Spring 2021

Anatomy, Vulnerability, and Musculoskeletal Injury of the Human Neck

Devon Treadway
devon.treadway@trincoll.edu

TRINITY COLLEGE

ANATOMY, VULNERABILITY, AND MUSCULOSKELETAL INJURY OF THE HUMAN NECK

BY

DEVON TREADWAY

A THESIS SUBMITTED TO
THE FACULTY OF THE DEPARTMENT OF BIOLOGY
IN CANDIDACY FOR THE BACCALAUREATE DEGREE
WITH HONORS IN BIOLOGY

DEPARTMENT OF BIOLOGY

HARTFORD, CONNECTICUT

7 MAY 2021

ANATOMY, VULNERABILITY, AND MUSCULOSKELETAL INJURY OF THE HUMAN NECK

BY

DEVON TREADWAY

Honors Thesis Committee

Approved:

____
Kent D. Dunlap, Advisor

____
Daniel G. Blackburn

____
Robert J. Fleming

Date: ____________________________________

Table of Contents

Section ***Page***

Abstract

Although its structure is vital to human functioning, the human neck is extremely susceptible to debilitating and life-threatening injury. This thesis explores the anatomy of the neck as well as two of the most common musculoskeletal neck injuries – cervical herniated disc and whiplash. The mechanics, pathology, risk factors, and predictors of outcome severity of both of these injuries were analyzed to contextualize the vulnerability of the human neck. Cervical herniated discs are generally caused by spinal trauma which causes the expulsion of the intervertebral disc from the spinal column. Risk factors include smoking, hard physical labor, and occupations that require prolonged bending of the neck such as dentistry and medical professions. Anxiety, affective, and substance-use disorders all increase likelihood of having a more severe injury outcome. On the other hand, whiplash is primarily caused by car accidents and has no clear pathology. Females are significantly more likely to experience whiplash than males. The presence of other vertebral damages as well as other diseases are all predictors of chronic and debilitating injury. However, regular exercise serves as a protector against severe whiplash injury outcome. This research revealed how safety of the human neck is sacrificed for the sake of mobility, as well as how the vulnerability of the neck contributes to the high incidence of musculoskeletal injuries.

I. Introduction

The human neck is complex in nature and remains somewhat enigmatic to both anatomists and philosophers. Dozens of structures from nearly every organ system are confined to this very small portion of the body. The tangle of nerves, muscles, blood vessels, endocrine glands, lymph nodes, and bones requires careful placement and interaction. The complexity of the neck raises several important questions – Why have a neck at all? How does the structure of the neck enable and limit its function? What are the costs and benefits of having a structure so susceptible to injury and malfunction? Exploring historical perspectives about the function of the neck, its vulnerability, and malfunction all contribute to an understanding of the significance of having such a complex structure.

Character and irony of the human neck

Although the human neck is similar in function and anatomy to that of most other mammals, the unique lifestyle and movement of humans has necessitated certain modifications in the cervical structure. The most significant difference between humans and other mammals is our bipedality. Holding the complete weight of the head directly atop the trunk requires immense load-bearing ability in the cervical region (Clark, 2005). Consequently, the cervical vertebrae must be shaped in such a way that they can rest easily directly on top of each other while being strong enough to constantly support the weight of those above. Unlike quadrupedal mammals, bipedal humans have a constant vertical compressive force imposed by gravity exerted on their vertebrae and intervertebral discs. One major consequence of human bipedality is heightened risk of disc degeneration due to increased pressure on the disc (Clark, 2005).

In addition to supporting the weight of the head, the neck must also allow for movement about all axes – a vital task for a species that relies almost exclusively on movement of the head to scan the environment for visual information. Additionally, activities such as participation in athletics require a highly mobile head-torso transition zone that permits movement in any plane by allowing independent motion of the head and the trunk of the body (Clark, 2005).

Although the mammalian neck has dozens of specializations to accommodate diverse movements and lifestyles, one near-universal weakness across mammals is the incredible vulnerability of the cervical region. As Babar (2000) notes, almost every single organ system has a structure that resides in or passes through the human neck, however the neck provides little protection for most of these structures. The most exposed of these structures belong to the circulatory system. Several major arteries reside mere centimeters beneath the surface of the skin. The carotid and subclavian arteries, both of which have several equally vulnerable branches, are essential for providing blood to the brain (Seagal, 2018). If either structure is damaged, an individual would quickly die from the blood loss and lack of oxygen to the brain. While other vulnerable body regions are protected by hard barriers, such as the rigid skull that houses the brain or the ribs that encase the lungs and heart, the neck is dangerously exposed from all angles. Rather than evolving to protect organs, the human neck design has been selected for greater mobility for surveilling the surroundings (Babar, 2000).

Historical views on the function of the neck

For centuries, the precarious morphology of the human neck has prompted discussion about its fundamental function. Philosopher Aristotle and anatomist Andreas Vesalius both wrote in detail about their hypotheses regarding the purpose of the human neck. To Aristotle, the neck functions to protect and accommodate the trachea and esophagus (Lennox, 2001). The presence of the neck provides space for the passage of food and air from the mouth to the rest of the body. Although the neck has no hard physical barrier protecting these vital tubes, the musculature is sufficient to protect against most trauma. Furthermore, Aristotle posited that the neck provides adequate space for the bifurcation of the windpipe into the lungs (Lennox, 2001). It is now clear from modern research that the bifurcation occurs in the thorax, however Aristotle may have been unaware of the precise location of this split. He argued that while housing other organ systems is an ancillary benefit of the neck, its anatomy is fundamentally designed to be a transition space between the pharynx and the lungs. Thus, Aristotle concluded that necks are merely a byproduct of lungs (Lennox, 2001). If an animal has two lungs, then it needs a neck to provide sufficient capacity for the singular windpipe to diverge into two pipes. Were it not for the two-part structure of the lungs, human anatomy would not necessitate the existence of a neck at all.

Flemish anatomist Vesalius agreed, at least in part, with Aristotle's hypothesis about the neck as a necessary consequence of the bifurcation of the respiratory system (Vesalius et al., 1998). He agreed with Aristotle's observation that animals that lack lungs also lack necks as proof that the human neck exists because of the lungs. He supported this claim by asserting that fish lack necks because they lack lungs (Vesalius et al., 1998). Additionally, Vesalius asserted that the neck served as a space for vocal cords and for nerves that control the movements of the head to exit the cervical vertebrae (Vesalius et al., 1998). He notes that the "rough artery" – today known as the trachea – which resides in the neck, allows for vocalization as air is exhaled (Vesalius et al., 1998). Therefore, without space for the rough artery it would be impossible to have a voice (Vesalius et al., 1998). Lastly, Vesalius believed the neck is instrumental in the process of food intake by elongating the area that can be used to capture food (Vesalius et al., 1998). This results in less energy expenditure required to move the whole body during food consumption, and provides a path for the food on its way to the stomach.

Although philosophers have questioned the exact reason for the neck, it is clear that the lives of humans would be drastically different without a neck. Regardless of the original purpose of the neck, mammals rely on it for dexterity, communication, visual scanning of their surroundings, feeding, and much more. Without proper function of the cervical region, one's mobility and visual breadth are limited. Relying solely on the torsion of the thoracic and lumbar regions can radically change not just the individual's quality of life, but can even reduce their survival.

Anatomy of the neck

Skeleton

The flexibility of the human neck allows for the passage of blood, food, and air, while at the same time is strong enough to support the weight of the head and agile enough to allow movement in all directions quickly and efficiently. The cervical vertebrae are specially designed to accomplish this multitude of tasks. It consists of seven vertebrae, named C1-C7 in order from most cranial to most caudal (Figure 1). This is further divided into two regions – the suboccipital cervical spine and the lower cervical spine (Calais-Germain, 2007). The suboccipital cervical spine consists of the anterior two vertebrae, C1 and C2, and the lower cervical spine region consists of the C3 through the C7, all of which share a similar morphology (Calais-Germain, 2007). The C1 vertebrae, also known as the atlas, is located just below the skull, and is specially shaped to hold the skull's posterior curve (Calais-

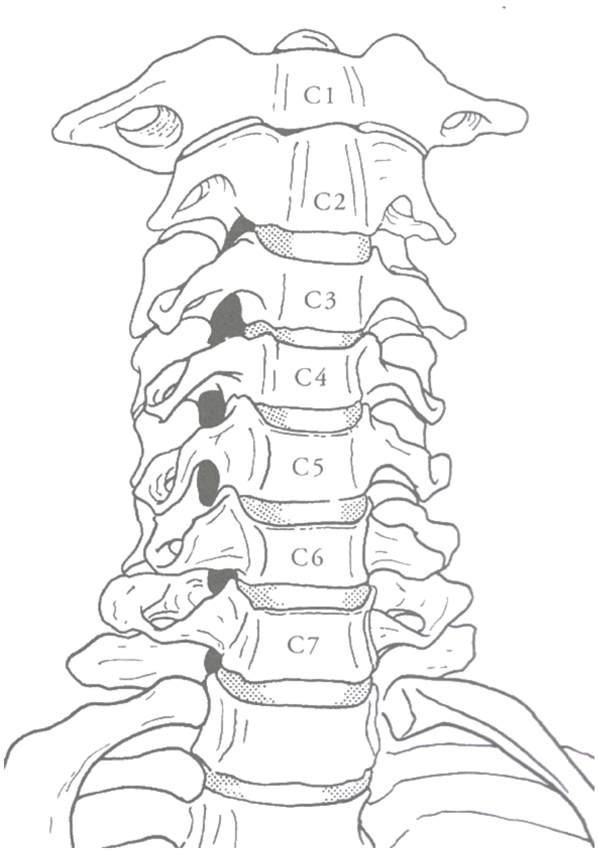
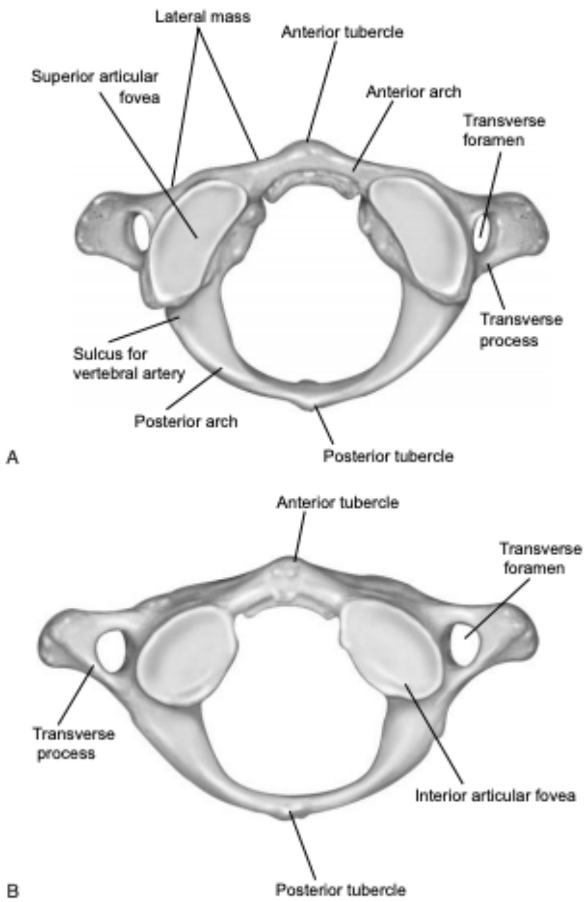


Figure 1. Cervical spine (Calais-Germain, 2007). The seven cervical vertebrae are labeled C1-C7. The shape of the vertebrae, as well as how they interact with each other to make up the cervical spine, is shown.

Germain, 2007). The C2 vertebrae, also known as the axis, serves as an intermediate between the atlas and the C3 vertebrae (Calais-Germain, 2007). The atlas is a unique structure that enables movements such as nodding the head "yes" and, together with the axis, shaking the head "no" (Calais-Germain, 2007). Unlike the other cervical vertebrae, the atlas lacks a vertebral body and a spinous process (Figure 2). While the other vertebrae function to support the vertebrae above them, the atlas must be shaped differently to fit together with the base of the skull while supporting the entire weight of the head (Calais-Germain, 2007). The atlas is essentially just a bony ring that has two thick lateral masses to bear the heavy weight of the head (Figure 2). These masses articulate with the occipital condyles of the base of the skull, and together these surfaces form a joint-like structure that permits rotation, flexion, and extension (Calais-Germain, 2007).



