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Feasibility and Reliability of a Commercially Available Stretch-Sensitive Sensor for Neck Movement

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Abstract

The ability to move the neck is usually a good indicator of neck health. However, the tools currently available to measure neck range of motion rely on gravity and the clinician's ability to accurately line the instruments on specific landmarks of the body. This study explored whether a commercially available wearable sensor, C-Stretch® that is flexible and lightweight can capture the functional performance of cervical motion across testing sessions. Furthermore, an assessment of the C-Stretch® against Aurora NDI, an electromagnetic tracking system was explored to determine the feasibility of transforming raw capacitance data into degrees of motion. Finally, a survey explored the user's experience with C-Stretch®. The C-Stretch® was able to monitor cervical motion across testing with good reliability for the Bag-Lift and poor reliability for the Bag-Slide and Star task ($ICC_{2,1}$ 0.57, 0.39, 0.37), respectively. The systems accuracy and agreement for rotational neck motion were evaluated. The C-Stretch® showed high correlation (r = 0.90-0.99, p < 0.01) for areas of overlap and was accurate for both sessions with average RMSE values of 5.06° (95% C.I = 0.30° to 10.10°) for the first session and 5.34° (95% C.I = 0.10° to 10.79°) for the second session with respect to the electromagnetic tracking system. Overall, users tolerated the C-Stretch® and did not find it uncomfortable. This study highlights the feasibility of using wearable stretch sensors that are light, unobtrusive and comfortable for assessing functional performance of the cervical spine.

Keywords

Summary for Lay Audience

The ability to move the neck is usually a good indicator of neck health. However, the tools currently available to measure neck range of motion rely on gravity and the clinician's ability to accurately line the instruments on specific landmarks of the body. The current study explores the use of a commercially available wearable stretch-sensitive sensor (C-Stretch®) along the sides of the neck of participants while they perform standardized tasks in a lab environment. The results were then compared against a gold-standard tracking system to assess whether this tool can be used to measure rotational neck movement. The results indicate that C-Stretch was able to monitor neck motion across testing sessions with good reliability for the first task, Bag-Lift and poor reliability for the second and third tasks, Bag-Slide and Star task ($ICC_{2,1}$ 0.57, 0.39, 0.37), respectively. For accuracy and agreement the C-Stretch® showed high correlation ($r = 0.90$-0.99, $p < 0.01$) for areas of overlap and was accurate for both sessions with average RMSE values of 5.07° (95% C.I = 0.30° to 10.10°) for the first session and 5.34° (95% C.I = 0.10° to 10.79°) for the second session in comparison to the electromagnetic tracking system. Overall, users tolerated the C-Stretch® and did not find it uncomfortable.

Acknowledgements

بِسْمِ اللّٰهِ الرَّحْمٰنِ الرَّحِيْمِ

In the name of Allah, the Most Gracious, the Most Merciful

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Chapter 1

Introduction

The spinal column is the body's main support structure divided into three parts; cervical, thoracic and lumbar spine. Of the three parts, the cervical spine is composed of seven vertebrae and allows the greatest freedom of movement. The cervical spine (neck) can move in all three cardinal planes of motion (frontal, sagittal, and horizontal) and, among other functions, the neck bears the load of the head for maintaining an upright posture. The cervical spine also serves as a layer of protection of several sensitive structures such as the cervical portion of the spinal cord and brainstem, the autonomic cervical ganglia, arterial supply to the brain, and is chiefly responsible for orienting the sense organs of the head towards environmental stimuli. As a result, the neck endures many daily strains and dysfunction in this region is responsible for one of the highest burdens of global disability [1]. With a peak burden in middle-age [1,2], the United States spent an estimated 87.6 billion dollars in 2013 on health care costs associated with ambulatory care, inpatient care and pharmaceuticals for low back and neck pain [3]. Furthermore, the tools currently used to assses neck mobility are limted to clinical settings, and use straight-plane movements that are not representative of day-to-day performance in the real-world [4]. Therefore, the motivation for this thesis is the inability to accurately capture cervical mobility in real-time. As a result, the purpose of this thesis was to explore whether a commercially available sensor can capture functional craniocervical movements in real-time with an emphasis on reliability.

1.1 Neck Pain Classification

Neck pain has many definitions, and the severity of pain can range from minor to severe. Therefore, the definition of neck pain in the literature is largely based on anatomical location, etiology, and duration. Based on the Bone and Joint Decade 2000-2010 Task Force on Neck Pain and it's Associated Disorders, neck pain can be best described by using a five-axis model. Of those, the axes used to describe pain are severity, duration and pattern. The severity of neck pain can then further be classified into four grades based

on symptom and pathology. A classification of Grade I and Grade II suggest that there are no symptoms or signs of major structural damage and disease, with Grade II neck pain is severe enough to interfere with daily life and requires the intervention of pain relief. Grade III and Grade IV differ from each other in that Grade III there are no signs or symptoms of major disease and damage, but neurological deficits are apparent. Grade IV differs from the other classifications in that there are signs and symptoms that support structural disease and damage (e.g. fracture or dislocation) and therefore require immediate intervention [5]. Recently, MacDermid et al. have added to this definition by classifying pain qualitatively into a seven-axis model to further classify pain. This incorporates the same model used by The Neck Pain Task Force; 1) Context , 2) Sample, 3) Severity, 4) Duration, 5) Pattern, but separating severity into two distinct sub-axes: 1) Symptom Severity and 2) Disability [6]. Of these axes, the nature of neck pain is usually described with respect to the symptom (i.e. localized to the neck, localized to the neck and shoulder, a combination of head and neck, shoulder and arm symptoms and so forth), severity (i.e. none, mild, moderate, severe), duration (i.e. transitory, short, long), the temporal pattern (i.e., a single episode, recurrent, persistent-stable, persistent-unstable) and effect on daily activity (i.e. basic hygiene, going to work, or participating in leisure activities)[5,6].

1.2   Prevalence

Neck pain is ranked within the top 4 non-communicable causes of global disability, which also includes low back pain, diabetes and heart disease according to the Global Burden of Disease studies [2,7]. It is estimated that about two-thirds of people will experience neck pain at some point in their lives, [8–10] with studies suggesting the incidence of neck pain is increasing [1,11]. Of those experiencing neck pain, epidemiological studies have shown that prevalence of pain increases with age and is more common in women [9,12]. In most cases, symptoms of neck pain will decrease with time without any intervention, though recent models conceptualize neck pain as commonly recurrent [13]. While not life-threatening, the high prevalence of neck pain, especially in the peak productive years, contributes to its huge global burden.

1.3 Cervical Anatomy

The cervical spine consists of seven vertebrae that articulate through seven intervertebral discs and seven pairs of zygoapophyseal (facet) joints. Some authors also recognize the existence of accessory or uncinate joints at the lateral portions of the vertebral body that are unique to the cervical spine [14,15]. The articulations are supported by 26 muscles in the neck (ten pairs of two and two sets of three). This provides the neck with the ability to move through multiple degrees of freedom (DOF), making the neck function collectively as a complex joint with multiple axes that are usually bound by the lower edge of the occiput cranially and the upper edge of the 1st thoracic vertebral body caudally. The first two vertebrae commonly referred to as the atlas (C1) and axis (C2) are considered atypical compared to the 3rd through 7th vertebrae, owing to their unique articulations and ligaments including the presence of an odontoid process on C2 and the lack of easily identifiable disc between C1 and C2. The cervical musculature can be split down the anatomical midline into left and right groups, meaning that most movements that occur at the cervical spine are a result of coordinated symmetrical or asymmetrical paired muscle contractions and relaxation. Sagittal plane flexion-extension movements are a direct result of paired muscle contractions of both sides of the neck leading to the bending of the upper cervical spine (C1-C5). Cervical rotation in the horizontal plane occurs through reciprocal contraction of an agonist on one side and antagonist on the other, resulting in a coupled rotation/lateral flexion of the neck. Left and right flexion (side bend) in the frontal plane similarly occur through coordinated asymmetrical contraction/relaxation of key muscle groups on each side of the neck.

The cervical spine is comprised of anterior, posterior and lateral muscles that wrap across the neck and are responsible for the multiple degrees of motion and stabilization with respect to gravity [16]. Although the muscles of the neck help with stabilization of the neck, alone they are insufficient for maintaining an upright posture. Rather a combined effort of finely controlled muscle activity, ligament support and bony articulations work together to support the head in an upright posture and to keep the neck stabilized with reference to the orientation of the body and gravity. As a result of the shape and

multiplanar orientation of the articular surfaces of the vertebrae, the motion of the neck during rotation or lateral flexion rarely occur in a single plane of motion [17–21].

