some debates on the approaches for the surgery and the concern with post-operative complications for the patient (Hirano *et al.*, 2018; Weinberg & Rhee, 2020; Lin *et al.*, 2019)

1.4 Objectives

1.4.1 General Objectives

To develop 3D FE model of cervical spine model and benchmark its mechanical and fluid dynamic properties using the 3D FE normal cervical spine model

1.4.2 Specific Objectives

1. To develop a 3D FE model of the normal cervical spine and CSM spine
2. To examine the morphological features of a 3D CSM FE model
3. To examine the morphological parameters of the 3D CSM FE model;
   a) Anteriorposterior diameter of CSF column
   b) Anteriorposterior and transverse diameter of spinal cord
   c) Spinal cord area
4. To examine the pressure exerted on the spinal cord surface in 3D normal cervical spine and CSM FE model
5. To examine the CSF dynamics by measuring the CSF pressure and CSF flow in 3D normal cervical spine and CSM FE model

1.5 Research Question

1. What is the difference in the morphological features between CSM and a normal cervical spine?
2. What is the difference in the pressure exerted on the spinal cord surface between CSM and a normal cervical spine?

3. What is the difference of pressure of the cerebrospinal fluid between CSM and a normal cervical spine?
4. What is the difference in the flow of the cerebrospinal fluid between CSM and a normal cervical spine?

1.6 Operational Definition

1. Finite Element Model

Finite Element Model (FEM) is a virtual representation of an anatomical structure and its biomechanics to provide a better understanding of its condition based on the different implemented parameters

2. Finite Element Analysis

Finite element analysis (FEA) is a computational analysis method used to analyse the numerical-computerised finite element model developed

3. Computational Fluid Dynamics

Computational fluid dynamics (CFD) is the process of mathematically modelling a physical phenomenon involving fluid flow and solving it numerically using the computational facility

4. Hounsfield Unit

Hounsfield unit (HU) is a relative quantitative measurement of radio density used in the interpretation of computed tomography (CT) images. The absorption or attenuation coefficient of radiation within a tissue is used during CT reconstruction to produce a grayscale image.

5. Region of Interest

Region of interest (ROI) is an area of an image that will be the focus in the image analysis or in the study

CHAPTER 2

LITERATURE REVIEW

2.1 Gross Anatomy of Vertebral Column

An adult human spine or vertebral column consists of 33 vertebrae, and in between the vertebrae, there is an intervertebral disc except at the fused sacral and coccygeal vertebrae. The vertebral column encloses and protects the spinal cord and supports the head and trunk (Moore, Dalley & Agur, 2018). The intervertebral discs act as the shock absorber and prevent the vertebrae from being damaged by the impact of stress and pressure of carrying a heavy object or walking to support body weight. The annulus fibrosus may rupture or weaken the nucleus pulposus content inside the intervertebral disc; thus, the intervertebral disc may protrude into the spinal canal when the vertebral column is under a lot of stress and pressure. The protrusion causes pain and compression of the spinal cord, which can cause impingement to the spinal cord and spinal nerves, including its branches. Additionally, the intervertebral discs may also degenerate, which occurs in response to ageing (Iyer, Azad & Tharin, 2016)

The cervical vertebrae have three main features which distinguish them from other vertebrae. For the typical cervical vertebra, C3, C4, C5 and C6 have a triangular vertebral foramen and a bifid spinous process, where their spinous processes split into two distally. The presence of foramen transversarium in the transverse process gives a passage to the vertebral artery, vein, and sympathetic nerves (Moore, Dalley & Agur, 2018). Atypical cervical vertebra, C1 vertebra has no vertebral body and no spinous process. However, it has a large, round vertebral foramen bounded by anterior and posterior arches, and it has lateral masses connected by an anterior and posterior arch (Wineski and Snell, 2019).

Each lateral mass contains a superior articular facet (for articulation with occipital condyles) and an inferior articular facet (for articulation with C2). The anterior arch contains a facet for articulation with the dens of the axis. Following that, the C2 vertebra bears the dens or the odontoid process on the superior aspect of its body. The dens articulate with the anterior arch of the atlas, forming the medial atlanto-axial joint. C6 to C7 bear the primary load from the weight of the head. Wineski and Snell (2019) also shares that, C7 vertebra is an atypical vertebra that started to change a little bit in its morphology. It has a relatively long and non-bifid spinous process; its foramen transversarium is small and does not transmit vertebral arteries.