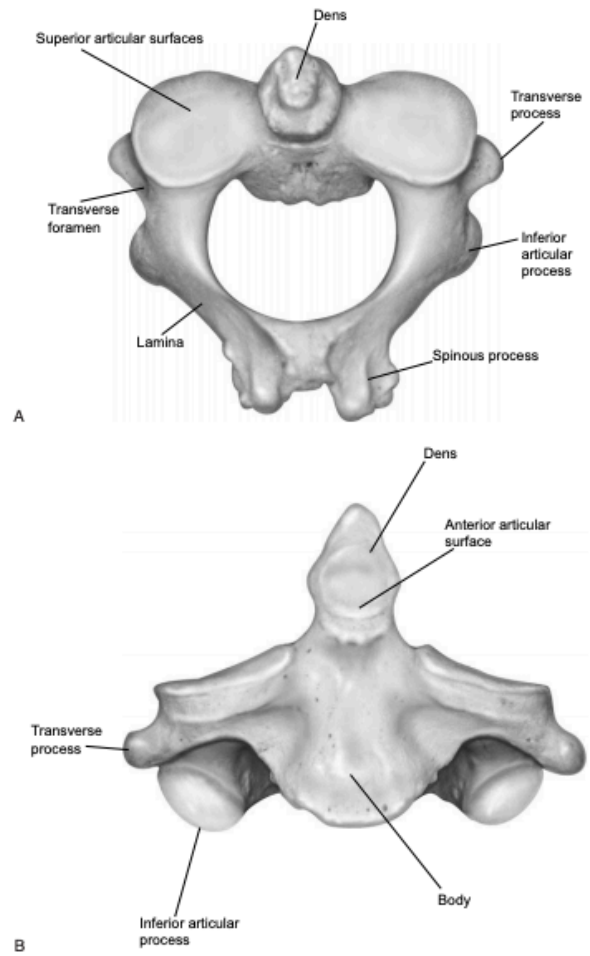


Figure 2. The atlas (Clark, 2005).
A. Cranial view. B. Caudal view.

Figure 3. The axis (Clark, 2005).
A. Cranial view. B. Anterior view.

By contrast, the axis is shaped similarly to the other cervical vertebrae. Unlike the atlas, the axis has a vertebral body to articulate with the C3 and a spinous process (Figure 3). The only structural difference between the axis and the rest of the cervical vertebrae is that the axis has bony projections that articulate with the atlas. The presence of the dens, a peg-like structure that is lodged in the anterior part of the atlas, eliminates the need for a vertebral disc between the atlas and the axis (Figure 3) (Calais-Germain, 2007). While every other adjacent vertebrae pair has a cartilaginous disc between them, the space between the atlas and the axis acts more like a hinge to allow greater mobility in the upper portion of the cervical spine (Calais-Germain, 2007). This allows for finely-controlled functions such as nodding and shaking the head (Calais-Germain, 2007).

Although the atlas and axis are both unique, the remaining cervical vertebrae all have the same form and function (Figure 4). C3 through C7 serve as the site of lateral flexion and each have a prominent vertebral body, as well as upward projections on the superior surfaces and downward projections on the inferior surfaces to articulate with adjacent vertebrae (Calais-Germain, 2007). Although the vertebrae are locked together in a highly controlled fashion, several factors increase the mobility of the cervical region. The flexible cartilaginous discs between the vertebrae are about one-third as thick as the vertebral bodies and permit for greater movement in all directions (Figure 5) (Calais-Germain, 2007). The length of the spinous processes, which vary throughout C2 and C7, also enhances mobility. Calais-Germain (2007) describes how the spinous processes of the middle cervical area, particularly C4, are shorter to allow adequate extension. On the other hand, the spinous processes of the more cranial and caudal vertebrae are longer to prevent over-extension that could occur due to the weight of the head (Calais-Germain, 2007). These differences contribute to the flexibility of the cervical spine without compromising the safety of the region. Range of motion is maximized while risk of injury due to over-extension is minimized.

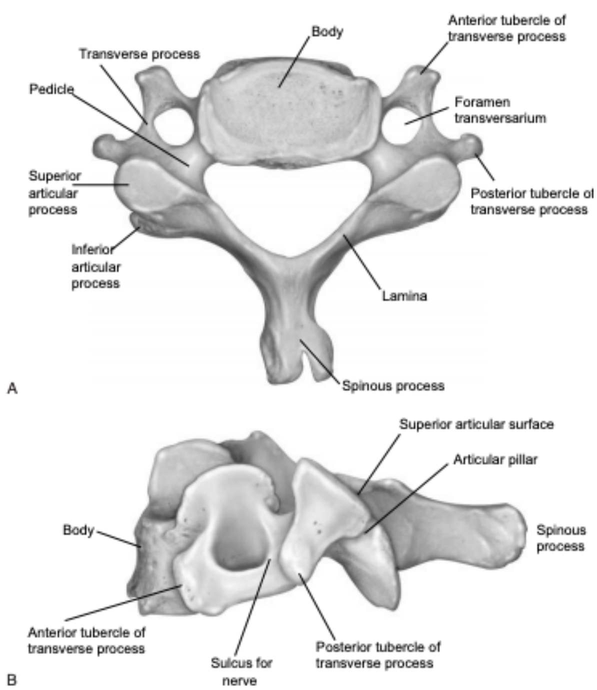


Figure 4. Typical cervical vertebra (Clark, 2005). A. Cranial view. B. Lateral view.

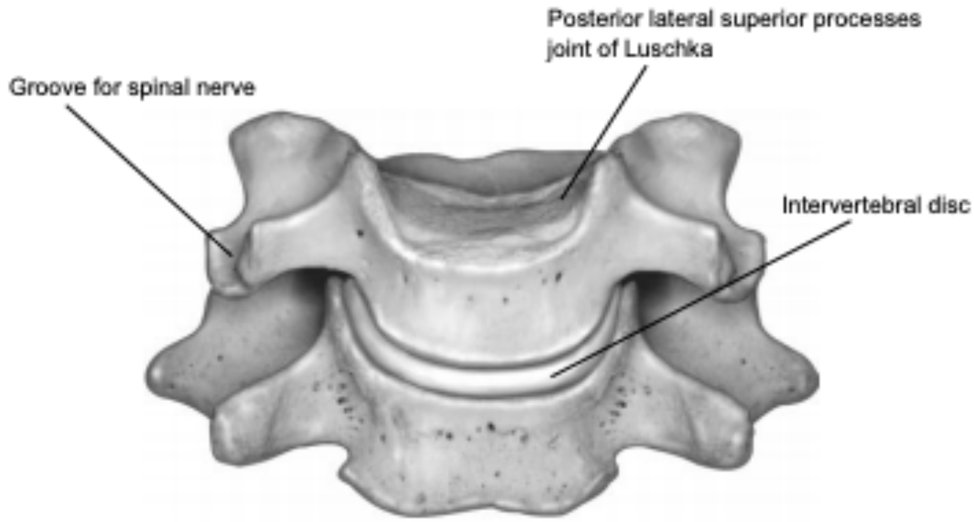


Figure 5. Lower cervical vertebra (Clark, 2005). The intervertebral disc separates the adjacent vertebrae and provides protection against degradation via direct contact between the vertebrae.

Another important feature of the cervical vertebrae is the presence of transverse foramina (Figure 4). These channels in the vertebrae allow for the passage of the vertebral arteries up the neck and into the head to deliver oxygenated blood to the brain (Calais-Germain, 2007). Every vertebra except for C7 has two transverse foramina on either side of the bony structure, and their alignment with adjacent vertebrae is crucial for the uninterrupted passage of blood to the cranial region (Calais-Germain, 2007). If the vertebrae are forced out of alignment, blood flow to the brain can be disturbed, which can be fatal or lead to significant deficits.

Musculature

Muscles in the neck – 26 in all – move the neck in all directions. British anatomist Henry Gray was one of the most prominent individuals to categorize the muscles of the neck. In his collective work, *Anatomy, Descriptive and Surgical* (1859), more colloquially known as *Gray's Anatomy*, he categorized each of the muscles of the neck and mouth into one of nine groups, describing their regions and general functions. According to Gray (1859), these groups are the: 1) superficial region, 2) depressors of the hyoid and larynx, 3) elevators of the hyoid and larynx, 4) muscles of the tongue, 5) muscles of the pharynx, 6) muscles of the soft palate, 7) muscles of the anterior vertebral region, 8) muscles of the lateral vertebral region, and 9) muscles of the larynx. The ability to control the contraction and relaxation of these muscles provides humans with an enormous range of flexibility and agility in the cervical region (Figure 6).

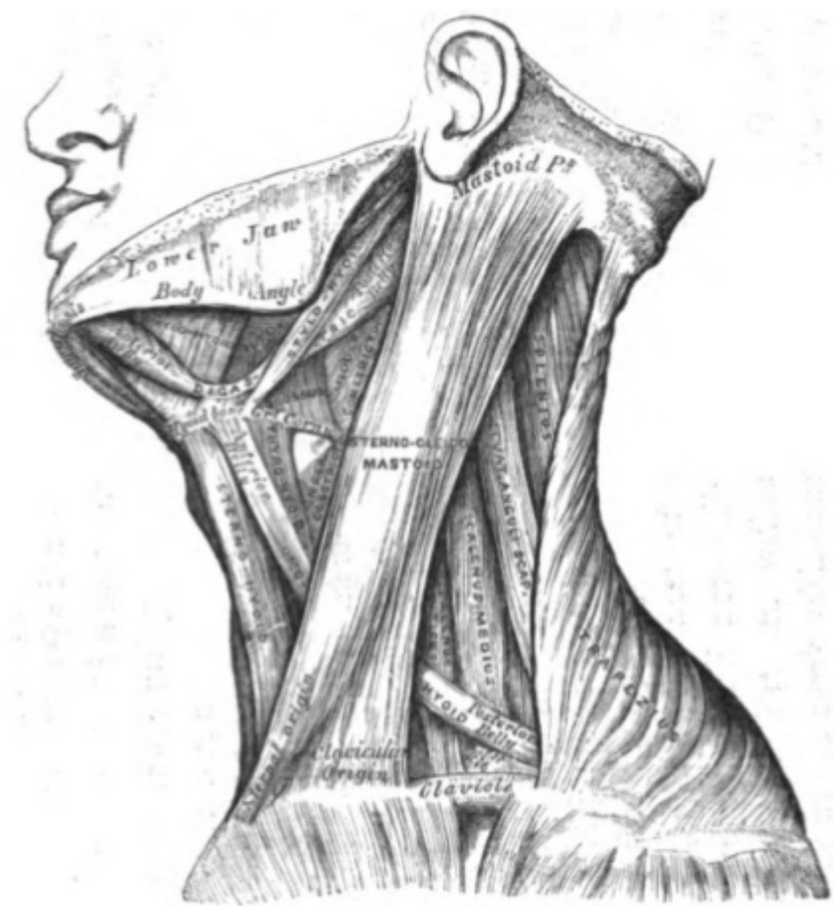


Figure 6. Lateral view of muscles (Gray, 1859). The extensive overlapping and intertwining of the neck muscles provides high levels of dexterity.

The muscles of the neck are enclosed by an important layer of fibrous tissue called fascia. The fasciae serve as a supportive layer to reduce the friction between muscles as they contract past each other, as well as to provide a flexible sheath for the nerves and blood vessels that pass between muscles (Bordoni et al., 2020). This allows for integration of the nervous system, the circulatory system, and the musculoskeletal system. Seagal (2018) identified five fasciae in the neck as well as their location. The most important of these are the fourth fascia, which covers all of the organs in the neck, and the fifth fascia, which separates the anterior part of the neck from the posterior part (Seagal, 2018).

Nerves

A network of finely-interwoven nerves relays information between the central nervous system and the rest of the body, particularly the upper extremities and torso. The nerves of the neck are divided into two groups – the cervical and the brachial plexus. The former is located from C1 through C4, and mostly transmits sensory and motor information in the neck and head, as well as the upper region of the trunk (Figure 7) (Glenesk et al., 2019). This bundle of nerves innervates muscles of the neck and shoulders, and is responsible for fine motor skills of the cervical region (Glenesk et al., 2019). Moreover, the cervical plexus allows for communication between spinal nerve C1 and cranial nerve XII (hypoglossal nerve), which is responsible for movement of the tongue (Glenesk et al., 2019). Additionally, the cervical plexus is the site of origin for the phrenic nerve, which innervates the diaphragm (Glenesk et al., 2019).

Most clinicians also distinguish between the superficial and the deep cervical plexus. The superficial plexus is composed of the lateral terminal branches of the nerves and gives rise to the sensory branches such as the great auricular nerve and the transverse cervical nerve, both of which innervate the skin of the neck and lower head (Glenesk et al., 2019). Conversely, the deep plexus is involved more in the motor function of the region and is composed of nerves that control movement (Glenesk et al., 2019). Differentiating between these regions is clinically important because physicians often use superficial cervical plexus blocks to anesthetize regions of the neck during surgery (Glenesk et al., 2019). Such practices, if done correctly, can provide anesthesia over the entire neck and into the shoulders, which reduces patient pain and discomfort.