1.4   Range of Motion

According to the dictionary of Modern Medicine, range of motion is the amount a joint can move as a result of the articular surfaces, ligaments and muscle contractions [20]. Normal values for the range of motion (ROM) are key identifiers for clinicians when discerning deficits, and assessing and monitoring joint health in people. In the literature, many studies have defined the normal active range of motion across many different age groups [22–25]. However, as described above, the complex multiplanar movements of the neck can make the evaluation of mobility difficult for clinicians. Table 1 shows normal values for 400 aspymptomatic people (males and females) for active cervical range of motion ranked by age groups with no difference between the sexes as reported by Swinkels et al., (2014) [22].

Table 1. Summary of active ROM from healthy people ranked based on age.

Age	Movement					
	Flexion	Extension	Left Lateral Flexion	Right Lateral Flexion	Left Rotation	Right Rotation
20-29	60°	75°	46°	45°	78°	79°
30-39	58°	69°	43°	42°	79°	79°
40-49	59°	43°	41°	40°	79°	78°
>50	53°	42°	38°	38°	71°	71°

1.5   Traditional Measurement Tools of ROM

Several tools exist to capture cervical range of motion (CROM) to evaluate joint function and motion patterns for objective assessment. Traditionally, tape measures, inclinometers, universal CROM goniometers, and standard manual goniometers have been endorsed as assessment tools for measuring cervical spine motion through single planes of movement [26]. The use of these tools relies on identification and palpation of specific landmarks and visual estimation for recording measurements of range of motion.

It is worth noting as with any measurement tool, especially when dealing with a clinical measurement tool, reliability (the degree to which measurements are stable in repeated testing under otherwise stable conditions) and validity (the degree to which the instrument measures the intended construct) are important properties that need to be understood in order to interpret patient results accurately. An instrument that is not reliable or valid can lead to misinformed decisions regarding diagnosis, treatment, prognosis, and evaluation of treatment effectiveness [26].

1.5.1 Tape Measure

A tape measure is a simple and easy to use tool that can assess CROM. It is attractive for clinicians for its small size, ease of use and low cost. The use of a tape measure relies on bony landmarks and measures motion via distance between landmarks rather than degrees. Measurements can be obtained in all of the three planes of motion (frontal, sagittal, and horizontal plane) with some variation in methods for measuring the rotation of the cervical spine in the transverse plane [27,28]. However, interobserver and intraobserver reliability for the tape measure has been poor to moderate [29]. Studies investigating the tape measure suggest that this method is least likely to capture accurate estimates of cervical range of motion [26,28,30].
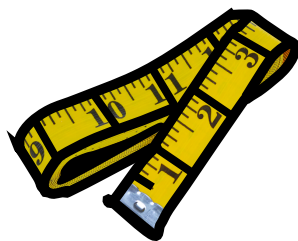
Figure 1. Tape Measure used for ROM.

1.5.2 Inclinometer

An inclinometer measures angles of slope (degrees of incline) in relation to gravity. The digital form of an inclinometer uses microelectromechanical sensors to align to gravity, while analog versions use simple weighted plumb lines or ball bearings. Often, the range

of motion is measured while the instrument is placed on top of the person's head under careful instruction from a clinician to perform CROM movements while keeping the thorax still [31]. Studies evaluating reliability and validity are inconclusive with some endorsing the inclinometer as a reliable tool [31,32] and other studies suggesting otherwise [26,31,33,34]. Furthermore, the reliance on orientation to gravity means that not all planes of motion can be tested without changing the orientation of the body (e.g. from sitting up to lying down). Bush et al., (2000) described the inclinometer as an inconsistent device in that they are unable to discriminate coupled movements of the cervical spine, particularly to the motions associated with lateral flexion and rotation [31].
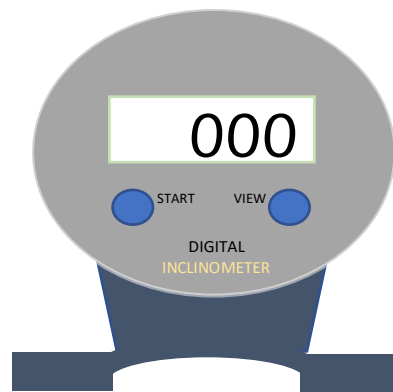
Figure 2. Digital Inclinometer used for ROM.

1.5.3 CROM Device & Universal Manual Goniometer

The CROM device is much like the inclinometer above, composed of a plastic frame made to sit on the bridge of the nose and strapped around the head and across the chin. Attached to this frame are three independent, usually ball-bearing inclinometers that track the head with reference to gravity [35]. Although reported to be reliable for measuring CROM in whiplash-associated disorder populations [27], some limitations exist in regards to cost and patient comfort, in addition to the limitations discussed above for inclinometers. A manual goniometer is essentially a transparent plastic protractor with two extended arms. The manual goniometer is different than the CROM device since it does not need to be strapped on the person to obtain ROM. Instead, one stationary arm

is lined up along a stationary body axis such as the trunk, and one moveable arm is lined up with a landmark on the head (e.g. the nose or ear line) to obtain degrees of ROM. Some studies have found the manual goniometer to be less accurate due to rater consistency, proper alignment with anatomical landmarks and the need to identify a neutral starting head position [36,37]. From de Konings [38] and Williams [30] review of these two instruments alongside the inclinometer and tape measure they suggest that these tools for measurement of cervical range of motion are at best 'good' estimates of CROM.

1.6   3D-Motion Tracking Systems for ROM

Given the complex motions of the cervical spine, a 3-dimensional motion capture system arguably provides a more realistic quantification of mobility, mainly as it can track movement through multiple planes simultaneously and is not bound by the orientation to gravity. Presently, different strategies have been proposed to evaluate the range of motion in 3D. These newer strategies involve the use of 3D-motion tracking systems, which include optoelectronic measurement systems, electromagnetic measurement systems and inertial measurement units.

1.6.1 Optoelectronic Measurement Systems

In these types of systems, infrared (IR) light is emitted from cameras that are then reflected by reflective markers attached on the subject to estimate spatial position [39]. These systems are primarily considered accurate though their accuracy is dependent on the number of cameras used, the number of markers used, the distance between cameras, and distance from the markers to the camera [39]. For accurate measurement, the markers need to be consistently in the line-of-site of the cameras; otherwise, the markers would not be detected [40,41].. The acquisition costs Including hardware and software set up and maintenance for optoelectronic measurement systems is high and time associated with application in a clinical setting remains a barrier to implementation, though these systems have become routine in lab-based biomechanical laboratories.
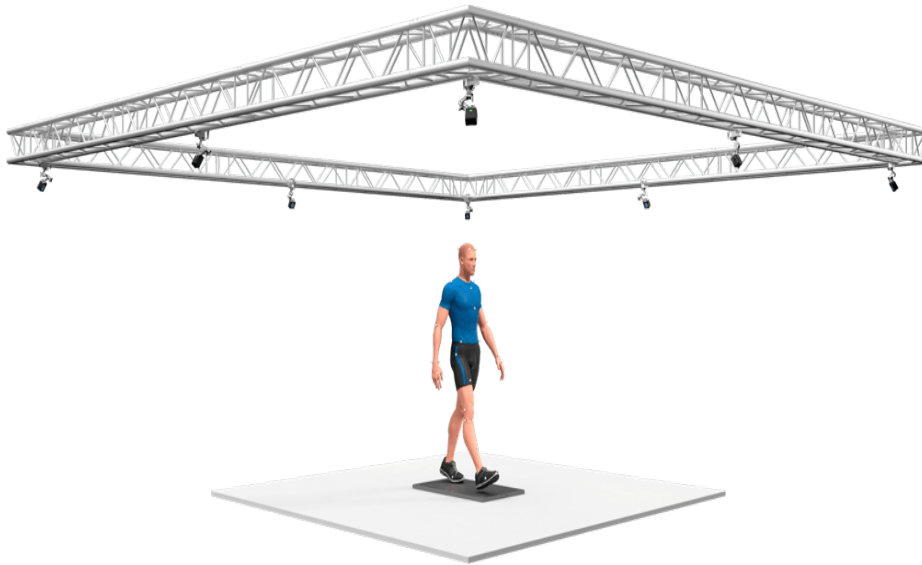
Figure 3. Optoelectronic motion capture setup. Obtained from www. OptiTrack.com

Another emerging trend that could be classed as an optoelectronic tracker is Virtual Reality (VR) headsets. While different hardware exists, many commercially available VR headsets use a similar setup of cameras that track IR emitting diodes on the head-mounted displays (HMD), such as the Oculus Rift® (Facebook Inc., Menlo Park CA) and the HTC Vive® (HTC Inc., Seattle WA). This type of system allows the user to interact with virtual objects or to complete objectives in a virtual world to illicit real-world motions that can be tracked [42]. The limitation with such a system is the discrepancy caused by lag, which is the delay between a performed action and its execution, usually resulting in nausea [43], dizziness [44], and motion sickness [45,46] in some users. Additionally, the loss and regaining of tracking is a source of inaccuracy for capturing movements that are seen with a line of sight dedicated 3D multi-camera IR systems[47].