The T1 vertebra, an atypical thoracic vertebra, has a smaller and circular vertebral foramen, a long pair of the transverse process that extends posteriorly, a long spinous process, and the presence of a complete facet for the articulation with the first rib and a demi-facet for the second rib. The demi-facets are on the sides of each vertebral body. The cervical spine has a curvature, known as the cervical lordosis, which is concave posteriorly. On the other hand, the vertebral canal is an anatomical region that extends from the foramen magnum through the vertebral column and houses the spinal cord and its covering. The vertebral canal acts as a protective space for the spinal cord, meninges, and cerebrospinal fluid (Moore, Dalley & Agur, 2018). However, the authors also mentioned that there are variations in vertebrae structure, where it can be influenced by race, gender, and developmental factors (genetic and environmental).

The spinal cord is a long tubular structure extending from the brainstem, and it continues distally until the conus medullaris. In the spinal cord centre is an 'H-like' or butterfly shaped grey matter. The grey matter is surrounded by white matter, which contains the long ascending and descending tracts. The spinal cord conducts sensory and motor impulses to and from the brain and controls many reflexes. CSM can cause impingement to the corresponding tracts located in the white matter of the spinal cord if the defect is severe (Martini *et al*., 2018).

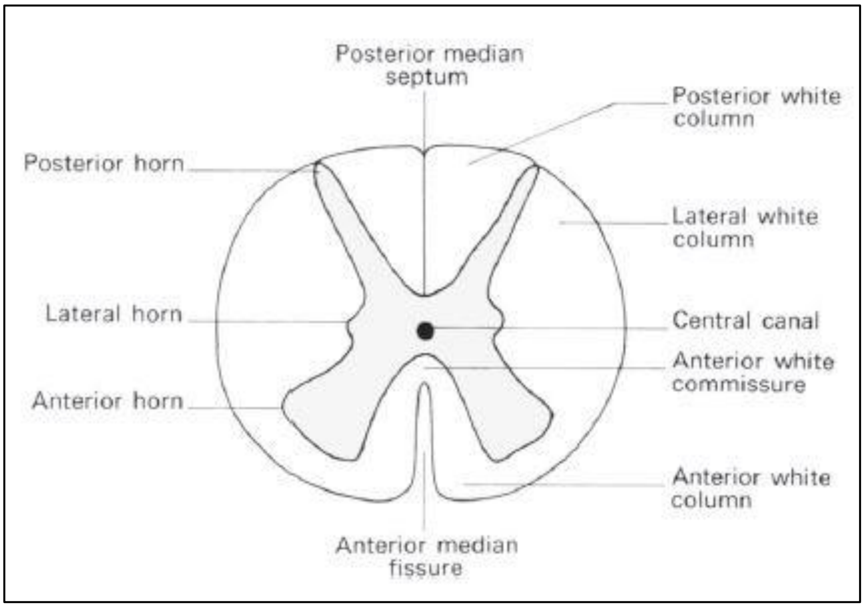

Figure 2.1 Spinal cord section (Retrieved from Ellis & Mahadevan, 2013)

It also has the cervical enlargement that stretches from the C4 to T1 spinal cord segments, and most of the anterior rami of the spinal nerves emerging from it form the brachial plexus that innervates the upper limbs (Moore, Dalley & Agur, 2018). The spinal cord is divided into 31 segments, in which each forms a pair of spinal nerves. Table 2.1 shows the spinal nerve segment and its exit level. The exit level is important if the osteophytes formed in CSM compress the root or spinal nerves that exit through each level.

Table 2.1 Spinal nerves segment and exit level

Segmental Level	Number of Nerves	Level of Exit from Vertebral Column
Cervical	8 (C1-C8)	Nerve C1 passes superior to the arch of vertebra C1
		Nerve C2-C7 pass through intervertebral foramina superior to the corresponding vertebrae
		Nerve C8 passes through the intervertebral foramen between C7 and T1
Thoracic	12 (T1-T12)	Nerve T1-L5 pass through intervertebral foramina inferior to the corresponding vertebrae
Lumbar	5 (L1-L5)	
Sacral	5 (S1-S5)	Nerve S1-S4 branch into anterior and posterior rami within the sacrum, with the respective rami passing through the anterior and posterior sacral foramina
Coccygeal	1 (Co1)	5th sacral and coccygeal nerves pass through the sacral hiatus

(Modified from Barr's The Human Nervous System. Retrieved from Moore, Dalley & Agur, 2018)

The anterior rami will form four major plexuses, namely the cervical plexus, brachial plexus, lumbar plexus, and sacral plexus. Focusing on the cervical and brachial plexus, Figures 2.2 and 2.3 shows its innervations. The cervical plexus innervates the skin and muscles of the neck, which also give rise to the phrenic nerve that extends into the thoracic cavity and innervates the diaphragm. Additionally, the brachial plexus innervates the pectoral girdles and upper limbs (Martini *et al.*, 2018).