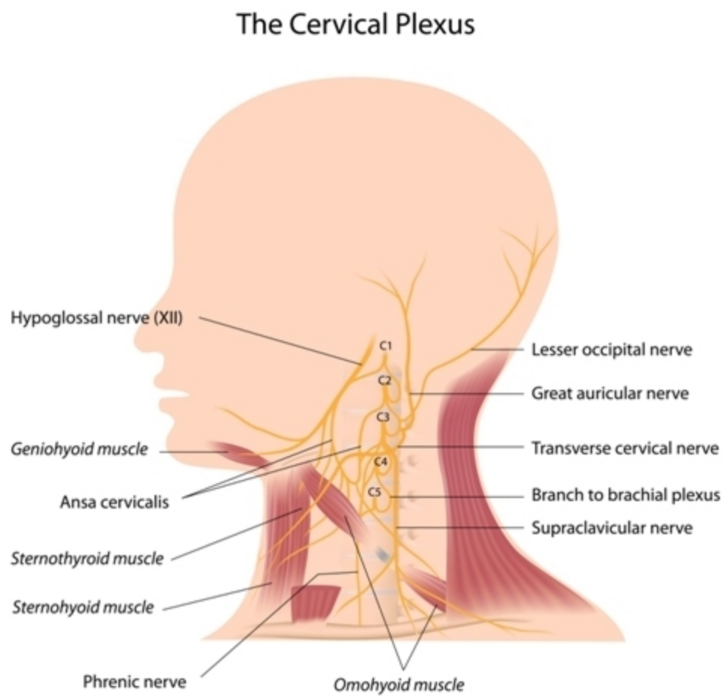


Figure 7. The cervical plexus (Glenesk et al., 2019). Nerve bundle between C1 and C4 that has a wide variety of functions, and plays an important role in the sensory innervation of the neck and head.

The brachial plexus spans from C5 to T1, the first vertebra of the thoracic region (Polcaro et al., 2020). This network provides sensory and motor innervation to the upper extremities, the shoulders, and the scapular region, and is further divided into the superior trunk, middle trunk, and inferior trunk (Polcaro et al., 2020). The superior trunk spans from

C5 to C6, the middle trunk from C6 to C7, and the inferior trunk from C7 to T1 (Polcaro et al., 2020). The most important nerves that originate from the brachial plexus are the dorsal scapular nerve and the long thoracic nerve, both of which direct the motor functioning of the scapular region, which positions the upper trunk and moves the arms (Polcaro et al., 2020). Additionally, the ulnar nerve, which is critical for fine motor activities of the hands and fingers, also originates in the brachial plexus and is especially important because humans rely on the use of their fingers for many daily activities (Polcaro et al., 2020). In all vertebrates, this nerve plays a vital role in locomotion, feeding, and communication, thereby exemplifying the importance of the brachial plexus.

The presence of these vital nerves provides a plausible explanation for the original function of the neck that neither Aristotle nor Vesalius considered. Rather than being a space simply for ventilation and vocalization, the neck provides an area of the spinal column for nerve networks that innervate the muscles of the head, neck, and upper extremities to exit from the spinal cord. Perhaps the space between the thoracic, lumbar, and sacral vertebrae is not sufficient for all of the necessary peripheral nervous system structures, and the cervical region provides this additional space to allow for the innervation of the upper regions of the body.

Vasculature

To transmit oxygenated blood from the heart to the head, humans require thick arteries that can carry the blood under high pressure against gravity. This is mainly performed by a paired set of vertebral arteries and two pairs of carotid arteries. The vertebral arteries move oxygenated blood superiorly by passing through the transverse foramina of the cervical vertebrae. They also branch to form the one anterior and two posterior spinal arteries that supply blood to the spinal cord (Glenesk et al., 2019). These two vertebral arteries join back together at the base of the skull, and form the basilar artery (Piccinin & Munakomi, 2021). The vertebral arteries and basilar artery, known together as the vertebrobasilar system, provide blood to various inferior regions of the brain such as the brainstem, cerebellum, and thalamus (Piccinin & Munakomi, 2021).

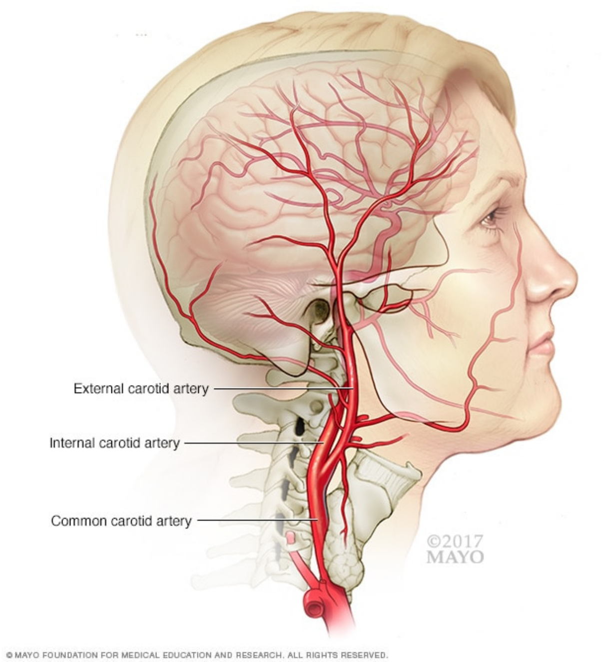


Figure 8. External carotid artery (“Carotid artery disease - Symptoms and causes,” 2018). Several circulatory structures lie superficially beneath the skin and are therefore vulnerable to external trauma.

The brain is also supplied by the dual common carotid arteries, each of which bifurcates at the C4 level into an internal and an external carotid artery (Figure 8) (Nguyen & Duong, 2020). These arteries lie more superficially than the vertebral arteries and are therefore very vulnerable to external trauma. Although the risk could prove to be fatal, this anatomy allows for the complex arrangement of blood vessels while also allowing space in the neck for other organs, musculature, and the vertebrae.

In addition to providing oxygenated blood to the brain, the common carotid arteries contain sensory systems that regulate aspects of the autonomic nervous system that control blood pressure, oxygen level, and blood pH (Nguyen & Duong, 2020). Sensory receptors sensitive to blood pressure, baroreceptors, detect the stretch and pressure exerted on the carotid arteries. Their impulses are then sent to the brain via cranial nerve IX (glossopharyngeal nerve), which then stimulates the release of hormones and other signals to correct somatic blood pressure (Nguyen & Duong, 2020).

Neck injuries

While the anatomy of the neck accommodates dozens of complex and integrated functions, the congregation of so many vital structures and systems in such a vulnerable area leads to a high risk of serious injury. According to Babar (2000), isolated neck injuries are rare, however neck injuries that co-occur with other injuries such as traffic accidents, occupational head and neck injuries, and criminal assaults are very common. Due to highly active modern lifestyles that include high-speed transportation, increased criminal violence, and participation in strenuous athletics, neck injuries are more prominent in traumatology (Babar, 2000). Neck injury can be caused by a plethora of factors, ranging from acute injuries to chronic ailments.

There are dozens of types of neck injuries, however those of the musculoskeletal system are of particular interest due to their high frequency and severity. Although some musculoskeletal neck injuries are relatively minor, others lead to significant disability and reduced quality of life. Examining risk factors and prevention methods is clinically relevant because a deeper understanding of these ailments reveals the function, strengths, and weaknesses of the human neck. Two of the most prevalent cervical musculoskeletal injuries are herniated cervical intervertebral discs and whiplash, and these pathologies illuminate the vulnerabilities of the human neck.

II. Herniated Cervical Disc Injury

Intervertebral discs in the spinal column are a great asset to the function of the neck, but they also leave humans susceptible to debilitating injury. One of the most common spinal injuries in humans is the extrusion of a disc from its proper positioning in the spinal column. Disc herniation can occur at any place in the spinal column, however cervical herniation is of special interest here. Cervical disc herniation has a wide variety of causes, risk factors, and impacts on other neck injuries. Therefore, examining the injury in detail is crucial to understanding the musculoskeletal function of the neck.

Anatomy and function of an intervertebral disc

Intervertebral discs form fibrocartilaginous joints between vertebrae and function primarily to absorb shock between adjacent vertebrae (Clark, 2005). They transfer compressive forces along the spinal column so that one vertebra is not under the entire pressure of a mechanical force. Thus, they reduce the strain placed on individual sections of the spine (Clark, 2005). Additionally, they provide more flexibility in the spinal column than just the stiff vertebrae (Shapiro & Risbud, 2014). Consequently, intervertebral discs are crucial to everyday human motion and activity. Without the proper function of these structures, the ability to perform tasks that require bending or torsion of the cervical region would be nearly impossible, thus drastically impacting daily life.

During embryological development, these discs arise from remnants of the notochord, one of the defining features of phylum Chordata (Shapiro & Risbud, 2014). After the notochord disperses into cellular remnants in early development, these cells become enclosed by rings of connective tissue (Shapiro & Risbud, 2014). These rings become one of the two components of an intervertebral disc – the annulus fibrosus (Shapiro & Risbud, 2014). The annulus fibrosus is the outer fibrous layer of the disc that contacts the vertebrae on either side (Figure 9) (Clark, 2005). Its fibers are organized such that the layer remains firm to support to the spinal column. The fibers are arranged in parallel, concentric patterns, which provide the rigid structure by dispersing mechanical loading forces (Figure 9) (Shapiro & Risbud, 2014). The inner layer of the discs, the nucleus pulposus, is composed of a gel-like structure that is rich in collagen fibers, connective tissue, and cartilage cells (Figure 9) (Clark, 2005).

Unlike the annulus fibrosus, the nucleus pulposus is fluid and flexible (Shapiro & Risbud, 2014). While the annulus fibrosus provides rigidity to the disc, the nucleus pulposus provides a degree of flexibility to allow for movement of the spinal column (Shapiro & Risbud, 2014). Together, these two structures provide structural support to the spine, protection against mechanical loading, and increased flexibility for a wide range of movement.

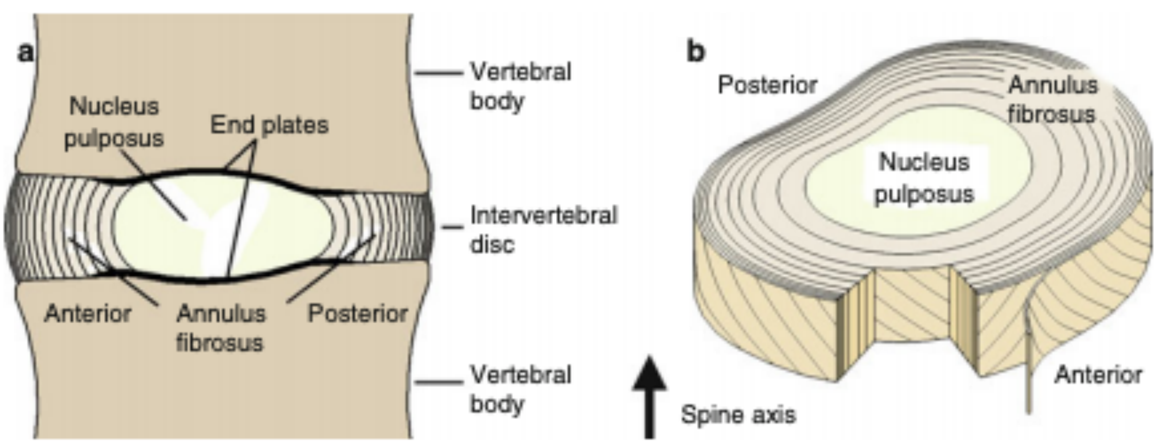


Figure 9. Adult intervertebral disc (Shapiro & Risbud, 2014). A – Midsagittal cross-section of a disc. B – 3-D view illustrating layers of annulus fibrosus rings.

Throughout fetal development, the ratio of nucleus pulposus to annulus fibrosus increases gradually (Shapiro & Risbud, 2014). In early fetal development the nucleus pulposus accounts for a small fraction of the intervertebral space, but by birth it occupies roughly half of the space (Shapiro & Risbud, 2014). This increase continues until the infant is about one year of age, at which point it takes up roughly three quarters of the intervertebral space (Shapiro & Risbud, 2014). This occurs primarily through remodeling of the intervertebral space early in life while the head and torso grow. Such growth necessitates a more rigid, fibrous disc that can bear the vertical compression of these structures (Shapiro & Risbud, 2014).

In healthy adult humans, intervertebral discs make up ~15-20% of the total length of the spinal column (Shapiro & Risbud, 2014). However, these discs vary in size throughout the spine. Discs of the cervical region are the smallest with a disc height of ~3 mm (Shapiro & Risbud, 2014). Lumbar discs are the largest at 9-17 mm with the tallest located more superiorly (Shapiro & Risbud, 2014). Lastly, those of the thoracic region are intermediate in size at ~5 mm (Shapiro & Risbud, 2014). The heights of intervertebral discs vary to allow different regions to serve their movement and load-bearing abilities, as well as to account for the smaller size of vertebrae in the upper regions of the spine. The structure of these discs plays an important role in healthy function of the spine, but can also cause of one of the most common spinal disorders – herniated discs (Shapiro & Risbud, 2014).

Pathology

Cervical disc herniation occurs when disc tissue protrudes from the spinal column, resulting in compression of nerve roots (Shapiro & Risbud, 2014). This occurs primarily when the gelatinous nucleolus pulposus displaces within the annulus fibrosus, thus resulting in disc malformation and the formation of a bulb of disc tissue between the two vertebrae on either side (Figure 10) (Shapiro & Risbud, 2014). The consequent compression of the nerve roots, as well as the irritation of the sensitive nerve endings in the annulus fibrosus, cause severe pain and disability in patients with herniated discs (Arrotegui, 2019).