1.6.2 Electromagnetic Measurement System

Electromagnetic tracking systems use wired sensor coils that work in proximity with a referenced electromagnetic field generator. The field generator emits electromagnetic signals to locate the position and orientation of the sensor coils. Aurora NDI is an example of this type of system. Unlike the optoelectronic systems, electromagnetic systems do not require a direct line of sight to track the position and orientation of the sensors coil [42].

This makes for an ideal system for out of sight motion tracking, as seen in tracking medical instruments during minimally invasive medical surgeries [42]. While these systems overcome some of the limitations with optical tracking systems, they require the subject to remain within proximity to the magnetic sensor preventing the capture of larger functional movements. For example, the Aurora NDI is only capable of capturing 3D-motion within a volume of 50cm by 50cm [48]. These tracking systems are also cost-prohibitive for routine clinical use and are sensitive to ferromagnetic materials in the environment that can add noise to the signal [49].
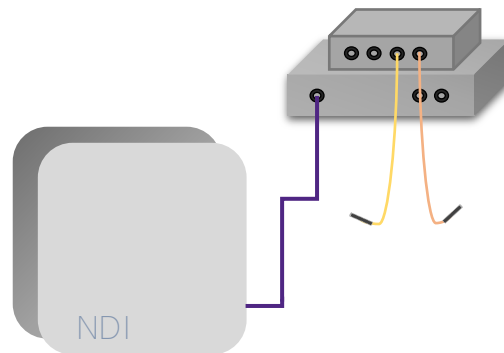
Figure 4. Aurora NDI, an electromagentic tracking system.

1.6.3 Inertial Measurement Unit Systems

An inertial measurement unit (IMU) is a device that consists of one or more motion sensors in a single device. They often consist of accelerometers that measure linear accelerations, gyroscopes that measure angular velocity, and at times incorporate the use of magnetometers that determines the orientation of the IMU with respect to earth's magnetic field [50,51]. In contrast to stationary optical or electromagnetic systems, IMUs are portable, unobtrusive, can be worn, and are not limited or tethered to a benchtop external sensor. In the literature, IMUs have been used to evaluate CROM. Zhou et al., (2018) used a single IMU to differentiate between impaired and healthy necks via circumduction movements measured using a head-worn wireless accelerometer [50]. However, limitations include the sensitivity of accelerometers to gravity, meaning that a reference sensor is generally required for the accurate range of motion calculations.

IMU's are also sensitive to interference by ferromagnetic materials because of the magnetometers, require frequent battery recharging, and often require complex computational models and algorithm development to make sense of the data.
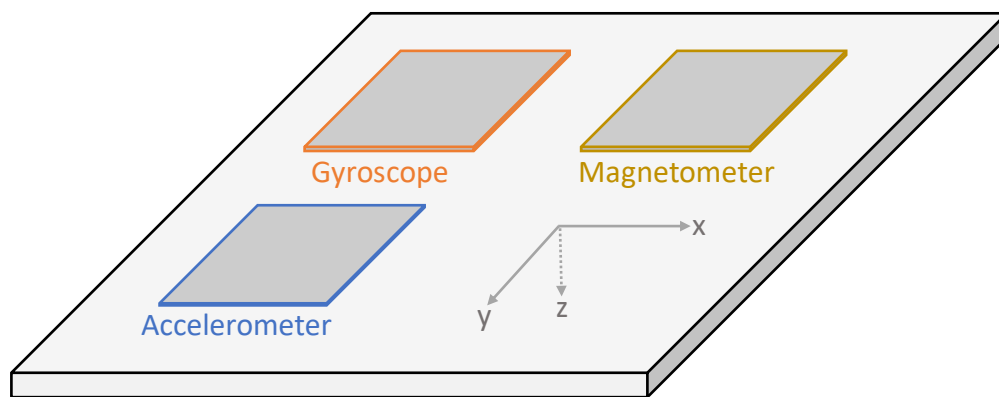
Figure 5. Example of an IMU with an embedded accelerometer, gyroscope and magnetometer.

1.7   A New Approach to CROM

Wearable sensors hold the potential to function as valid metrics of ecological 'real-world' cervical mobility in that they are not constrained to a clinic or laboratory environment. Wearable sensors are seeing an increase in popularity in health and rehabilitation as clinicians are finding value in more real-world metrics of mobility or vital signs beyond those captured during a 15-minute clinic visit [52,53]. They can also provide wearers and healthcare providers near-instantaneous feedback, in real-time, without complicated equipment or setup offering the potential for more personalized and on-demand health recommendations.

Commercially there are many examples of wearable devices that range in shape from smartwatches to armbands, smart clothing, jewellery, and eyeglasses amongst others. A common example of this is the increasing trend for wearable activity monitoring devices such as the Fitbit® (Fitbit Inc. San Francisco CA), Apple watch® (Apple Inc. Cupertino CA),

and Samsung Gear® (Samsung Inc. Seoul South Korea) wrist-worn devices. Most of these devices use IMUs to detect motion with a purpose to provide the user with 'real-time' feedback about motion and activity, and some can be taught through algorithms and sensors to differentiate types of activity (e.g. walking vs. running, vs. climbing stairs). Other metrics can be captured depending on the sensors embedded within, including heart rate, skin temperature, and blood oxygenation [54]. A review of wearable and implantable sensors for biomedical applications by Koydemir and Ozcan [55] demonstrated the breadth of embedded wearable devices for health monitoring. They found that there are many more wearable devices that can be donned on various body parts, from anywhere and as small as an earring on the ear to socks on the feet with the ability to monitor activity levels, blood oxygen saturation levels, calories burned, body temperature, sleep quality/pattern and monitoring.

1.7.1 Electronic Textiles

Wearables have also become increasingly integrated, embedded and implanted into everyday items in a way that is intended to not interfere with day-to-day activities. Further technological advancements in material science have enabled the development of wearable technology that sees embedded electronics on flexible substrates that are then put into fabrics allowing for sensing capabilities. As a result, e-fabrics have gained attention for their ability to monitor parameters such as heart rate, respiration rate, skin temperature and human movement [55,56]. An example, is the Smart Sock introduced by Alpha-FitGmbH (Wertheim, Germany) [57], that can measure the dynamic pressures across the entire foot as a result of loading caused by walking. This allows clinicians to then customize patient-specific shoes for monitoring abnormal forces on the feet of those who suffer from diabetes-related sensory loss. Fabrication is achieved by weaving or printing conductive components onto the fabric and then sensing the changes in the resistance of the material as it deforms.

1.7.2 Stretch-Sensitive Sensors

Flexible wearable sensors are known as "soft sensors". Soft sensors are configured as silicone films known as dielectric (insulating) elastomer sensors (DES). These are soft,

lightweight, stretchable, can withstand large strains and are relatively low cost [58–61]. DES are non-intrusive and can be oriented or designed as well as integrated into fabrics in a way that they are responsive to multiple degrees of freedom at once [59]. DES are based on electroactive polymers (EAP) which are comprised of a soft insulating silicone amongst other soft materials. DES function based on the principle of a parallel plate capacitor [62]. In this case, the parallel plate capacitor consists of a soft dielectric material sandwiched between stretchable electrodes, as seen in Figure 6.
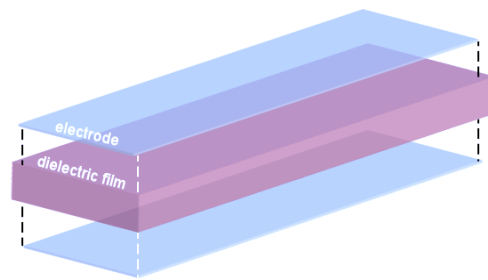
Figure 6. The basic structure of a dielectric elastomer sensor.