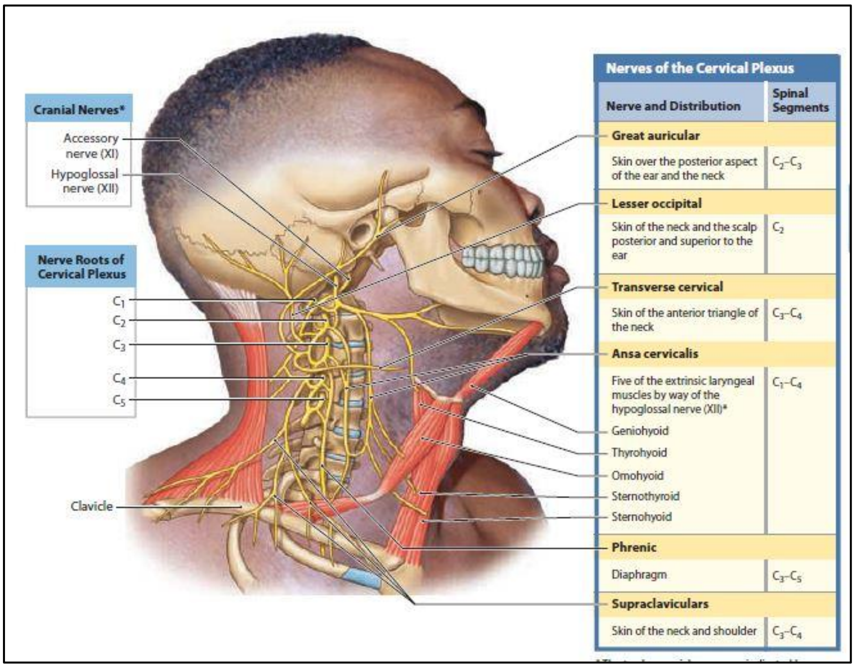

Figure 2.2 Cervical plexus innervation (Retrieve from Martini *et al.*, 2018)