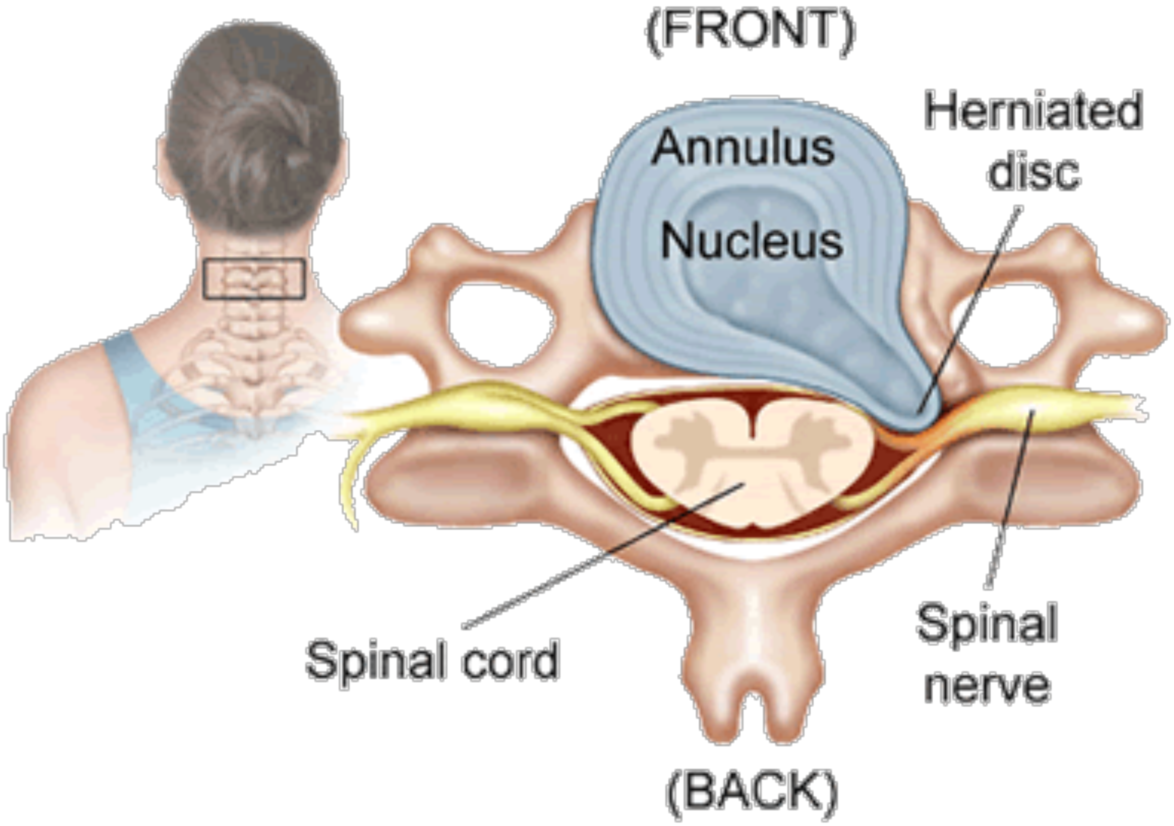


Figure 10. "Cervical Herniated Disc" (2020). Malformation of the nucleus pulposus within the annulus fibrosus, thus resulting in the protrusion of the matrix of the disc out of the spinal column and into a spinal nerve.

Arrotegui (2019) identifies three distinct degrees of herniated discs – disc protrusion, slipped disc, and disc extrusion. Disc protrusion, the least severe of the various types, is when the nucleus pulposus has not yet left the annulus fibrosus ring, but the disc is beginning to push out and away from the spinal column (Arrotegui, 2019). An intermediate degree of herniation, a slipped disc, occurs when the nucleus pulposus fully exits the typical limits of the annulus fibrosus (Arrotegui, 2019). The annulus fibrosus remains intact, however it is now stretched far beyond its natural resting state. Lastly, the most severe type of disc herniation is disc extrusion. This arises when the exit of the disc from the spinal column is so forceful that it not only pushes on the spinal nerve roots, but also breaks the posterior common ligament, thus causing free fragments of the ligament to float around the vertebral canal (Arrotegui, 2019). This type of herniation is by far the most damaging, and therefore the most difficult to treat.

Symptoms

Symptoms of a herniated cervical disc depend on the cause and severity of the herniation, however most people experience the same basic symptoms. The most common symptom is general pain surrounding the area of herniation caused by compression of the spinal nerves (Jomin et al., 1986). This pain typically peaks at the time of herniation, but usually persists at a lower intensity until the disc is returned to its typical location between the vertebrae by physical manipulation from a physical therapist, chiropractor, or, in extreme cases, a surgeon. Other common symptoms include sensory and motor deficits, particularly of the upper extremities, neck, and head (Jomin et al., 1986). Although these symptoms are less common, some type of motor deficit is noted in ~25% of all patients with a herniated cervical disc, which is a large portion of people whose daily lives are disrupted (Jomin et al., 1986). These deficits are likely due to pressure on the cervical and brachial plexuses, which convey sensory input and motor output to the arms, shoulders, neck, and head (Glenesk et al., 2019). Furthermore, reflex disorders are observed in a small number of cases. These cases usually only arise in individuals that experience motor deficits, implying that compression of the cervical nerves can disrupt important relay systems in the neuroanatomy of the neck (Jomin et al., 1986).

Causes

Although cervical disc herniation can occur for a number of reasons, the most common causes of herniation are disc degeneration, spinal trauma, and a sedentary lifestyle. Disc degeneration is a slow, chronic ailment in which the annulus fibrosus ring slowly cracks, leaving the disc susceptible to damage (Jomin et al., 1986). Because the annulus fibrosus is cracked, the nucleus pulposus can easily push through its boundaries when force is applied to the disc. Consequently, a degenerated disc deforms at a much faster rate than a healthy disc during spinal compression (Clark, 2005). Disc degeneration can make it easier for the disc to herniate upon trauma, even when that trauma is minimal (Shapiro & Risbud, 2014).

One of the most significant factors responsible for increased risk of cervical disc herniation is genetic predisposition to disc degeneration. Currently 20 genes are associated with an increased risk of intervertebral disc degeneration (Shapiro & Risbud, 2014). The estimated heritability of disc degeneration is 74%, which suggests a polygenic inheritance (Shapiro & Risbud, 2014). This value also indicates a high likelihood that more genes unidentified are involved in this process.

Additionally, disc degeneration is often caused by spondylosis, a type of spinal arthritis (Kolenkiewicz et al., 2018). This condition is caused by abnormal wear and tear of the discs and joints in the neck and can lead to radiating pain throughout the upper extremities (Kolenkiewicz et al., 2018). Although spondyloses occur predominantly in the lumbar region of the spine due to the greater compressive force from the body weight, it is also common in the cervical region (Kolenkiewicz et al., 2018). This condition is typically chronic with a gradual onset as an individual ages, however it can also rarely be triggered by trauma to the spine such as whiplash (Kolenkiewicz et al., 2018).

Spinal trauma is a secondary cause of cervical disc injury. Typically, this trauma is caused by traffic accidents or sport-induced injuries, both of which commonly torque the cervical region beyond the natural scope of movement (Jomin et al., 1986). Forced movements of flexion, extension, and rotation can shear the ligaments around the discs, and can ultimately weaken structures that stabilize the discs (Jomin et al., 1986). This then leads to the rapid ejection of the disc from the spinal column into the spinal canal (Jomin et al., 1986). Unlike the chronic nature of disc degeneration, trauma-induced herniation is an acute condition that does not depend on previous wear and tear.

Kolenkiewicz et al. (2018) found that different discs in the cervical region could withstand different levels of force before the disc was damaged. The most sensitive disc in the cervical region was the disc between C2 and C3, which was damaged after a muscle force replication of only 6 G-forces (Kolenkiewicz et al., 2018). On the other hand, the discs most resistant to force trauma were those between C3 and C4, and between C5 and C6, both of which could withstand forces up to 10 G-forces (Kolenkiewicz et al., 2018). This study demonstrated that cervical discs vary in the ability to resist force before damage is incurred, and thus traumatic injury resulting in disc herniation is very sensitive to the precise location of the trauma. Thus, two individuals with seemingly very similar traumas might experience completely different outcomes.

The last significant cause of cervical disc herniation is the shift in many human cultures towards a more sedentary lifestyle. According to Arrotegui (2019), this causes significant muscle weakness the neck, which endangers the cervical spinal column because the weight of the head, although usually mostly supported by the neck muscles, must now rely more heavily on the spine for support. This increases the mechanical loading on the cervical spine and the force on the intervertebral discs. This can lead to disc degeneration and impaired ability to stabilize neck movements. Furthermore, the seated position in which a large portion of humans spend most of their workday can strain the cervical spine. The position of a slight forward incline with the head bent somewhat forwards towards a computer screen or desk exerts a greater mechanical force on the discs than if the person were sitting in a perfectly upright position (Arrotegui, 2019). The rise of jobs that require this seated position for most work hours has contributed significantly to the increased prevalence of herniated cervical discs.

Co-occurrences caused by cervical disc herniation

Herniated cervical discs are often debilitating, but, on their own, are rarely life-threatening. However, when combined with other disorders, they can be fatal if not treated quickly. One such co-occurrence is a condition called vertebrobasilar insufficiency, in which the circulation of oxygenated blood to the brain via one or both of the vertebral arteries is occluded (Nemecek et al., 2003). A directionally-specific protrusion of a disc between C2 and C6 can compress the vertebral artery as well as the spinal nerves (Nemecek et al., 2003). This arterial obstruction can cause symptoms ranging from mild to severe, depending on the amount of disc protruding and the amount of contact between the disc and the artery. For example, some patients only present symptoms when they rotate their head, indicating that the herniated disc is not always compressing the artery, but can when the cervical vertebrae are rotated (Nemecek et al., 2003). Symptoms of vertebrobasilar insufficiency most often include vertigo and nausea, but in more severe cases, also a loss of consciousness due to cranial hypotension (Nemecek et al., 2003). These cases can usually be resolved with surgery, but if not treated they can cause life-threatening oxygen deprivation to the brain.

Another serious injury that can result from a herniated cervical disc is a ruptured anterior spinal artery aneurysm (Nakhla et al., 2016). Although rare, if left untreated, this aneurysm can burst, causing a potentially fatal subarachnoid hemorrhage in the brain (Nakhla et al., 2016). The compression of the anterior spinal artery by the bulging disc constricts blood flow and raises blood pressure, which causes a ballooning of a blood vessel in the brain (Figure 11) (Nakhla et al., 2016). The main symptom of this ailment is an excruciating headache that progressively worsens (Nakhla et al., 2016). An angiogram can be used to show the reduced blood flow in the anterior spinal artery, and an MRI can be used to locate the herniated cervical disc (Nakhla et al., 2016). With these images, surgery can treat the aneurysm and restore healthy blood flow in the brain (Nakhla et al., 2016).

Figure 11. Herniated disc occludes anterior spinal artery (Nakhla et al., 2016). Sagittal MRI image showing the C3/C4 herniated disc at the location of the red arrow that is causing compression of the anterior spinal artery.

Risk factors

Demographics

A wide variety of factors increase a person's risk for a herniated cervical intervertebral disc. First, a person's age, gender, and skin color all influence their likelihood of experiencing a disc herniation. During aging, intervertebral discs degenerate from wear and tear throughout life. Consequently, the elderly population is more susceptible to disc herniation than younger populations (Huang et al., 2019). However, this risk peaks in the later years of middle adulthood because these individuals are still physically active. Extremely elderly populations are unlikely to experience herniated discs because they are often sedentary and no longer participate in activities that involve intense torsion of the cervical region.

Gender also plays a role in a person's risk of disc herniation. Radhakrishnan et al. (1994) examined the incidence of cervical radiculopathy, a condition in which a spinal nerve root is pinched due to pressure from an intervertebral disc. The team found that men were at increased risk for cervical radiculopathy, with the annual incidence rates of 107.3 per 100,000 for men compared to 63.5 per 100,000 for women (Radhakrishnan et al., 1994). Although this difference could be due to increased genetic predisposition in men, several environmental factors likely account for this variation. Increased participation in hard physical labor or more aggressive standards in athletics might explain why men are at such a higher risk for cervical radiculopathy.

Skin color or ethnicity might also influence the risk for a herniated cervical disc, but the reason is not well understood. Iyer & Kim (2016) describe how "white individuals" are at increased risk for herniation compared to those of "other races". Although race is not a valid biological category, this finding could indicate a correlation between skin color or ethnicity and risk of herniation, however there is very little information on why this difference exists. For clinicians to better understand the pathology of herniated discs, it would be worthwhile for this demographic factor to be examined more closely.