From this parallel capacitor, the capacitance can be recorded, which is the electrical potential of a system. In the case of a parallel plate system, when the distance between the two plates decreases or increases as a result of mechanical deformation, the capacitance changes. Therefore, mechanical work can transduce a change in the electrical signal [58,62]. This allows for a DES to act as a stretch/strain sensor. Capacitance can be defined as the change proportional to the area of overlap and inversely proportional to the separation between the two conducting layers. As thickness decreases, surface area increases, and as a result, a higher value of capacitance (Figure 7)[61]. Capacitance can be calculated by the equation:

$$C = \frac{\varepsilon_0 \varepsilon_r \, A}{d}$$

Where ε_0 is the vacuum permittivity (the measure of the materials ability to store an electric charge—since it's a vacuum this value is a constant), ε_r ε_r is the relative permittivity of the material that makes up the dielectric (the material of choice ability to store charges), A is the area of the overlapping electrodes, and finally d is the thickness of the dielectric layer [58,63,64]. As the dielectric film is strained or stretched, the thickness and area displacement incur change in capacitance measurements. This change in capacitance can then be converted to output voltage through capacitance to voltage converter circuit [65].
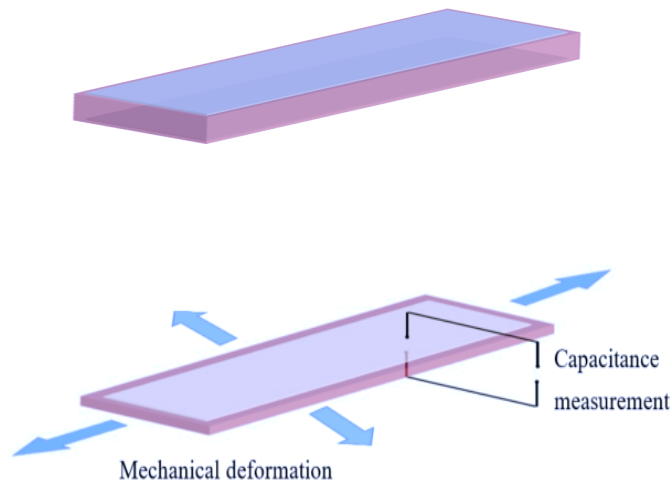
Figure 7. Unstrained dielectric elastomer sensor with a stable capacitance and strained DES with higher capacitance reading.

Based on this principle, a change in capacitance as a result of strain or stretch in one direction leads to many possible applications, specifically attaching such a sensor to textiles or directly to the human body for activity monitoring and the collection of movement data at specific joints. An attractive aspect of DES polymers is that they can be worn or adhered to the skin directly and can 'sense' movement as a function of stretch/compression, without requiring orientation to gravity or a fixed external sensor. As a result, I believe these polymers may represent a novel, convenient approach to capturing ecological real-world neck mobility. If that is the case, then the DES should be

able to sense subtle changes in neck motion and should provide stable metrics across testing sessions when other conditions are held consistent.

1.8   Objectives

The objective of this thesis is to assess whether a commercially available stretch-sensitive polymer, C-Stretch® (Bando Chemical, Kobe Japan), can capture functional cervical motion with an emphasis on reliability across testing sessions. A secondary objective is to determine the feasibility of converting raw capacitance data into degrees of motion, with a focus on cervical rotation as a traditionally difficult movement to quantify (Figure 8). A third sub-objective is to explore ratings of comfort and other elements of the user experience with C-Stretch®.

1.9   Thesis Outline
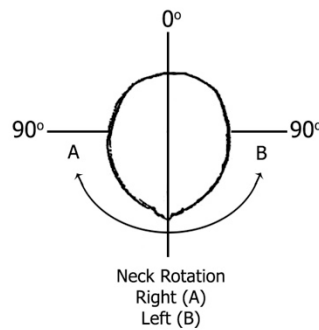
Figure 8. Rotation of the neck along the horizontal plane.

The following chapters of this thesis include a methodology chapter (Chapter 2) split by subheadings to describe the process of orientation and positioning of the C-Stretch® and Aurora NDI an electromagnetic tracking system (EMTS) along the neck to capture cervical motion for calibration and performance tasks. In chapter two, a detailed description is presented for how the data were processed for each objective. Following this, the bulk of this thesis is presented in the results (Chapter 3) based on each objective presented in the previous chapter. To conclude, a discussion chapter (Chapter 4) and a conclusion (Chapter 5) are prestented to summarize the objectives and associated implications for future work.

Chapter 2

Methods & Protocol

In this chapter, the methods of adhesion and the protocol for assessing C-Stretch® are introduced. Adhesion and orientation were reliant on motions that were consistently yielding data in the key planes of cervical motion. The protocol for this study was developed to focus on cervical rotation as a difficult-to-measure movement [66] but one that is important for functional tasks in the day-to-day, real-world activities [67].

2.1   Positioning and Orientation of C-Stretch®

The size of each sensor element used was 10 mm in width and 50 mm in length. Two stretch sensitive sensors were manipulated extensively to assess the best position and orientation that provided consistent movement data in the three planes of motion associated with the cervical spine, with rotation as the priority when positioning led to differential motion sensitivity. For safe attachment of the sensors to the neck, a double-sided thermoplastic elastomer tape (#2477P Medical Speciality Tape, 3M™, London ON) was used. Three volunteers aided in piloting the C-Stretch® sensors by following instructions for head movement (Figure 9) in the three cardinal planes (sagittal, frontal, and transverse plane). At first, the sensors were directly placed vertically to line up with the ear and shoulder. Placement of the sensor was to be centred between these two points along the neck without any pre-stretch. This yielded poor movement data when monitoring head movements in the sagittal (flexion and extension) and transverse plane (axial rotation). For the next attempt, the sensors were placed posteriorly on the neck, without any pre-stretch in the shape of an 'X'. When monitoring head movements in the three cardinal planes, only movements in the frontal plane yielded moderately acceptable data. A fatal drawback with this orientation was the overlap between the sensor and the double-sided thermoplastic tape used to form the 'X' shape. This overlap caused adhesion between the two sensors which restricted their ability to follow the head movements in the three planes.
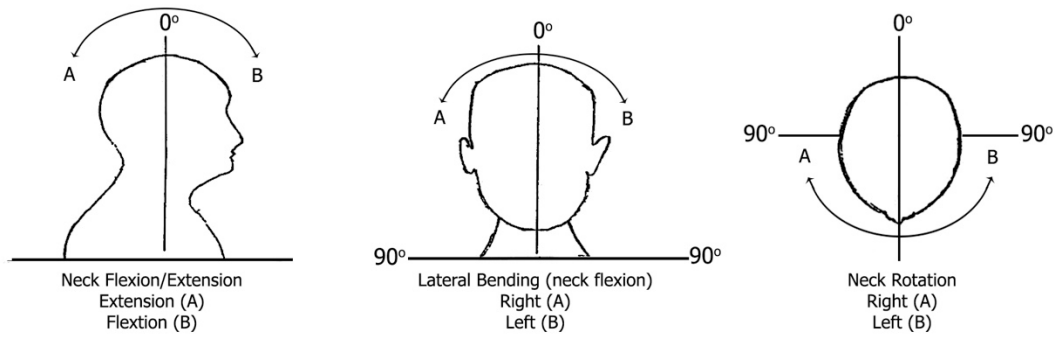
Figure 9. Movement participants were asked to produce in the three cardinal planes.

After additional trials, an orientation of the sensors and adhesive along the bilateral sternocleidomastoid (SCM) muscles provided the most reliable movement data in all three planes. This was identified by palpating the origin and insertion of these paired large muscles that are easy to identify through surface landmarking. Through further piloting, we determined that by pre-stretching to 1 V which corresponded to approximately 25% of pre-stretch length the C-Stretch® sensors allowed for cyclic deformation between compression and extension and therefore provide a more accurate representation of the movements being explored. Therefore, the sensors were placed on the mid-portion of SCM with the wire-end of the sensor closer to the clavicle (Figure 10).

Figure 10. Placement and orientation of the C-Stretch® along the SCM.

2.2 Positioning of the EMTS Sensor Coil

An additional two sensor coils connected to a system interface unit for Aurora NDI (Northern Digital Inc, Waterloo ON), an electromagnetic tracking system (EMTS) were also piloted to optimize the capture of rotational movement in the transverse plane. Two sensor coils were placed on the head and thorax. The sensor coil on the head was positioned at the midsagittal line of the head and was secured by a customizable Velcro headband. The second sensor was placed close to the sternum. The magnetic field generator was then placed behind the head to allow full ROM in the three cardinal planes to occur. Figure 11 demonstrates a schematic of all sensor positions on the body.
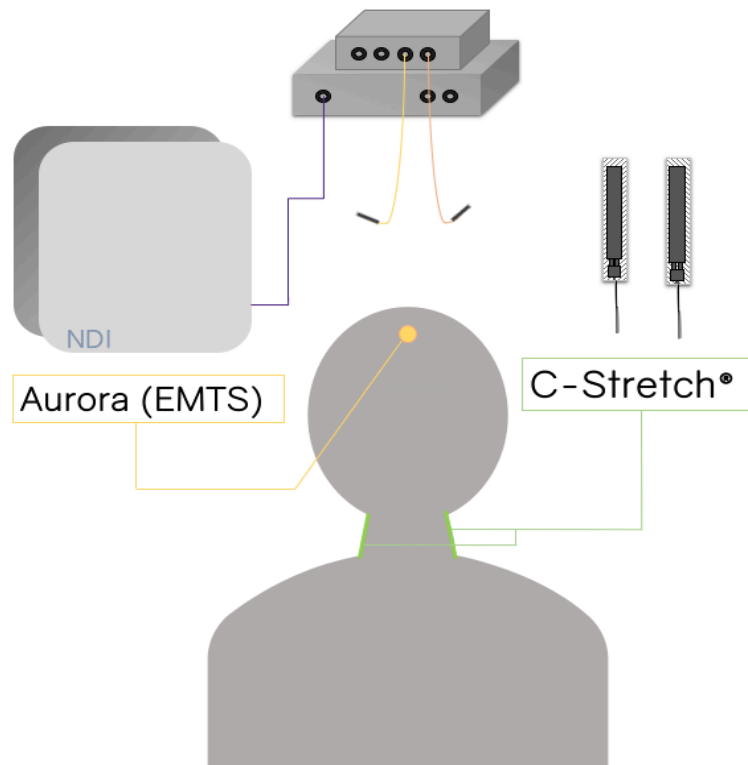
Figure 11. Sensor positions for both systems.