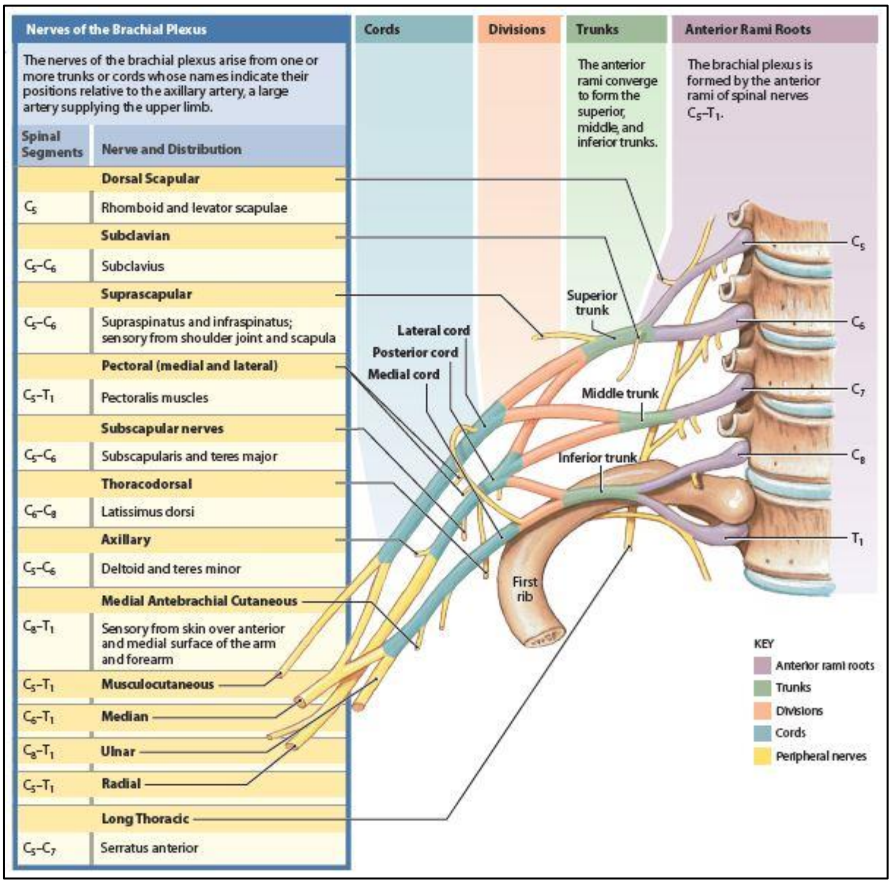

Figure 2.3 Brachial plexus innervation (Retrieve from Martini *et al.*, 2018)

Surrounding the spinal cord, there are three spinal meninges layers: the innermost layer is the pia mater, followed by the arachnoid mater, and the outermost layer is the dura mater. There is a presence of space between the arachnoid mater and the pia mater known as the subarachnoid space, and the space between the arachnoid mater and the dura mater is known as the subdural space (Martini *et al*., 2018).

The subarachnoid space contains cerebrospinal fluid. The subarachnoid space is identifiable in FE analysis. Cerebrospinal fluid (CSF) in subarachnoid space is a clear, colourless fluid that circulates between the brain's ventricles, the vertebral canal, and the meninges (Martini *et al*., 2018). CSF flow results from the pressure gradient between the arterial system and the CSF-filled cavities. CSF also act as a shock absorber to prevent or reduce an impact or damage to the brain and spinal cord.

2.2 Cervical Spondylotic Myelopathy

Cervical spondylotic myelopathy, CSM, is the most common disorder in the elderly population. Patients above the age of 55 years old are most likely diagnosed with symptomatic or asymptomatic CSM (Matsumoto *et al*. 1998 as cited in Vijay Kumar, Ray and Das, 2019; Vilaça *et al*., 2016) Several factors can cause CSM, including disc degeneration linked to ageing, hypertrophy of the flavum ligament, and genetic factors (Vilaça *et al*., 2016; Wang *et al*., 2017). Due to the ageing process, degenerative changes in the cervical spine can be observed, and it may lead to spinal cord compression in severe cases.

Thinning of the vertebral body, decreasing of disc space, and osteophytes formation are some examples of degenerative changes that can be seen in a CSM spine. Osteophyte is defined as a small bony outgrowth or spurs. When the osteophyte grows towards the vertebral canal, it will impinge on the meninges, which eventually may affect the CSF flow and impinge on the spinal cord that contains the white matter which contains major ascending and descending tracts. Moreover, previous studies shows that in middle-aged patient C5/C6 and C6/C7 are most affected while in more elderly patient, aged 65 and above, CSM changes are more commonly observed in C3/C4 and C4/C5 (Tani, Yamamoto and Kimura, 1999 as cited in Vijay Kumar, Ray and Das, 2019; Vilaça *et al*., 2016)

According to Boogaarts & Bartels (2015), Kovalova *et al.* (2016); Wang *et al.* (2017), the accurate prevalence and incidence of CSM are not known. However, there are reported studies on the prevalence of surgically treated or CSM-related admission. The pathophysiology of CSM is said to be multifactorial, but 54% is mainly caused by degenerative spine disease in North America (Iyer, Azad and Tharin, 2016; Bakhsheshian, Mehta and Liu, (2017). Diagnosis of CSM starts when the cervical spondylosis presents with spinal cord compression with the presence of clinical myelopathy.

Spondylosis generally is degenerative osteoarthritis, and changes to the spine occur by excessive motion and repetitive trauma, which begins with degenerative changes in the disc and surrounding soft tissue and bony structures. The classification of CSM severity can be observed using the Nurick Grade and the Modified Japanese Orthopaedic Association scoring system, as shown in Tables 2.2 and 2.3.

Zileli *et al.* (2019) shares that it is best to use both scoring systems in determining the severity of the CSM because both test on a different aspect of functionality. CSM severity is mainly classified according to the severity of symptoms related to the nerve injury resulting from the spinal cord compression, root or spinal nerve impingement.