Lifestyle

Regular alcohol consumption and smoking both significantly increase a person's risk for a herniated disc by accelerating disc degeneration (Shin, 2014). These habits decrease blood oxygenation and tissue perfusion, both of which are required to supply the intervertebral discs with nutrients (Shin, 2014). Additionally, nicotine interrupts cell proliferation in the nucleus pulposus, thereby dramatically decreasing cell number in the matrix (Shin, 2014). This also contributes to the degeneration of the intervertebral discs, and slows the healing and regeneration processes.

Athletic participation also contributes both positively and negatively to a person's risk for cervical disc herniation. Lack of regular exercise weakens cervical muscles, thus making the neck less resistant to impact trauma or unnatural torsion (Huang et al., 2019). However, participation in certain sports can also increase this risk. Mundt et al. (1993) found that intensive weight lifting actually dramatically increases risk of both herniated cervical and lumbar discs. Use of free weights significantly increases an individual's risk of cervical disc herniation, however use of weight lifting equipment showed no such correlation (Mundt et al., 1993). They hypothesize that this discrepancy is explained by the difference in the quality of the loads applied to the spine. When using equipment, the forces applied to the spine from the weights distributes evenly across the spine and the individual experiences minimal lateral swinging (Mundt et al., 1993). However, when using free weights lateral forces are not controlled, thereby increasing the lateral bending of the spine (Mundt et al., 1993). Because some upper arm and shoulder muscles are interconnected with the muscles of the neck, the destabilization of the arm muscles likely radiates up into the neck, thus unevenly distributing stress across the cervical spine (Mundt et al., 1993).

Mundt et al. (1993) also evaluated the risk of cervical disc herniation in sports that involve spinal torsion or compression. Participation in baseball, golf, swimming, and diving all had a negative correlation with incidence of cervical disc herniation, therefore indicating that participation in these sports may actually serve as a protective factor against herniation (Mundt et al., 1993). This is likely due to the maintenance of muscles in the neck, which can serve to protect the cervical spine.

Occupation

Jobs that require heavy lifting or prolonged static postures are associated with higher risk of disc herniation. Liu et al. (2016) demonstrated an increased risk for cervical disc herniation in physicians, which they attribute to long working hours and poor posture during examinations when they lean over patients. Long working hours tire the neck muscles, therefore requiring the cervical spinal column to bear more weight from the head. To counteract this increased prevalence among physicians, Liu et al. (2016) recommend short exercise breaks throughout the work day to stretch and reengage the neck muscles. Similarly, Huang et al. (2019) found that dentists have increased risk for cervical disc herniation compared to the general public. Like physicians, dentists maintain static postures for most work hours and tend to bend their heads forward during patient examinations (Huang et al., 2019). This poor posture causes the sustained contraction of cervical muscles, which can place too much pressure on the cervical discs (Huang et al., 2019). This increased pressure, combined with the muscle fatigue in later parts of their shift, causes the cervical discs to become more prone to damage and herniation (Huang et al., 2019).

Another profession that is associated with an increased risk for herniated cervical discs is truck driving (Lan et al., 2015). Lan et al. (2015) posited that this was due to the vibration of the truck during and after loading a container. The weight of the container bumping up and down on the road sends vibrations to the driver's seat, which creates simultaneous vertical and horizontal vibrational acceleration in the muscles of the driver (Lan et al., 2015). Because truck drivers are often exposed to this motion for many hours almost every day, the rattling of the cervical spine can cause accelerated disc degeneration, therefore increasing risk for cervical disc herniation (Lan et al., 2015).

Healthcare professionals and truck drivers are common professions, however one significantly less common occupation has also been shown to increase risk of cervical disc herniation. Johnston et al. (2010) found that the risk of disc herniation is 4.3 times higher in astronauts than in non-astronauts. They hypothesized that this was due to the elongation of the spine due to zero gravity in outer space (Johnston et al., 2010). In space, the spinal column becomes accustomed to lower mechanical loading, but when the astronaut returns to Earth, increased strain is reintroduced to the spine. Additionally, exposure to G-force during in-flight transitions introduces intense strain on the spinal column, which can lead to damage in the intervertebral discs (Lan et al., 2015). This damage to the annulus fibrosus then increases the ability of the nucleus pulposus to extrude from the boundaries of a healthy disc.

Overall, these studies demonstrate that cervical disc herniation is caused by both intrinsic characteristics such as age and skin color, and extrinsic factors such as occupation or substance use. A combination of these risk factors likely causes cervical disc herniation in many patients. Examining the interplay of these intrinsic and extrinsic factors has the potential to reveal more information about why some people are more likely to experience this injury than others.

Treatment

Treatment of a herniated cervical disc relieves the pain of a compressed nerve root and restores full sensory and motor function of the upper extremities. It is divided into two categories—a conservative approach and a surgical approach (Gebremariam et al., 2012). Clinicians typically start with a conservative approach, and if no improvement is seen surgery is often necessary (Gebremariam et al., 2012). Conservative treatment is non-invasive, and typically involves a combination of lifestyle changes and medication. Patients are advised to refrain from activities that might increase their risk of a second herniation and a combination of rest and physical therapy is used to return the ejected disc to its natural placement in the spinal column, thus relieving the symptoms (Gebremariam et al., 2012). Patients usually also take nonsteroidal anti-inflammatory drugs and oral corticosteroids to relieve discomfort and pain during their healing process (Gebremariam et al., 2012).

In more severe cases, such as when a conservative approach fails or when the disc causes serious impairment, surgery is required. In most cases, a cervical discectomy, removal of a cervical disc, is performed (Gebremariam et al., 2012). By removing the herniated disc completely, this procedure ensures that the pressure on the nerve root is completely relieved. This procedure destabilizes the adjacent vertebrae, but this is usually not a problem for people who live moderately active lives (Gebremariam et al., 2012). However, in patients that lead very active lives, such as athletes and workers that do a lot of heavy lifting, surgeons often fuse the two adjacent vertebrae (Gebremariam et al., 2012). In these cases, a titanium graft is attached to the bodies of the vertebrae, thus stabilizing the cervical region (Gebremariam et al., 2012). This procedure allows for participation in more strenuous activities, however it also significantly limits range of motion (Gebremariam et al., 2012). In less severe cases, surgeons often perform a cervical nucleotomy in which they remove extruded tissue, leaving the disc a little bit smaller but removing pressure on the spinal nerve roots (Zieger et al., 2011). This procedure is less invasive than the discectomy, but is still only warranted in cases where a conservative approach is not sufficient.

Psychiatric influences on severity

Because surgery indicates a more serious case, Zieger et al. (2011) sought to identify psychiatric trends in patients undergoing cervical nucleotomy, thereby potentially associating certain psychiatric conditions with a severe herniated cervical disc. Interestingly, the results revealed that disc surgery patients are more likely to suffer from mental health disorders than the general population (Zieger et al., 2011). Zieger et al. (2011) does not distinguish whether these findings indicate a causal relationship between psychiatric disorders and surgical treatment, or whether these increased rates are a non-specific result of undergoing surgery. Regardless, their findings are relevant because they have implications about patient recovery time and ability to return to normal life after treatment is completed.

Anxiety disorders, affective disorders, and substance-use disorders were all correlated with severe injury outcomes (Zieger et al., 2011). In fact, 33.7% of German patients undergoing cervical nucleotomy had a 12-month prevalence rate of an anxiety, affective, or substance-related disorder, which is higher than the 23.5% prevalence for patients undergoing lumbar nucleotomy (Zieger et al., 2011). Of these psychiatric comorbidities, affective disorders such as major depressive disorder and bipolar disorder are the most common among patients undergoing cervical nucleotomy (Zieger et al., 2011).

There are several explanations for these findings. For one, substance-use disorders are likely associated with greater severity of cervical disc herniation because the toxins from the substances damage the discs by accelerating degeneration, thus inhibiting disc repair (Shin, 2014). The lack of repair mechanisms and the constant damage to the discs can cause aggressive herniations, and require surgical treatment. Additionally, the increased pervasiveness of psychiatric disorders could result from multiple medical problems in addition to a herniated disc (Zieger et al., 2011). If an individual has another medical disorder that limits their mobility, they might develop depressive symptoms due to the lack activities they once enjoyed. Both physical and mental health disorders can lead to a more sedentary lifestyle and thereby increase risk for disc herniation due to atrophy of the neck muscles (Huang et al., 2019). Furthermore, lack of a strong social support network can contribute to psychiatric disorders. Single marital status increases the risk for requiring cervical nucleotomy, perhaps indicating that these patients feel as though they have a limited network of people upon whom they can rely while undergoing rehabilitation (Zieger et al., 2011). This can then lead to decreased mental health, which can reflect in these findings.

Overall, Zieger et al. (2011) demonstrated that the severity of cervical herniated discs is associated with several psychiatric comorbidities. First, understanding this correlation is critical during the recovery process for patients that have undergone cervical nucleotomy. If healthcare professionals are aware that these patients are at greater risk for mental health disorders, they can take extra precautions to ensure the mental health of the patient in addition to the physical recovery. This could include encouraging meeting with a psychiatrist before and after surgery to discuss potential anxieties regarding the procedure. Additionally, physicians could stress the importance of physical activity in patients suffering from psychiatric disorders by explaining the increased risk for requiring spinal surgery. This could potentially encourage these individuals to stretch or exercise to avoid surgery. More research on these methods is required to prove their effectiveness, however understanding the correlation between psychiatric disorders and severe cervical disc herniation is vital to fully comprehending how neck injury outcomes can be influenced by a person's mental state.

Cervical intervertebral disc herniation can cause significant debilitation and long-term deficits that range from small sensory malfunctions to the inability to control muscle movement of the upper extremities and excruciating pain. Certain people are at higher risk of this injury due to their age, gender, occupation, and participation in athletic activity. Awareness of these risk factors can encourage people to pursue a healthy lifestyle that includes exercise and avoiding harmful toxins. While understanding the anatomy of the cervical discs contributes to the understanding of the functioning of the human neck, it is also crucial to explore the pathology of cervical disc injury because doing so clarifies why it is necessary for each component of the neck to function efficiently and healthily.

III. Whiplash Injury

While many neck injuries are well understood, whiplash remains somewhat mysterious to researchers. The general mechanism of the injury has been identified, but the exact causes of the pain and debilitation that whiplash patients face is not fully understood. Researchers have proposed hypotheses ranging from the build-up of adipose tissue to inflammatory responses in tissue surrounding cervical muscles, however multiple factors likely contribute to the development of whiplash pathology.

Overview of whiplash pathology

The term whiplash was first used in 1928 to describe neck injury after a rear-end motor collision (Alpini et al., 2014). Since then, the definition has remained controversial due to lack of consistent symptoms and diagnostic criteria (Stemper & Corner, 2016). Today, whiplash is most often associated with motor vehicle accidents and occurs in roughly 3 out of every 1,000 inhabitants in North America and Western Europe (Alpini et al., 2014). According to Alpini et al. (2014), the incidence of whiplash injury in developed nation has increased over the past 30 years, likely due to a combination of more populated roads, faster cars, and an increased rate of seeking medical treatment after an injury.

In addition to its painful symptoms for the patient, the injury is also a major economic burden on the healthcare systems of industrialized countries (Hendriks et al., 2005). Diagnostic tools such as imaging are often inconclusive, and because these techniques are expensive they waste money and resources (Stemper & Corner et al., 2016). Additionally, 25% of those with a cervical spine injury caused by a car accident have pain that progresses to a chronic condition. This lifetime of treatment is a burden on not only the patient but also the healthcare system as a whole (Aljinović et al., 2020). This statistic reveals an important distinction in whiplash treatment and pathology. While many patients have pain that lasts only two to three months, others have chronic symptoms and disability (Kasch et al., 2016). This difference between acute and chronic whiplash is important when considering severity and lifetime disability.