2.3   Adhesion of EMTS and C-Stretch

An adjustable Velcro headband with one of the two coil sensors was worn on the participants head so that the coil sensor pointed outwards (perpendicular to the forehead) at the midsagittal line. At the same time, the second coil sensor was placed on the suprasternal notch with double-sided tape. To apply the C-Stretch®, each participant's neck was palpated to identify the two SCM muscles. The skin was first cleaned with an alcohol swab, and a piece of double-sided thermoplastic elastic tape (15cm x ~3cm) was placed lengthwise on top of the SCM muscles. Once one end was secured, the C-Stretch® sensors were pre-stretched to achieve a voltage of approximately 1.0 V when the head and neck were in the neutral starting position by visually inspecting the commercial software that displayed the amount of stretch applied. The sensors were then placed on the adhesive under their pre-stretch condition. For the adhesion and sensor positioning, see Appendix A.

2.4   Protocol

A total of 30 participants (39.3% female) were included for this study. All participants were healthy without any reported mechanical or myofascial pain in the neck or head area and were able to actively move their heads in the three DOF. Mean age of all participants was 26.7 (SD 3.9, range 19 to 34) years. Excuslion criteria included any person who self-reported any neck pain, trauma, or impariments to the head and neck region six weeks prior to starting the study. This project was approved by the University of Western Ontario's Health Sciences Research Ethics Board (UWO REB ID number 112806). Every participant was asked to come in for two sessions at the Amit Chakma Engineering building on the campus of Western University (London, Ontario Canada). All participants returned for the their second session. Each session lasted up to 45 minutes. During each session, a calibration phase and a performance phase were performed. During the calibration phase, ROM was measured with both systems to provide data for whether capacitance can be linearly converted to degrees. For the performance phase, three tasks adapted from the Functional Impairment Test for the Head, Neck/Shoulder/Arm (FiT-

HaNSA) protocol were used to provide a validated measure of performance for the neck [68].

2.4.1 Calibration Phase

With both the C-Stretch® and the EMTS donned for the first part of each session, all participants were asked to perform neck movements in the three cardinal planes (flexion, extension, left and right-side flexion, and left and right axial rotations) as seen in Figure 9. In this order, all participants performed five repetitions of each movement with five-second between each movement. Participants were asked to actively move their heads to reach their maximum ROM for each head movement. This captured voltage as the software converted capacitance in picofarads to volts and degrees of motion measured from the EMTS simultaneously. Participants were asked to sit upright and as far back in the chair and were reminded to only use their heads for the movements to limit any movement from the thorax. Data collection from both the EMTS and C-Stretch® were initiated together, using a consistent time-stamp sampling at 40 Hz and 10 Hz, respectively.

2.4.2 Performance Phase

For the performance tasks, only the C-Stretch® was used as the requirement to remain within the sensing dimensions of the EMTS limited free functional movement of the head and arms. Each participant was asked to perform three separate tasks. For the first and second task, an adjustable table and standing shelf approximately 30cm above the table were used to mimic functional head performance. The table was either lowered or raised to meet the edge of the participant's fingers when the participant's arms were tucked to their sides and elbow at 90 degrees with their palms facing upward. For a detailed protocol of all tasks performed, see Appendix B.

For the first task (Bag-Lift), participants were asked to move each bean-bag from the shelf to the desk 30 cm directly below it at waist level (Figure 12). This was performed at a rate of 60 bean-bag level changes per minute, controlled by a smartphone metronome

application (Metronome, ONYX Apps). On the first beat, the participant grasped a beanbag positioned at the far left of the shelf, and on the second beat placed the beanbag on the desk below. Each participant was asked to look at the beanbag without moving their torso (rotating the head in the direction of their arms as much as possible to complete the task). Participants were asked to do this for a total of one minute and fifty seconds (110 seconds).
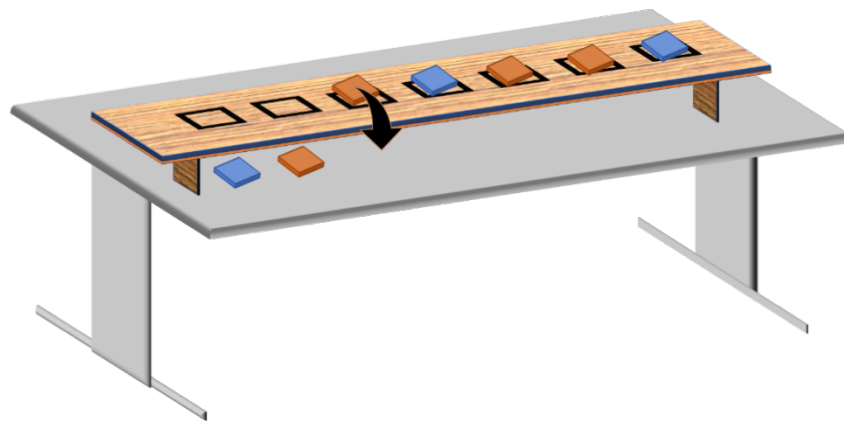
Figure 12. Desk and shelf setup with beanbags, Task 1.

In the second task (Bag-Slide), all participants were asked to slide one beanbag from the centre of the shelf to the left as far as possible using the left hand only and then slide it to the right as far as possible using their right hand while their heads followed the movement of the beanbag (Figure 13). The speed of movement was again set by a metronome at 45 beats per minute. The first beat saw the participant grab the beanbag at the center, and the second beat saw the participant slide the beanbag left, the third beat saw the participant slide the beanbag back to the middle and switching from their left hand to their right hand, the fourth beat saw the participant slide the beanbag to the right. This task was again repeated for one minute and fifty seconds (110 seconds).
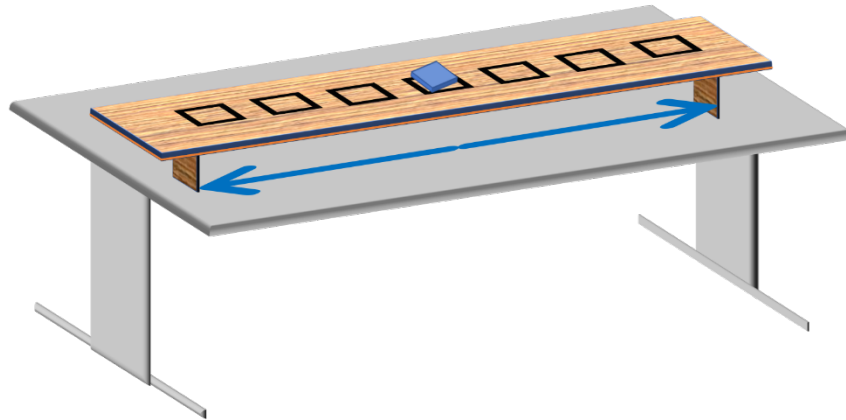
Figure 13. Desk and shelf setup for Task 2.

The last performance task (STAR) asked the participants to trace a path in the shape of a five-point star at a speed of 60 beats per minute. Using a head-mounted laser pointer, participants guided the laser from neutral (head facing forward) following an outline of the star in a counter-clockwise fashion starting with the point at 12 o'clock and with each beat from the metronome moving the laser following the path corresponding to the edges of the star (Figure 14).

Participants then returned to the lab 5 to 7 days following the first session, and the full procedure was repeated. Conditions were kept as consistent as possible between the two testing sessions, including the time of day, lighting, ambient temperature, environmental noise and other distractions. No marks were made on the neck for the reapplication of the C-Stretch® sensors, relying instead on the researcher's ability to identify the same landmarks as a means to more closely mimic real-world practice.

After completion of the performance task participants were surveyed to explore ratings of comfort and other elements of the user experience with C-Stretch using a study-specific standardized self-report questionnaire. The same researcher conducted all data capture sessions.
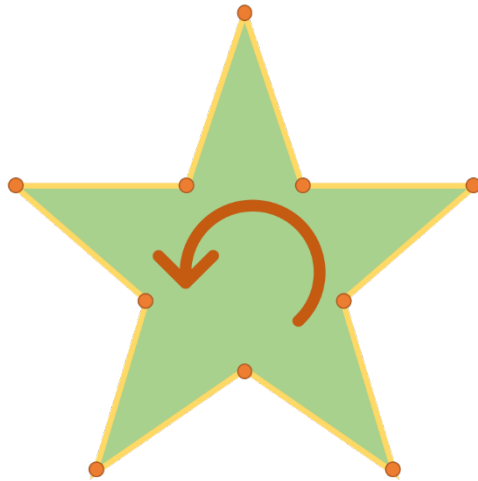
Figure 14. The five-point star used for Task 3. Arrow indicating a counterclock motion participants observed.