Table 2.2: Nurick Grade

Grade	Explanation
0	Signs or symptoms of root involvement but without evidence of spinal cord disease
1	Signs of spinal cord disease but no difficulty in walking
2	Slight difficulty in walking that did not prevent full-time employment
3	Difficulty in walking that prevented full-time employment or the ability to do all housework, but that was not so severe as to require someone else's help to walk
4	Able to walk only with someone else's help or with the aid of a frame
5	Chair bound or bedridden
0–3 = mild to moderate disease; 4–5 = severe disease	

(Retrieved from Shiban & Meyer, 2014)

Table 2.3: Modified Japanese Orthopaedic Association scoring system

Dysfunction		Explanation	Score
Motor dysfunction	Upper extremities	Unable to move hands	0
		Unable to eat with a spoon but able to move hands	1
		Unable to button shirt but able to eat with a spoon	2
		Able to button shirt with great difficulty	3
		Able to button shirt with slight difficulty	4
		No dysfunction	5
	Lower extremities	Complete loss of motor and sensory function	0
		Sensory preservation without the ability to move legs	1
		Able to move legs but unable to walk	2
		Able to walk on a flat floor with a walking aid (cane or crutch)	3
		Able to walk up and down stairs with the aid of a handrail	4
		Moderate to substantial lack of stability but able to walk up and down stairs without a handrail	5
		Mild lack of stability but able to walk unaided with smooth reciprocation	6
		No dysfunction	7
Sensory dysfunction	Upper extremities	Complete loss of hand	0
		sensation Severe sensory loss or pain	1
		Mild sensory loss	2
		No sensory loss	3
Sphincter dysfunction		Unable to micturate voluntarily	0
		Marked difficulty in micturition	1
		Mild to moderate difficulty in micturition	2
		Normal micturition	3
mJOA ≥12 = mild to moderate disease; mJOA <12 = severe disease			*18

(Retrieved from Shiban & Meyer, 2014)

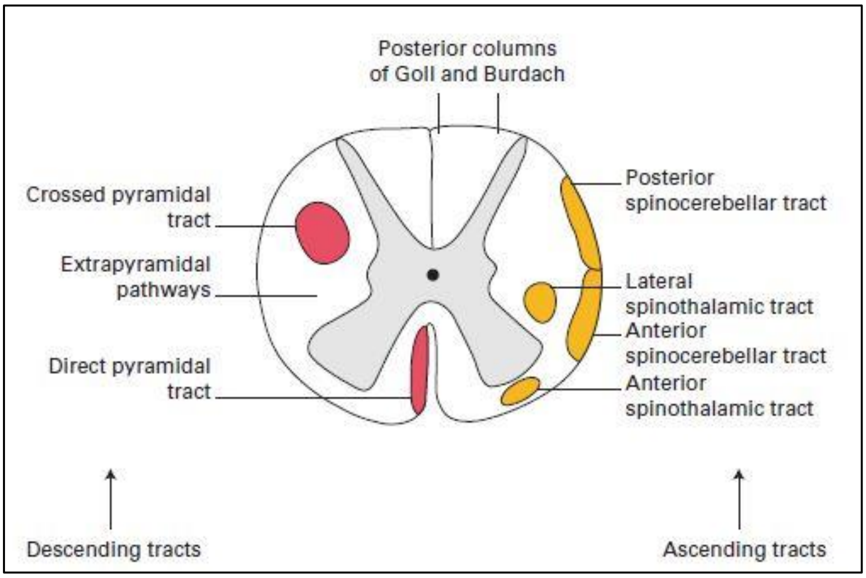

Figure 2.4 Tracts of the spinal cord; Descending tracts (Left) and Ascending tracts (Right) (Retrieved from Ellis & Mahadevan, 2013)

Figure 2.4 shows the position of the tracts in the spinal cord. The ascending tracts carry sensory information to the brain, while the descending tracts transport motor commands to the spinal cord (Martini et al., 2018). As classified by the Nurick grading and Modified Japanese Orthopaedic Association scoring system, CSM can cause symptoms that impinge on the ascending and descending tracts, as shown by motor and sensory dysfunction in table 2.3.

In terms of management and treatment of CSM, decompression surgery is the most common approach. Fehlings *et al.* studies in 2013 and 2015 (cited by Mowforth *et al.,* 2019) share that decompression surgery is an evidence-based treatment to cease the progression of the disease. However, the management and treatment of CSM depend on its severity. As mentioned by Zileli *et al.* (2019), patients with severe CSM do need surgical treatment, but for the patient with mild and low CSM, another treatment option is considered more ideal.