Although no diagnostic technique has been implemented universally in the healthcare system, Linnman et al. (2011) identified one potential method that could provide a more definite diagnosis of whiplash. They injected whiplash patients and healthy control subjects with C-D-deprenyl, a tracer that is used to locate areas of inflammation, to observe neck inflammation in the injured patients. The team then used PET scan imaging to visualize the uptake of C-D-deprenyl, with higher uptake levels indicating increased inflammation (Linnman et al., 2011). This experiment revealed elevated C-D-deprenyl uptake in cervical tissues of whiplash patients, indicating that whiplash causes an inflammatory response (Linnman et al., 2011). This inflammation was highest near C2 and around the *semispinalis cervicis muscle*, thus suggesting that this location is disproportionately damaged during whiplash-causing movements (Figure 12) (Linnman et al., 2011). Because contraction of the *semispinalis cervicis muscle* causes extension of the head, this muscle would be likely strained during the

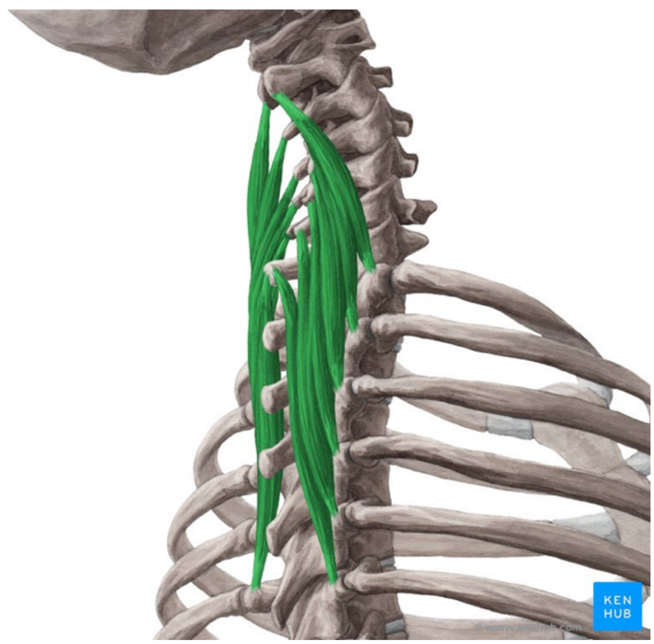


Figure 12. *Semispinalis cervicis muscle* (Vasković, 2020). The *semispinalis cervicis muscle* is a deep cervical and back muscle that is found on either side of the vertebral column.

flexion phase of a whiplash-causing event (Vasković, 2020). This PET scan finding is therefore consistent with the biomechanics of whiplash injury. While this diagnostic tool is not yet widely used, this study provides a better understanding of the pathology of whiplash injury, lays the foundation towards a more concrete diagnostic protocol and targeted treatment, and could reveal the cause of pain and other symptoms.

The most common symptoms of whiplash injury are neck pain, dizziness, nausea, limb numbness, cognitive difficulties, and tinnitus (Kasch et al., 2016). These symptoms typically improve over time, but can persist in more debilitating cases. In severe cases, symptoms also include cognitive deficits in attention, concentration, and memory, however none of these are associated with any lesions in the CNS when an MRI is performed (Alpini et al., 2014). Because no damage to the CNS can be visualized, the cause of these cognitive symptoms remains somewhat of a mystery to physicians.

Another less common symptom of whiplash is restricted jaw and head movements, however there is no correlation between movement ability and neck pain intensity (Eklund et al., 2020). A potential cause of some of these movement-restricting and pain-related symptoms is an increase of fatty infiltrates in the cervical region (Elliott et al., 2006). These infiltrates take up space in the neck and therefore prevent normal movement and likely press on nerves, thus causing pain as well as sensory deficits (Elliott et al., 2006). Whiplash patients were found to have significantly higher amounts of fatty infiltrates in the cervical extensor muscles around C3 than healthy control subjects (Elliott et al., 2006). The *multifidus muscle* (Figure 13) had the most significant difference in fatty infiltrate composition between whiplash patients and control subjects (Elliott et al., 2006). The *multifidus muscle* is involved in the extension of the spine, therefore the trauma is likely inflicted on this region during the flexion phase of whiplash injury (Figure 13) (Gorman, 2020). This finding is consistent with those of Linnman et al. (2011) as discussed earlier.

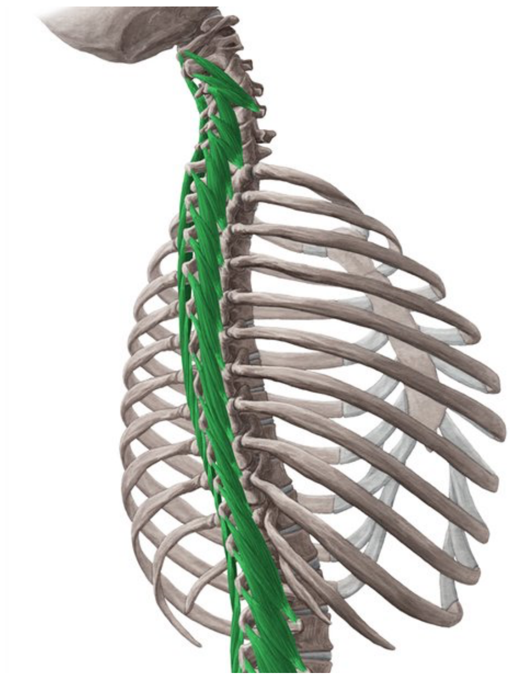


Figure 13. ***Multifidus muscle*** **(Gorman, 2020).** The *multifidus muscle* is a deep cervical and back muscle on either side of the vertebral column.

Biomechanics of whiplash

Whiplash is generally caused by the differential acceleration of the head and the thorax. This causes the force of impact to be transmitted throughout the neck in a fast motion of alternating flexion and extension, thus causing the cervical spine to be moved in a whip-like fashion – hence the name whiplash. The more specific biomechanics of whiplash injury depends on the type of car collision. When the individual rear-ends another vehicle, the car decelerates quickly, which then causes the deceleration of the passenger when they are restrained by either the seatbelt or impact with the steering wheel (Babar, 2000). As this restraint occurs, the cervical spine flexes and the head keels forward because it is still accelerating momentarily after the thoracic movement has stopped (Babar, 2000). After the restraint occurs, the passenger recoils backwards, causing extension of the upper cervical spine (Babar, 2000). Then the passenger's back impacts their seat and head rest, causing the reciprocal motion in which the upper cervical spine flexes again (Babar, 2000).

When the individual is rear-ended, the vehicle accelerates forward, pushing the passenger forward primarily at the level of the thorax (Kasch et al., 2016). This acceleration of the thorax in relation to the head causes the head to snap backwards into hyperextension, which is then quickly knocked forwards again after making contact with the headrest, while at the same time the thorax is restrained by either the seatbelt or steering wheel (Kasch et al., 2016). This causes a whip-like flexion of the cervical spine as the head travels forwards and the thorax travels backwards (Kasch et al., 2016). Sterling and Kenardy (2011) summarize this head movement in three phases – retraction, extension, and rebound (Figure 14). These two scenarios are almost identical, however in the case that the

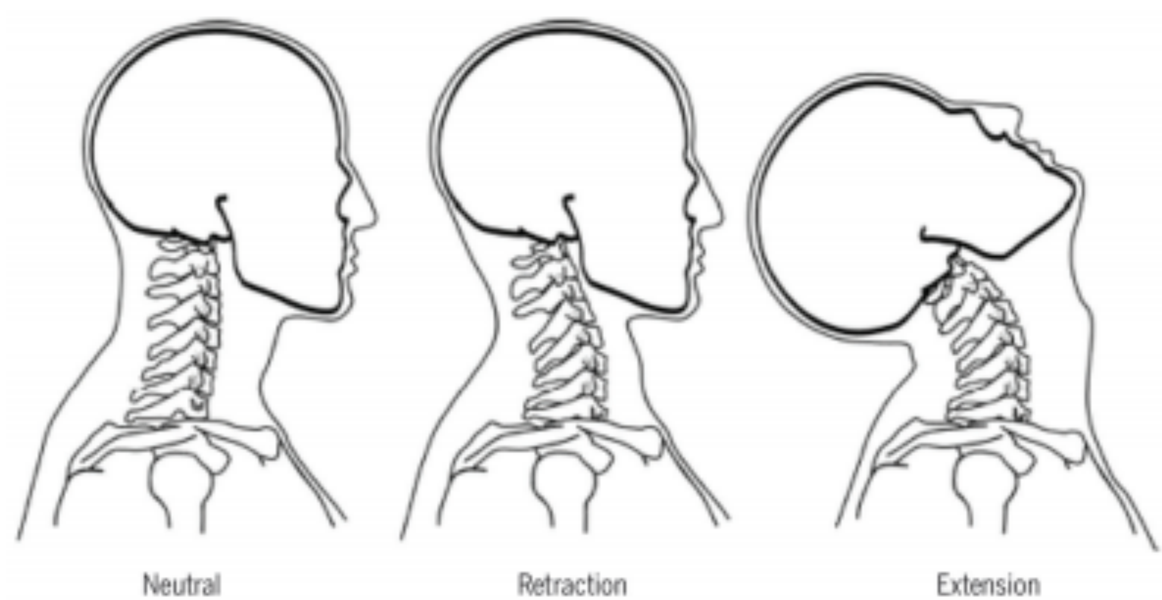


Figure 14. Two of the three phases of whiplash injury (Sterling & Kenardy, 2011). Head-neck response to motor vehicle rear-endings.

passenger does the rear-ending, the process begins with the deceleration of the thorax and the flexion of the cervical spine, whereas in cases where the passenger gets rear-ended the process begins with acceleration of the thorax and the extension of the cervical spine.

Female-bias susceptibility to injury

Women are more likely than men to experience whiplash (Kasch et al., 2016). This is due to two factors – 1) the mismatch between the female body proportions and the design of car seats, and 2) the general physical differences in body size and proportion between males and females. First, car seats are designed to be "one size fits all" and must accommodate adult occupants of all sizes ranging from small females to large males (Stemper & Corner, 2016). However, most car safety assessments are solely based on the response of the average-sized male. Therefore occupants with different body sizes, especially females who are typically shorter and lighter in weight, are not as well-protected by the safety features of most cars (Stemper & Corner, 2016). On average, females are 6 cm shorter than males, thus their heads are positioned closer to the head restraint, which in modern cars have a rearward slope (Stemper & Corner, 2016). This discrepancy causes the heads of females heads to more likely hit against the part of the head restraint that juts out, therefore causing a more drastic impact and rebound.

Furthermore, female bodies are shaped slightly differently than male bodies in a way that exacerbates whiplash symptoms. Firstly, females have a more exaggerated S-shaped curvature in their cervical spines. They can flex and extend their cervical spines more than men, thus exerting more strain on the flexor and extensor muscles (Kasch et al., 2016). Additionally, because the female spine is more curved than the male spine, extreme flexion and extension against the natural grain of the S-shape results in greater deviation from the normal resting position. This increased strain in the musculature and vertebrae could be a potential cause of more severe whiplash injury in females.

Additionally, women have a lower center of gravity than men which, when combined with a lower body mass, causes greater thoracic acceleration and a greater displacement of the thorax relative to the head in females than in males (Kasch et al., 2016). This also contributes to the more extreme extension of the cervical spine in female passengers (Kasch et al., 2016). The smaller stature of most females also decreases the surface area of the thorax that touches the seatback during the head extension phase, thus placing more of the mechanical load on the head and neck rather than having the force of impact with the seat dispersed between the head and the large surface area of the thorax (Kasch et al., 2016).

Stemper et al. (2003) measured this more extreme flexion and extension and determined that the magnitude of the angulation during whiplash injury between all cervical vertebrae was greater in females than in males, with the largest discrepancy between C6 and C7. In females, the angle of extension between C6 and C7 is roughly 7°, whereas the angle is only approximately 4° in males (Stemper et al., 2003). This difference in severity of extension indicates greater soft tissue strain in the areas around these vertebrae, which likely contributes to increased whiplash injury risk in females (Stemper et al., 2003).

In addition to the differences in body placement, females also have neck proportions that make them vulnerable to the movement that causes whiplash injury. Females have a smaller head-to-neck cross-sectional area ratio than males and proportionately less muscle and fat in their necks (Kasch et al., 2016). Muscles resist unwanted movement, therefore the additional muscle mass in males protects against whiplash injury (Kasch et al., 2016). This is supported by the finding that female neck muscle strength is estimated to only be about 71% that of males (Kasch et al., 2016).

Factors that influence severity

Severity of whiplash injury varies among patients, with some recovering in a couple of months while others have persistent pain and disability for the rest of their lives. Typically, recovery happens within three months of injury. However, if pain and other symptoms persist, the chance of chronic pain increases (Ritchie & Sterling, 2016). Exploring the factors that lead to such different outcomes is important both in understanding whiplash pathology and developing potential preventions. Risk factors for more severe cases can be divided into post-collision and pre-collision risk factors.

Post-collision risk factors

According to Kasch et al. (2016), the most significant post-collision predictor of poor recovery from whiplash injury is the first report of neck pain intensity. On a typical scale from 1 (no pain) to 10 (the most intense pain ever experienced), a rating of greater than 5.5 out of 10 during the initial injury assessment is associated with a nearly sixfold increase in the risk of lasting pain or disability (Kasch et al., 2016). This staggering statistic reveals that the severity of the initial pain greatly influences pain persistence and chronic disability.

Additionally, a score of 40% or higher on the Neck Disability Index (NDI), a questionnaire used to determine a patient’s ability to continue with everyday life after neck injury, also accurately predicted that those patients will develop more severe and debilitating whiplash symptoms (Kasch et al., 2016). This indicates that the more disabling the symptoms are immediately after the injury occurs, the more likely it is for those symptoms to be chronic. One possible explanation for this finding is that an initially high NDI score could disrupt occupations that require hard manual labor, which could therefore jeopardize job security. With no steady income, the patient could not afford treatment such as physical therapy and pain-management medication. Higher disability ratings immediately after the injury could cause a cyclic effect in which the causes for these high ratings could prevent effective treatment to relieve severe symptoms.