2.5   Data Processing

Real-time data were recorded directly to a laptop through Bluetooth communication using commercial software (BCI CST BTVO v.4.0) for the C-Stretch® sensor. For the EMTS, data were recorded via USB using commercial software (NDI Toolbox 5.001). C-Stretch® and motion data from the EMTS were sampled at 10 Hz and 40 Hz, respectively. All data were initially zeroed out to remove any negative offset, and data from the EMTS were down-sampled to 10 Hz to compare both systems for the second objective of this thesis.

2.5.1 Objective 1

For the first objective (normative data and between-session reliability) data were first normalized to a zero baseline by identifying a constant variable for each participant by taking one minus the minimum negative value and adding that value across the participant's entire dataset for that task. Visual exploration of the data revealed moderate noise in the signals. Therefore, the smoothing of C-Stretch® data was performed using a

low pass Savitzky-Golay filter. This filter uses a least-squares method to maintain the shape and height of the signal while reducing noise[68].

For the Bag-Lift, Bag-Slide, and STAR the start and end of the tasks were identified visually and by time stamps for each participant, with separate plots created for the left and the right sensors. MATLAB Signal Analyzer was used to determine the precise moments that sensor data indicated the initiation of movement. The entire movement envelope was then extracted for 108 out of the 110 seconds of the full duration of each of the tasks (to limit noise at the end of the movement) for further analysis. The `trapz` function in MATLAB was applied to the smoothed dataset to obtain the area under the curve (through an approximation of the area under the curve with trapezoids) as an indicator of the overall motion envelope, and the primary metric for this analysis.

2.5.2 Objective 2

For Objective 2 (extracting degrees of motion from C-Stretch® capacitance) data were first transformed so that the minimum value was zero by adding a constant to the entire dataset. Both systems exhibited considerable noise, so again the Savitzky-Golay filter was used to smooth the signals. Analysis of both datasets was conducted using the MATLAB signal analyzer package. As per the protocol, five-movement curves for each direction (flexion, extension, left side bend, right side bend, left rotation, right rotation) could be identified and were extracted into three separate databases (one for each pair of movement direction: sagittal, frontal, and horizontal planes). Ten motion curves of each participant for left and right rotations in the horizontal plane (5 left rotations and 5 right rotations) were visually evaluated and their correlations compared, and the one with the best agreement (overlap) and the highest correlation between the C-stretch and the EMTS data was used as the reference curve for that motion. Due to the nature of cervical movement and the nature of stretch-based sensing, the peaks and valleys of each movement curve were non-linear, approximating sinusoidal curves. Therefore, the motion segments extracted where the linear mid-ranges between the peaks and valleys of the sinusoidal curves. This accounted for a total of 40 linear segments per session (10 segments for left rotation x 2 sensors and 10 segments for right rotation x 2 sensors).

2.5.3 Objective 3

For Objective 3 (rating of comfort and user experience with C-Stretch®) each participant completed a ten-question survey after their second session. The survey included items such as "I found the that C-Stretch® interfered with the tasks I was asked to perform", I would be willing to wear the C-Stretch® during an exercise session" and "I felt like the C-Stretch® was secured on my neck". These types of questions were presented in the form of an ordinal scale with four severity-based options (0 = 'Not at all', 1 = 'A little', 2 = 'A lot', and 3 = 'Extremely') to choose from. The scale used an even number of items to avoid neutral responses from the participants. The responses were explored descriptively using median, mode, and range. See Appendix C for survey used.

2.6 Statistical Analysis

IBM Statistical Package for the Social Sciences (SPSS Version 25, Chicago IL) was used to conduct inferential statistical analyses.

2.6.1 Objective 1

Normative data were explored using descriptive statistics (mean, range, standard deviation, 95% confidence intervals). Two of the 30 participant datasets were removed from the analysis for this objective. These outliers deviated markedly from the sample mean of the area under the curve. On furthere analysis, the outliers were found to be greater than three standard deviations beyond the sample mean. Outliers in reliability studies usually mislead to an agreement when an agreement does not exist. According to Koo et al., (2016) there are four guiding questions to select the correct form of ICC for reliability [69]. They are the following: 1) is the rater the same across all subjects, 2) is the rater selected at random from a larger pool or is the rater selected specifically, 3) is the outcome dependent on a single rater or an average of multiple raters, and finally 4) is the model of interest looking for consistency among the raters or whether the raters measurements agree over time. The work in this objective assessed a single specific 'rater' (C-Stretch®) to rate the performance tasks administered at two different time points. The total motion envelope (area under the curve) at each of two sessions

separated by 5-7 days was the primary metric. Each of the three performance tasks (Bag-Lift, Bag-Slide, and Star) was analyzed using the intra-class correlation estimates and their 95% confidence intervals based on single rating (k = 1), absolute-agreement, two-way mixed-effects model type 2,1 ICC ($ICC_{2,1}$). The Intra-class correlations were interpreted according to Koo (2016) as poor (0 – 0.5), moderate (0.5 – 0.75), good (0.75 – 0.90) and excellent to perfect (0.90 – 1) [69]. Bland Altman plots were used to determine agreement between session one and session two for the areas under the curve. These analyses were conducted separately based on the average of both sensors (right and left) from each task.

2.6.2 Objective 2

For this objective of the study intended to explore whether degrees of motion could be extracted from capacitance, the researchers plotted data from both sensors systems to identify the linear parts of each curve and chose to extract only the segments of each curve that were linear (mid-range motions). The linear data were plotted as a scatter of capacitance (in V) from both the left and right C-Stretch® sensors to degrees of motion measured from the mobile (forehead) EMTS sensor. Next, a linear regression equation was developed using degrees of motion as the dependent variable and capacitance as the predictor (independent variable) plus a constant for the trace with the best overlap between the two sensors (a 'best case' approach). As a result of this best-case approach, model fit (coefficient of determination, r^2) was very strong for the best trace, and a regression equation was derived for left and right rotation for each sensor on the side of the neck to predict the line of the EMTS using only the C-Stretch data. These equations were considered the 'reference standard' equations and then applied to the data from all other traces for that motion segment corresponding to the rotation and the side of the sensor. In other words, the reference standard equations were used to predict the angle of motion from C-Stretch® data across all traces. The difference between the reference standard predicted degrees and the observed EMTS degrees was considered the residual, calculated for every data point (10 points per second). As a result, 40 (10 midrange segments for left rotation x 2 sensors and 10 midrange segments for right

rotation x 2 sensors, per session) tables of residuals were created for each session, and a root mean square error (RMSE) of the entire trace was calculated to assess the agreement/consistency between the prediction and observation. RMSE values from both sensors for both left and right rotation were then averaged to obtain a final RMSE for each session. According to Chai and Draxler,[70] RMSE is a statistical measure that measures a model performance by keeping units consistent. In this case, the closer the error is to zero, the stronger the observed and estimated motion values were in agreement. In other words, the RMSE score indicated how well the predicted angles of degrees from C-Stretch fit the observed degrees of motion from EMTS. To evaluate the stability of the magnitude of error across sessions (RMSE Session one and Session two), an $ICC_{2,1}$ was calculated using the mean RMSE from each participant extracted from the two testing sessions.

2.6.3 Objective 3

A frequency table based on participant responses to the paper survey at the end of the second session was used to explore the comfort and the user's experience in a descriptive fashion.

2.7   Sample Size Estimation

To evaluate reliability between the stretch-sensitive sensors (the agreement) at two different time points (test–retest) we need an optimal sample size. Using Walter and Eliasziw (1998) study on sample size and optimal designs for reliability studies, that a minimum sample size of 27 is sufficient to test the hypothesis of an ICC reliability coefficient of 0.60 that is signigicantly greater than 0.20, when alpha error rate and power are fixed at 0.05 and 0.80, respectively. Therefore, a minimum sample size of 27 was used for the study. To account for a 10% attrition in the sample size, the final sample size was increased to 30 [71].

Chapter 3

Results

In this section, the findings of the three objectives of this thesis are presented. A total of 30 participants provided informed written consent before participating in the study. The first objective outlines the normative data of all three tasks and the between-session reliability for the average motion (AUC) recorded by both sensors for each session. For the second objective, the coefficient of determination (r^2) and root mean square error (RMSE) are presented to determine the agreement between degrees predicted using raw capacitance data and degrees observed from EMTS for cervical rotation using linear regression. An intraclass correlation ($ICC_{2,1}$) is presented to determine the agreement between session one and session two for the residuals observed. Finally, the third subsection in this chapter will describe the user's experience with regards to comfort and tolerance of the C-Stretch®.