Besides that, according to Badhiwala *et al.* (2020), decompression surgery can also be considered for patients with mild to moderate symptoms or those who show progression during conservative treatment. Therefore, we can conclude that surgery should be the first line of treatment when CSM is severe. For decompression surgery, the anterior approach carries a greater risk of complications. Examples of anterior approach cervical surgery complications are vocal cord paralysis, esophageal injury, and tracheal injury (Cheung & Luk, 2016).

Thus, surgeons tend to favour the posterior approach to cervical surgery. For instance, in the posterior approach surgery, laminectomy alone is said to be the standard procedure, while laminoplasty is considered an alternative method (Lin *et al*., 2019). The author further adds that laminoplasty was preferable due to fewer complications, including a better postoperative cervical range of motion and a decreased risk of trigeminal nerve palsy.

2.3 Finite Element Method

A finite element method is a standard tool used in the engineering field to assess a complex geometry structure's stability and stress-strain distribution (Cattaneo, Dalstra & Frich, 2015). Nowadays, in recent advancements in the medical field, a mathematical model of an anatomical structure or a finite element model is widely used, especially in biomechanics.

As the human spine is a complex structure, a finite element model promotes a better understanding of the spine conditions dynamically. The FE model is also an alternative method used to study the human spine because gaining ethical approval to study the spine biomechanics in humans may be prevented (Stoner *et al*., 2020). Early FE models were in 2-dimensional (2D) form, and with time, the FE model is now in 3-dimensional (3D) form. Most previous literature indicates that a FE model is developed using the data from computed tomography (CT) images (Cattaneo, Dalstra & Frich, 2015; Manickam & Roy, 2021).

Improvements can be seen in every model development research, as mentioned by Kim *et al.* (2018); however, there are some drawbacks, such as limited reviews on some structures such as the spinal cord and cerebrospinal fluid and other specific parts. In CSM, it is also essential to gain information on the spinal cord and the cerebrospinal fluid because CSM effects can be seen as the compression of the spinal cord (Stoner *et al*., 2020). Bartlett *et al.* study in 2013 (cited in Stoner *et al.*, 2020) reported that CSM is a dynamic pathological process; thus, understanding the physiological motion of the spine is recommended.

An imaging-related procedure helps to investigate a dynamic process of an anatomical structure, known as the dynamic magnetic resonance imaging, dMRI. MRI is recognised as the best imaging modality to visualise the soft tissue. However, the dMRI is not widely known (Kolcun *et al.*, 2017) due to the limitation or contraindication in doing the MRI in general. As opposed to other techniques of an experiment, such as the dMRI and the usage of cadaveric specimens, finite element analysis gives access to parameters that are not measurable by experimental means, like the measurement of local stress and strain (Galbusera *et al.*, 2020).

2.4 Computational Fluid Dynamics

Computational Fluid Dynamics, CFD is a tool used in the engineering field to analyse heat transfer and the fluid-flow phenomena (Reid, 2021). According to Tryggvason (2016), CFD has become a well-established tool with computations routinely used for scientific inquiries and engineering studies.

CFD is used essentially in all engineering designs, where it helps significantly in reducing the need for expensive prototyping and testing. In recent years, there have been rapid developments in biomedical and health research with CFD applications. Reid (2021) also shares that advancement in technology and decreases in computational cost allows CFD to be more widely accessible and therefore used in more varied contexts, from cardiovascular medicine and now in studies of cerebral fluid, synovial joints, and intracellular fluid.

CFD applies fluid motion equations to a wide range of complex circumstances, resulting in quantitative predictions. It has been used to test medication delivery systems, analyse physiological processes, plan surgeries, and build medical equipment. The meninges are one of the important structures in the central nervous system that contains cerebrospinal fluid. Based on the study by Puy *et al*. in 2016 (cited by Attier-Zmudka *et al.*, 2019), the cerebrospinal fluid helps to regulate the brain homeostasis.

Attier-Zmudka *et al.* (2019) study also found that CSF flow obstruction is linked with the cognitive deficit in the elderly. Although it can produce a good result, it is challenging to interpret the data for those who do not have a solid understanding of mathematical and technical principles. This is why we need to involve a multidisciplinary team, for example, the engineering team, computer scientist, medical team and anatomist, in a computational approach to establish clinical research.