Furthermore, an age of ≥35 also increases an individual's risk of developing a more severe case (Kasch et al., 2016). This could be due to the heightened likelihood of damage caused by years of use and other previous injuries in older individuals (Kasch et al., 2016). Because their cervical regions have already been exposed to potentially weakening events, older adults are more susceptible to more extreme whiplash injury.

Another factor that contributes to the development of chronic whiplash is the range of motion of the head and neck regions after the initial trauma. According to Sterling et al. (2005), decreased range of motion is correlated with a higher likelihood of developing more severe symptoms. This is likely another reason individuals with higher NDI scores are more likely to have long-lasting pain. As discussed earlier, Weber et al. (2019) found that muscle fatty infiltrate build-up in the cervical region is strongly correlated to persistent disability. In addition to pressing on spinal nerves, these infiltrates in the deep cervical spine extensor muscles also restrict normal movement by taking up additional space in the spinal column and therefore decrease range of motion (Weber et al., 2019).

In addition to physical factors, psychological factors can also play a role in post-collision whiplash recovery. Sullivan et al. (2006) found that whiplash patients that participated in both physical therapy and a Progressive Goal Attainment Program, a 10-week psychosocial intervention that aims to minimize psychological stress, had a 1.5 times higher return to work rate than patients that participated in physical therapy only. This study demonstrates the impact psychological factors can have on recovery and indicates that lower mental health is associated with poorer recovery. The team hypothesized that this could be due to many factors, not limited to the fact that better mental state increases chances of making productive contributions to society, therefore perpetuating the belief that recovery is possible (Sullivan et al., 2006).

Dual risk factors

Some risk factors are both a pre-collision and post-collision predictors of whiplash severity. Bendix et al. (2016) found that diseases of the endocrine, nervous, respiratory, genito-urinary, and digestive systems were associated with an approximately 1.5 times higher risk for severe symptoms and persistent pain. This risk was the same regardless of the timing of the onset of the disease – it could have developed before or after injury (Bendix et al., 2016). Furthermore, parasitic infection also significantly increases a patient’s chance of developing chronic whiplash (Bendix et al., 2016). A likely explanation for these findings is that these diseases and infections weaken the individual, therefore leaving them susceptible to more severe injury and less effective recovery efforts (Bendix et al., 2016). This weakening could be in the muscles that protect the neck, but could also be in the systems that repair damage after injury.

Additionally, training and physical therapy that strengthen muscles in the neck successfully improve whiplash symptoms (O’leary et al., 2015). Strength training increases the cross-sectional area of the neck muscles, which allows them to better withstand force and decrease the amount of strain on vertebrae and other tissues (O’leary et al., 2015). This allows the neck to heal more efficiently, thereby decreasing healing time and overall disability. O'leary et al. (2015) found that another potential explanation for the decreased symptoms is that exercise also decreases muscle fatty infiltration. Because higher levels of fatty infiltrates are associated with more serious and chronic symptoms, decreasing these quantities can significantly improve a patient's whiplash recovery. Although these findings focus on injury recovery, it is likely that regular exercise before the collision and physical therapy could serve as protective factors against severe whiplash.

Pre-collision risk factors

Another pre-collision consideration that influences whiplash severity is the presence of other vertebral damage. Elliott et al. (2020) took CT scans of whiplash patients and looked for vertebral pathologies. The type of pathology found on the scan was noted, and the total number of pathologies were added together. They found that people with a central stenosis, uncovertebral degeneration, and three or more abnormal vertebral pathological findings were more likely to have chronic symptoms (Elliott et al., 2020). Central stenosis occurs when the spinal cord is compressed by an enlarged ligament or bony protrusion, therefore this injury likely weakens the cervical region and causes additional pain and disability. Similarly, the degeneration of the uncovertebral joints of the cervical vertebrae likely also weakens the cervical spine. Other examples of pathologies that individually did not significantly impact whiplash severity, but when combined indicated a higher likelihood of a severe case included cervical disc protrusion, forward sliding of vertebral column, and rearward sliding of vertebral column (Elliott et al., 2020). The pain from whiplash injury likely compounds with the pain from these pathologies and may even make the pre-existing conditions worse.

As discussed above, post-collision psychological intervention influences whiplash prognosis, however pre-collision psychological distress is also associated with injury outcomes. Andersen et al. (2019) examined the role of attachment styles – cognitive-emotional schemata that form early in life from interactions with attachment figures – on whiplash recovery. They found that an insecure attachment style increases risk for chronic pain, maladaptive coping mechanisms, and pain-related disability. Furthermore, both attachment-avoidance and attachment-anxiety conditions were correlated with higher physical and psychological disability resulting from whiplash injury (Andersen et al., 2019). A plausible explanation for these results is that people with insecure attachment styles are less likely to reach out to a support network to help them recover (Andersen et al., 2019). By not asking for help, they might not have the time to appropriately rest or might not be as consistently able to attend physical therapy sessions.

Diagnostic controversy

Because whiplash is not easily diagnosable, there is some controversy regarding the validity of experiencing chronic symptoms. Beck (2016) published an article in *The Atlantic* expressing doubt that such a high number of whiplash patients have persistent and debilitating symptoms. The lack of a standardized diagnostic test to confirm a cause of symptoms has led to a number of people faking whiplash injury to receive a payout from insurance companies (Beck, 2016). This scam is an easy way for people who have been in minor car accidents to receive several thousands of dollars, and Beck (2016) argues that a large portion of whiplash patients use this logic to justify chronic symptom malingering. In addition to the monetary incentive, the high rates of chronic whiplash could be explained by what Beck (2016) refers to as "whiplash culture" – the assumption that a car accident will result in serious injury. Because patients have psychological expectations, they are more likely to think they are experiencing intense pain or will indicate so when asked by a doctor (Beck, 2016). According to Beck (2016), this combination of malingering and exaggerating symptoms based on expectation of injury leads to an over-reported incidence of chronic whiplash injury.

In response to this article, Elliott et al. (2016) published a rebuttal, which argued that chronic whiplash should not be dismissed as merely malingering or the result of psychological expectations. Elliott et al. (2016) point out that there are, in fact, clear clinical signs and symptoms to explain why some patients recovery quickly while others do not. Furthermore, Elliott et al. (2016) point out the flaw in the logic used by Beck (2016) that assumes that if there are no clear diagnostic tests or consistent symptoms then the disability must not be real. Just because an injury or illness does not have clear means of diagnosis now, does not mean those answers do not exist. Elliott et al. (2016) used the example of stomach ulcers, which were once thought to be the result of stress and overstimulation of the sympathetic nervous, but in 1982 were discovered to be caused by the bacteria *H. pylori*. Medical understandings change over time, and the lack of a clear cause should not indicate a conclusion that no such cause exists. The juxtaposition of these two articles reveals the complicated nature of whiplash diagnosis, as well as the controversy surrounding injuries with no clear physical source.

In conclusion, whiplash injury remains enigmatic despite recent research regarding causes, diagnoses, and treatment options. Because it is a common injury, it is a huge burden for both the individual and the healthcare system as a whole, therefore continuing research is important for successfully preventing severe and chronic symptoms. Although whiplash-causing accidents are largely unavoidable, understanding factors that decrease one's chances of serious pain and disability could potentially lead to the implementation of programs that stress the importance of preventative factors such as regular exercise and seeking psychological intervention after injury. Overall, the complexity of whiplash injury reflects the intricacy and vulnerability of the human neck.

IV. Conclusion

Comparison of herniated cervical disc injury and whiplash injury

Evaluating the complexity and vulnerability of the human neck through the lens of herniated cervical disc injury and whiplash injury is an important step towards a deeper understanding of neck injury. Comparing these two injuries provides a more holistic comprehension of the general causes, symptoms, and risk factors of neck injury. Both disc herniation and whiplash are caused by the inability to effectively prevent mechanical loading, most often during a traumatic event. The circumstances of these unwanted forces and the biomechanics of the movement cause two dramatically different injuries. In addition to their differences, a herniated disc and inflammation resulting from whiplash injury are similar because they both compress spinal nerves and elicit similar symptoms of neck pain, arm numbness, and some loss of dexterity in the upper extremities.

In addition to similar causes and symptoms, herniated cervical disc injury and whiplash injury can both be mitigated by regular exercise. Muscular strengthening serves as a protective factor against both injuries due to the ability to better resist the mechanical unloading that occurs during the traumatic event. Similarly, both injuries are more severe when the patient reports a lower baseline health. Thus, regular exercise and a healthy lifestyle is imperative to protect the neck against potentially disabling injury and pain. Programs that spread awareness of this particular benefit of exercise could potentially help high-risk populations avoid serious injury.

It is also useful to explore what makes these injuries distinct. Perhaps the largest difference between herniated cervical disc injury and whiplash injury is the recovery timeline. While most herniated discs are acute cases that resolve in a matter of weeks, if not faster, many whiplash patients experience a lifetime of chronic. This discrepancy impacts outcome severity and influences the availability of treatment options. Someone with a herniated disc likely has access to treatment that reliably returns the intervertebral disc to its appropriate position in the vertebral column. However, whiplash treatment is often not as consistent or immediately effective. This has major implications for ability to return to work after injury and lifetime expenses to treat the symptoms. Someone with a herniated disc will likely pay for a few one-time expenses, but a whiplash patient could require a lifetime of pain management medication and physical therapy, and may never return to work. These more serious outcomes are possible with either injury, however the higher incidence of chronic whiplash demonstrates that this injury is more likely to cause chronic disability and long-term financial burden.

Herniated cervical disc injury has a pathology that is very well-understood, therefore treatment options specifically target the cause of the pain and discomfort. On the other hand, whiplash pathology is not very clear. The biomechanics of the injury are well described, however the exact cause of pain and disability is still largely unknown. Consequently, treatment options are less targeted and often less effective. This likely contributes to the higher development of chronic pain and disability after whiplash injury, and provides an incentive to fully understand the pathology of whiplash injury.

Psychological impacts of neck injury

Neck injury can cause a lifetime of physical deficits, but it also has a significant impact on the patient's long-term mental health. Psychological factors account for ~37% of the variance in a neck injury patient's perceived disability, thus suggesting that an individual's psychological status has a major impact on factors such as predicted improvement and outlook on the severity of the injury (Sullivan et al., 2002). One reason this should be explored further is because this pain impacts a large number of people. Roughly 4-5% of the general population experiences chronic daily headaches, 15% of which are caused by head and neck injury (Couch et al., 2007). In general, neck pain can lead to lower quality of life and decreased ability to effectively contribute to the workforce (Couch et al., 2007).

One specific psychological impact is dependence on pain-relieving drugs, resulting from long-term medication to manage pain and other symptoms (Clark, 2005). Many people desire temporary relief from debilitating symptoms of chronic pain. This can lead to drug dependence and over-use that is difficult to reverse, especially if the chronic pain persists. Additionally, if the patient depends on medication, they might perceive their symptoms to be under control when they are not, thus reducing their likelihood of seeking alternative treatments that relive pain.

Mental health disorders such as Post-Traumatic Stress Disorder (PTSD), major depressive disorder, and generalized anxiety disorder commonly result from neck injury. The prevalence of these disorders in whiplash patients are roughly 25%, 31%, and 20% respectively, indicating the strong impact of traumatic neck injury (Kasch et al., 2016). Mayou and Bryant (2002) found that whiplash patients had a higher frequency of PTSD the more they remembered the accident, which was also correlated with more severe symptoms. In general, people with more pain and disability report lower mental health, which can add to the stress and economic burden of living with chronic pain (Kasch et al., 2016).

Lastly, a patient's pain intensity and perceived disability are also influenced by the extent to which they catastrophize, or believe the worst will happen due to an exaggerated negative attitude. Sullivan et al. (1998) found that higher scores on a catastrophizing measurement were associated with higher ratings of disability, greater pain intensity, and a greater likelihood of unemployment. This finding could be due to decreased participation in treatment programs because the patient is already convinced the treatment will not be effective. Additionally, a negative outlook could contribute to a dramatization of symptoms, which after some time can be perceived more severely than they actually are. This correlation between catastrophizing and outcome severity necessitates rehabilitation interventions that specifically target catastrophizing in patients that are more likely to have these negative expectations (Sullivan et al., 1998).

Importance of studying neck injury

Studying musculoskeletal neck injuries such as herniated cervical discs and whiplash is crucial to contextualize the vulnerability of the human neck. Both injuries have complex pathologies and a plethora of risk factors that influence severity of the symptoms. While herniated discs have a clear-cut pathology and thorough comprehension surrounding the exact causes, whiplash injury is significantly less understood.

Studying the human neck is important because injuries to that region are extremely common, and can range from mild to chronically debilitating. A better understanding of these issues will improve treatment options by allowing clinicians to accurately target injured regions based on the individual's presentation of symptoms. This would not only accelerate recovery, but could also prevent the development of more severe and chronic cases. Additionally, more research can lead to prevention methods, which can lead to a decrease in total neck injury incidence. Decreasing the frequency of these injuries will improve population health and lessen the economic strain these injuries place on the healthcare system as a whole.