3.1 Objective 1

Normative data for each performance task for the movement data are summarized descriptively using the unitless area under the curve for each the side of the neck and each session in Table 2.

Table 2.Descriptive summary (Means, standard deviation, 95% confidence intervals) of neck movements from 28 participants for each performance task, by sensor side and testing session.

Tasks	Right Sensor		Left Sensor	
	Session One	Session Two	Session One	Session Two
Bag-Lift	18.1 (11.7, 5.3 to 41.5)	15.5 (9.5, 3.6 to 34.6)	21.4 (13.4, 5.4 to 48.2)	14.7 (8.5, 2.3 to 31.7)
Bag-Slide	33.6 (20.1, 6.6 to 73.8)	28.1 (14.9, 1.7 to 57.9)	29.6, (16.5, 3.5 to 62.6)	23.7 (11.5, 0.70 to 46.7)
Star	40.3 (23.5, 6.7 to 87.3)	31.5 (14.1, 3.3 to 59.7)	39.1 (18.8, 1.50 to 76.7)	33.7 (14.5, 4.7 to 62.7)

The ICC for the average of both sensors between sessions for the first performance task, Bag-Lift, was moderate ($ICC_{2,1}$ = 0.57, 95%CI = 0.19 to 0.79), whereas the second and third performance tasks, Bag-Slide and Star, showed poor agreement ($ICC_{2,1}$ = 0.37, 95%CI = 0.05 to 0.66, and $ICC_{2,1}$ = 0.39, 95%CI =0.03 to 0.64, respectively). Figures 15 through 17 illustrate the average movement data for the right sensors with 95% confidence intervals as a result of neck rotation for each task performed.
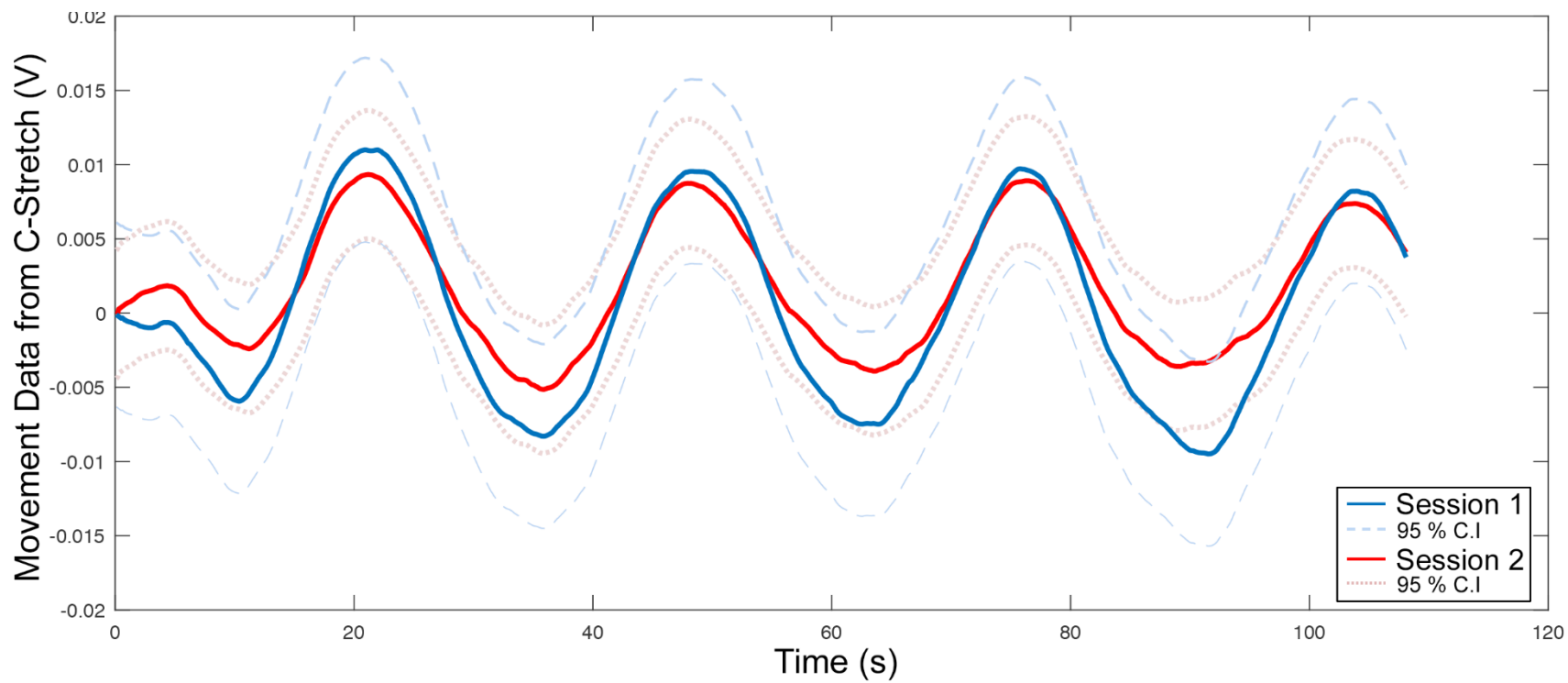
Figure 15. Average movement data of all participants (n=28) for the right sensor from both sessions with 95% confidence intervals for Bag-Lift (Task 1).
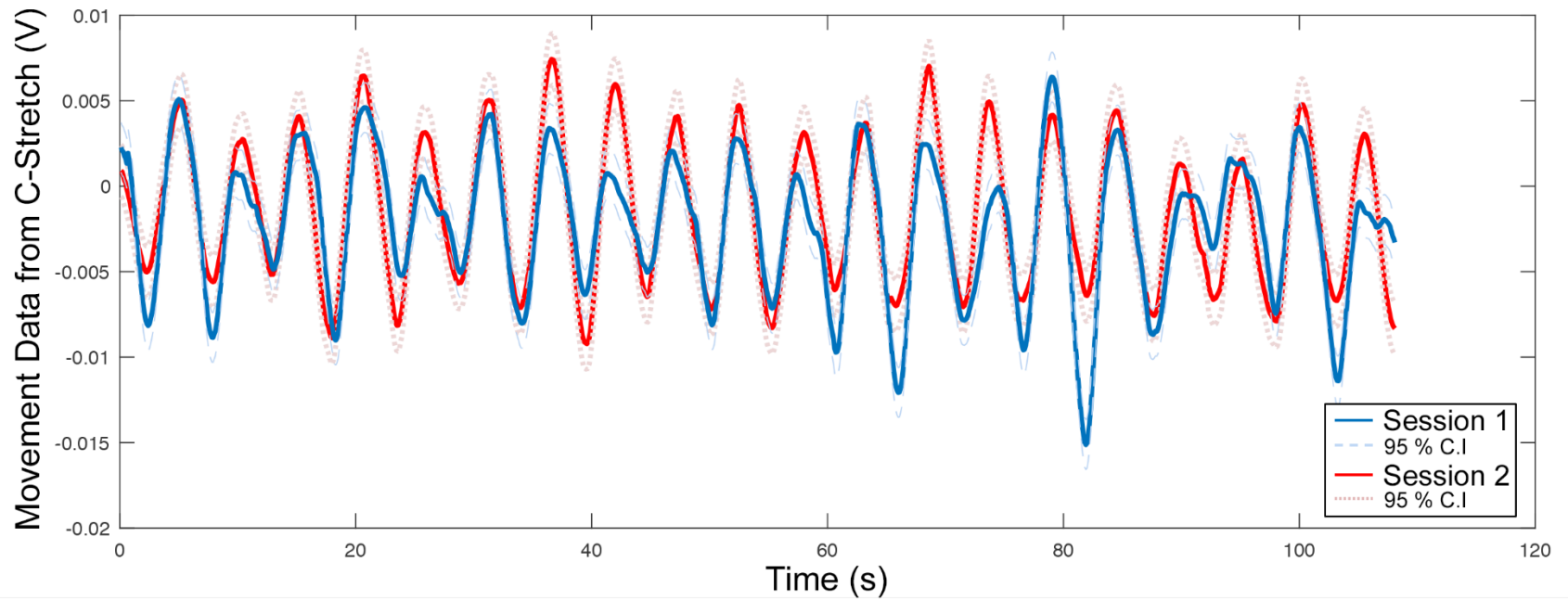
Figure 16. Average movement data of all participants (n=28) for the right sensor from both sessions with 95% confidence intervals for Bag‑Slide (Task 2).
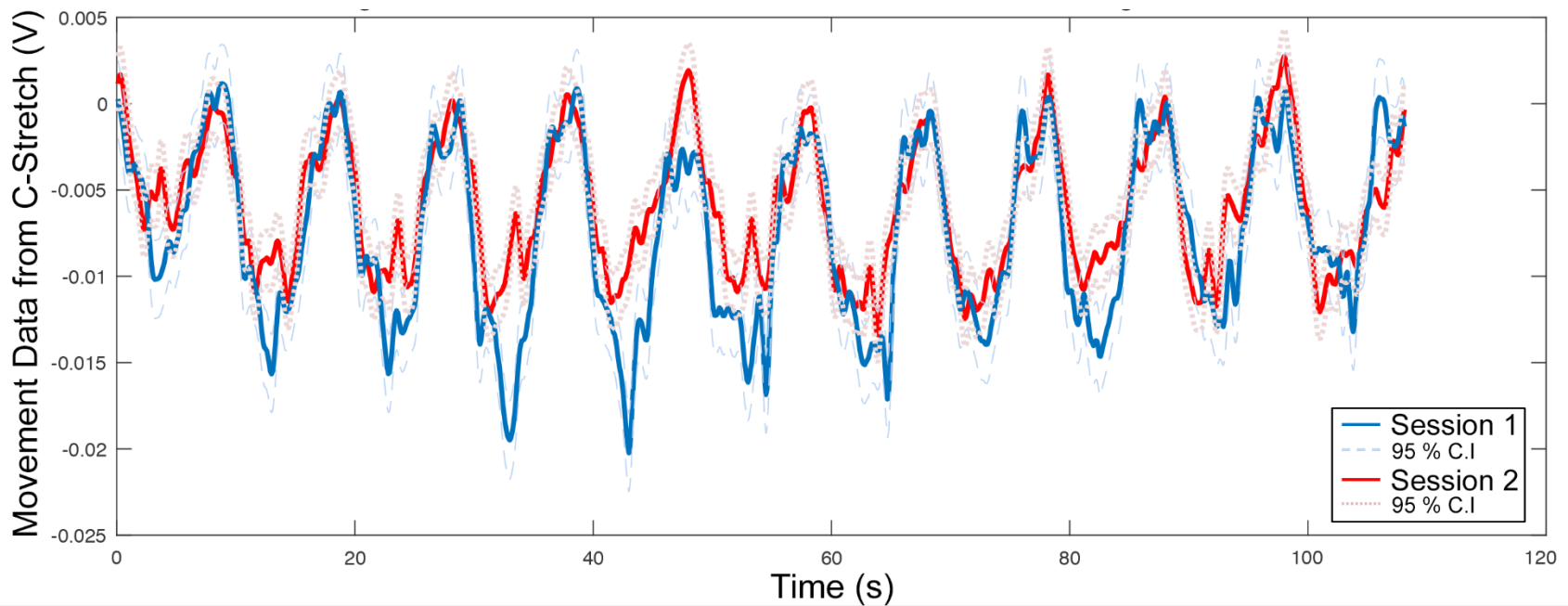
Figure 17. Average movement data of all participants (n=28) for the right sensor from both sessions with 95% confidence intervals for the Star (Task 3).