To conclude, the human neck is a complex region occupied by components from almost every organ system. Exploring the general anatomy of the structure emphasizes the intricacy of the region as a whole, and also reveals the impact one injury can have on the entire body. Herniated disc injury and whiplash injury both illustrate the vulnerability of the human neck and highlight the gaps in neck injury research. Causes, risk factors, and outcome severities of these injuries exemplify the complex nature of neck injury, and call attention to the importance of physical and mental health. Neck injury greatly impacts the global population, therefore continuing to examine these factors is imperative to protect human health.

Acknowledgements

I would like to thank Dr. Kent Dunlap for all of his guidance, feedback, and support throughout this process and during my time at Trinity College. His commitment to my success at Trinity and beyond made me a better student, a stronger writer, and a more critical thinker. Dr. Dunlap not only served as my academic mentor – he also taught me several valuable life lessons that I will carry with me long after graduation. Under his mentorship I have grown as both a student and a person, and I am incredibly grateful for the time and thoughtfulness he has given me over the years.

I would also like to express my gratitude towards Dr. Daniel Blackburn and Dr. Robert Fleming for their careful revisions to the early drafts of this thesis. The culmination of my research in this paper would not have been possible if not for their comments and suggestions. I would also like to thank the entire Biology Department. I owe a great deal of my success to the excellent professors I have had the privilege of working with over the past four years. Their instruction has deepened my interest in biology, and I know I am well-prepared for life after graduation because of the many lessons I have learned from them.

Literature Cited

Aljinović, J., Barišić, I., Poljičanin, A., Kuzmičić, S., Vukojević, K., Bokun, D. G., & Vlak, T. (2020). Can measuring passive neck muscle stiffness in whiplash injury patients help detect false whiplash claims?. *Wiener klinische wochenschrift*, 1-9.

Alpini, D., Brugnoni, G., & Cesarani, A. (2014). *Whiplash Injuries Diagnosis and Treatment* (2nd ed. 2014.). Springer Milan. https://doi.org/10.1007/978-88-470-5486-8

Andersen, T. E., Sterling, M., Maujean, A., & Meredith, P. (2019). Attachment insecurity as a vulnerability factor in the development of chronic whiplash associated disorder–A prospective cohort study. *Journal of Psychosomatic Research, 118*, 56-62.

Arrotegui, I. (2019). Slipped cervical disc: Treatment by means of, all in one. *Open scientific journal of surgery,* 34-40.

Babar, S. (2000). *Neck Injuries* (1st ed. 2000.). Springer London. https://doi.org/10.1007/978-1-4471-0787-3

Beck, J. (2016). *The Mystery of Chronic Whiplash Pain After a Collision*. The Atlantic. https://www.theatlantic.com/health/archive/2016/03/chronic-whiplash-is-a-medical-mystery/476052/

Bendix, T., Kjellberg, J., Ibsen, R., & Jennum, P. J. (2016). Whiplash (-like) injury diagnoses and co-morbidities–both before and after the injury: A national registry-based study. *BMC musculoskeletal disorders, 17*(1), 24.

Bordoni, B., Mahabadi, N., Varacallo, M., (2020). *Anatomy, Fascia*. In StatPearls. StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK493232/

Calais-Germain, B. (2007). *Anatomy of movement* (English language ed., rev. ed.). Eastland Press.

Carotid artery disease - Symptoms and causes. (2018). Mayo Clinic.

Cervical Herniated Disc. (2020). Altair Health.

Clark, C. (2005). *The cervical spine* (4th ed.). Lippincott Williams & Wilkins.

Couch, J. R., Lipton, R. B., Stewart, W. F., & Scher, A. I. (2007). Head or neck injury increases the risk of chronic daily headache: a population-based study. *Neurology*, 69(11), 1169-1177.

Eklund, A., Wiesinger, B., Lampa, E., Österlund, C., Wänman, A., & Häggman-Henrikson, B. (2020). Jaw-neck motor function in the acute stage after whiplash trauma. *Journal of oral rehabilitation*, *47*(7), 834-842.

Elliott, J., Jull, G., Noteboom, J. T., Darnell, R., Galloway, G., & Gibbon, W. W. (2006). Fatty infiltration in the cervical extensor muscles in persistent whiplash-associated disorders: a magnetic resonance imaging analysis. *Spine*, 31(22), E847-E855.

Elliott, J. M., Parrish, T. B., Walton, D. M., Vassallo, A. J., Fundaun, J., Wasielewski, M., & Courtney, D. M. (2020). Does overall cervical spine pathology relate to the clinical heterogeneity of chronic whiplash?. *The American journal of emergency medicine*, 38(5), 869-873.

Elliott, J., McMenamin, P., & Walton, D. (2016). *Chronic Whiplash: is it really a medical mystery?* PT Think Tank. http://ptthinktank.com/wp-content/uploads/2016/10/Whiplash_Medical-Mystery_Atlantic.pdf

Gebremariam, L., Koes, B. W., Peul, W. C., & Huisstede, B. M. (2012). Evaluation of treatment effectiveness for the herniated cervical disc: a systematic review. *Spine, 37(2)*, E109-E118.

Glenesk, N. L., Kortz, M. W., & Lopez, P. P. (2020). *Anatomy, Head and Neck, Posterior Cervical Nerve Plexus*. In StatPearls. StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK538514/

Gray, H. (1859). *Anatomy, descriptive and surgical*. Blanchard and Lea.

Gorman, N. (2020*)*. *Multifidus muscle*. Kenhub. https://www.kenhub.com/en/library/anatomy/multifidus-muscle

Hendriks, E. J., Scholten-Peeters, G. G., van der Windt, D. A., Neeleman-van der Steen, C. W., Oostendorp, R. A., & Verhagen, A. P. (2005). Prognostic factors for poor recovery in acute whiplash patients. *Pain*, 114(3), 408-416.

Huang, C. C., Kuo, P. J., Hsu, C. C., Lin, H. J., Su, S. B., Wang, J. J., & Weng, S. F. (2019). Risk for cervical herniated intervertebral disc in dentists: a nationwide population-based study. *BMC musculoskeletal disorders, 20(1)*, 189.

Iyer, S., & Kim, H. J. (2016). Cervical radiculopathy. *Current reviews in musculoskeletal medicine, 9(3)*, 272-280.

Johnston, S. L., Campbell, M. R., Scheuring, R., & Feiveson, A. H. (2010). Risk of herniated nucleus pulposus among US astronauts. *Aviation, space, and environmental medicine, 81*(6), 566-574.

Jomin, M., Lesoin, F., Lozes, G. A., Thomas, C. E., Rousseaux, M., & Clarisse, J. (1986). Herniated cervical discs. *Acta neurochirurgica, 79*(2-4), 107-113.

Kasch, H., Turk, D. C., & Jensen, T. S. (2016). *Whiplash injury: perspectives on the development of chronic pain*. Lippincott Williams & Wilkins.

Kolenkiewicz, M., Włodarczyk, A., & Wojtkiewicz, J. (2018). Diagnosis and incidence of spondylosis and cervical disc disorders in the university clinical hospital in olsztyn, in years 2011–2015. *BioMed research international*, 2018.

Lan, F. Y., Liou, Y. W., Huang, K. Y., Guo, H. R., & Wang, J. D. (2015). An investigation of a cluster of cervical herniated discs among container truck drivers with occupational exposure to whole-body vibration. *Journal of occupational health*, 15-0050.

Lennox, J. G. (2001). *Aristotle's philosophy of biology: studies in the origins of life science*. Cambridge University Press.

Linnman, C., Appel, L., Fredrikson, M., Gordh, T., Söderlund, A., Långström, B., & Engler, H. (2011). Elevated [11C]-D-deprenyl uptake in chronic Whiplash Associated Disorder suggests persistent musculoskeletal inflammation. *PLoS One, 6*(4), e19182.

Liu, C., Huang, C. C., Hsu, C. C., Lin, H. J., Guo, H. R., Su, S. B., & Weng, S. F. (2016). Higher risk for cervical herniated intervertebral disc in physicians: a retrospective nationwide population-based cohort study with claims analysis. *Medicine, 95*(41).

Mayou, R., & Bryant, B. (2002). Psychiatry of whiplash neck injury. *The British Journal of Psychiatry, 180*(5), 441-448.

Mundt, D. J., Kelsey, J. L., Golden, A. L., Panjabi, M. M., Pastides, H., Berg, A. T., & Hosea, T. (1993). An epidemiologic study of sports and weight lifting as possible risk factors for herniated lumbar and cervical discs. *The American journal of sports medicine, 21(6)*, 854-860.

Nakhla, J., Nasser, R., Yassari, R., Pasquale, D., & Altschul, D. (2016). Ruptured anterior spinal artery aneurysm from a herniated cervical disc. A case report and review of the literature. *Surgical neurology international, 7*.

Nemecek, A. N., Newell, D. W., & Goodkin, R. (2003). Transient rotational compression of the vertebral artery caused by herniated cervical disc: Case report. *Journal of neurosurgery: spine, 98(1)*, 80-83.

Nguyen, J., & Duong, H. (2020). *Anatomy, Head and Neck, Anterior, Common Carotid Arteries*. In StatPearls. StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK546613/

O'leary, S., Jull, G., Van Wyk, L., Pedler, A., & Elliott, J. (2015). Morphological changes in the cervical muscles of women with chronic whiplash can be modified with exercise—a pilot study. *Muscle & nerve, 52*(5), 772-779.

Piccinin, M.A., Munakomi, S., (2021). *Neuroanatomy, Vertebrobasilar System*. In StatPearls. StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK540995/

Polcaro, L., Charlick, M., Daly, D.T. (2020). *Anatomy, Head and Neck, Brachial Plexus*. In StatPearls. StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK531473/

Radhakrishnan, K., Litchy, W. J., O'fallon, W. M., & Kurland, L. T. (1994). Epidemiology of cervical radiculopathy: a population-based study from Rochester, Minnesota, 1976 through 1990. *Brain, 117(2)*, 325-335.

Ritchie, C., & Sterling, M. (2016). Recovery pathways and prognosis after whiplash injury. *Journal of orthopaedic & sports physical therapy, 46*(10), 851-861.

Seagal, Z. M. (2018). *Atlas of topographical and pathotopographical anatomy of the head and neck*. ProQuest Ebook Central https://ebookcentral.proquest.com

Shapiro, I., & Risbud, M. (2014). *The Intervertebral Disc Molecular and Structural Studies of the Disc in Health and Disease* (1st ed. 2014.). Springer Vienna. https://doi.org/10.1007/978-3-7091-1535-0.

Shin, B. J. (2014). Risk factors for recurrent lumbar disc herniations. *Asian spine journal, 8(2)*, 211.

Stemper, B. D., & Corner, B. D. (2016). Whiplash-associated disorders: occupant kinematics and neck morphology. *Journal of orthopaedic & sports physical therapy, 46*(10), 834-844.

Stemper, B. D., Yoganandan, N., & Pintar, F. A. (2003). Gender dependent cervical spine segmental kinematics during whiplash. *Journal of biomechanics, 36(*9), 1281-1289.

Sterling, M., Jull, G., Vicenzino, B., Kenardy, J., & Darnell, R. (2005). Physical and psychological factors predict outcome following whiplash injury. *Pain, 114*(1-2), 141-148.

Sterling, M., & Kenardy, J. (2011). *Whiplash: evidence base for clinical practice*. Elsevier Australia.

Sullivan, M. J., Adams, H., Rhodenizer, T., & Stanish, W. D. (2006). A psychosocial risk factor–targeted intervention for the prevention of chronic pain and disability following whiplash injury. *Physical therapy, 86*(1), 8-18.

Sullivan, M. J., Stanish, W., Sullivan, M. E., & Tripp, D. (2002). Differential predictors of pain and disability in patients with whiplash injuries. *Pain research and management, 7*(2), 68-74.

Sullivan, M. J., Stanish, W., Waite, H., Sullivan, M., & Tripp, D. A. (1998). Catastrophizing, pain, and disability in patients with soft-tissue injuries. *Pain, 77*(3), 253-260.

Vasković, J. (2020, October 29). *Semispinalis cervicis muscle*. Kenhub. https://www.kenhub.com/en/library/anatomy/semispinalis-cervicis-muscle

Vesalius, A., Richardson, W. F., Carman, J. B., Renick, S., & Milwaukee Academy of Medicine. (1998). *On the fabric of the human body: A translation of De humani corporis fabrica libri septem*. Norman Publishing.

Weber, K. A., Smith, A. C., Wasielewski, M., Eghtesad, K., Upadhyayula, P. A., Wintermark, M., & Elliott, J. M. (2019). Deep learning convolutional neural networks for the automatic quantification of muscle fat infiltration following whiplash injury. *Scientific reports, 9*(1), 1-8.

Zieger, M., Luppa, M., Matschinger, H., Meisel, H. J., Günther, L., Meixensberger, J., & Riedel-Heller, S. G. (2011). Affective, anxiety, and substance-related disorders in patients undergoing herniated disc surgery. *Social psychiatry and psychiatric epidemiology, 46*(11), 1181-1190.