Bland Altman plots for each task performed indicate agreement between session one and session two. The mean difference and the values for the 95% confidence intervals are reported in figures 18-20.
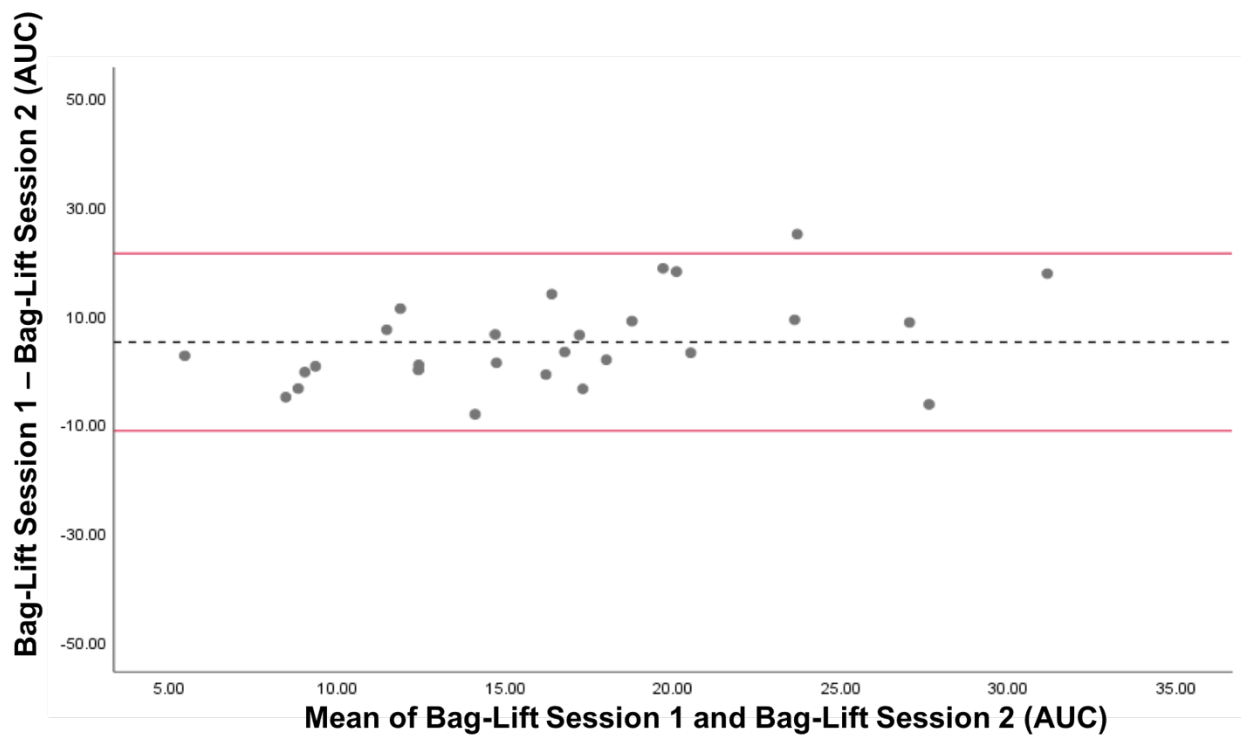
Figure 18. Bland Altman plot of agreement between session 1 and session 2 for the Bag-Lift task. Dashed horizontal line represents the mean difference (5.03) and the red lines represent the lower and upper limits of agreement (-11.25 to 21.33).
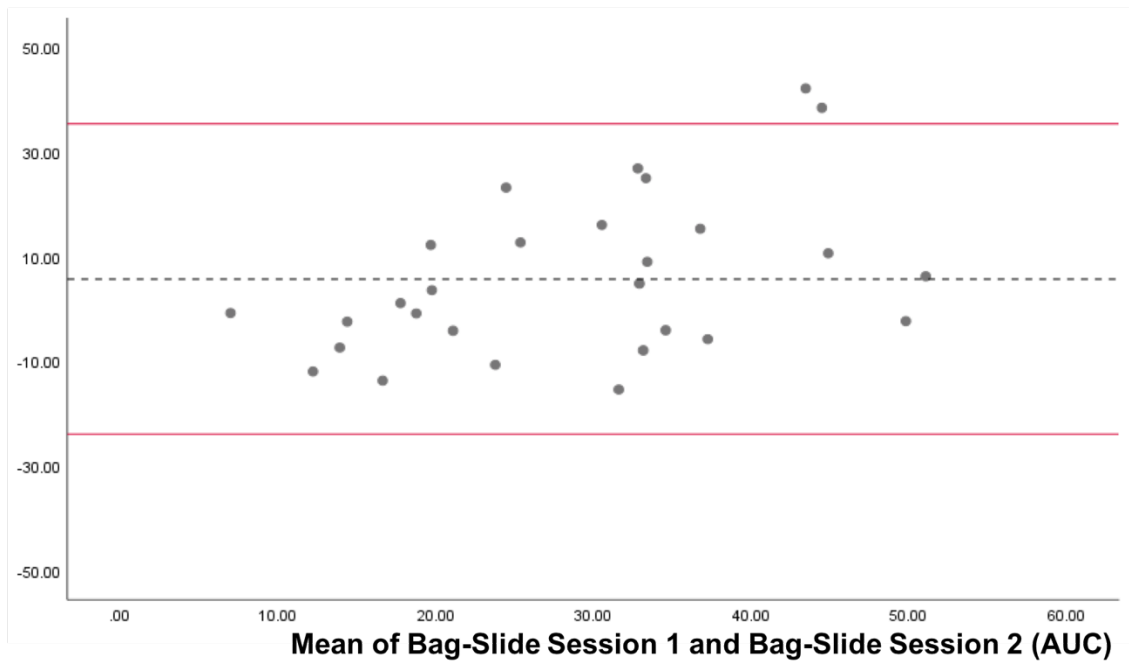
Figure 19. Bland Altman plot of agreement between session 1 and session 2 for the Bag-Slide task. Dashed horizontal line represents the mean difference (5.68) and the red lines represent the lower and upper limits of agreement (-23.95 to 35.31).
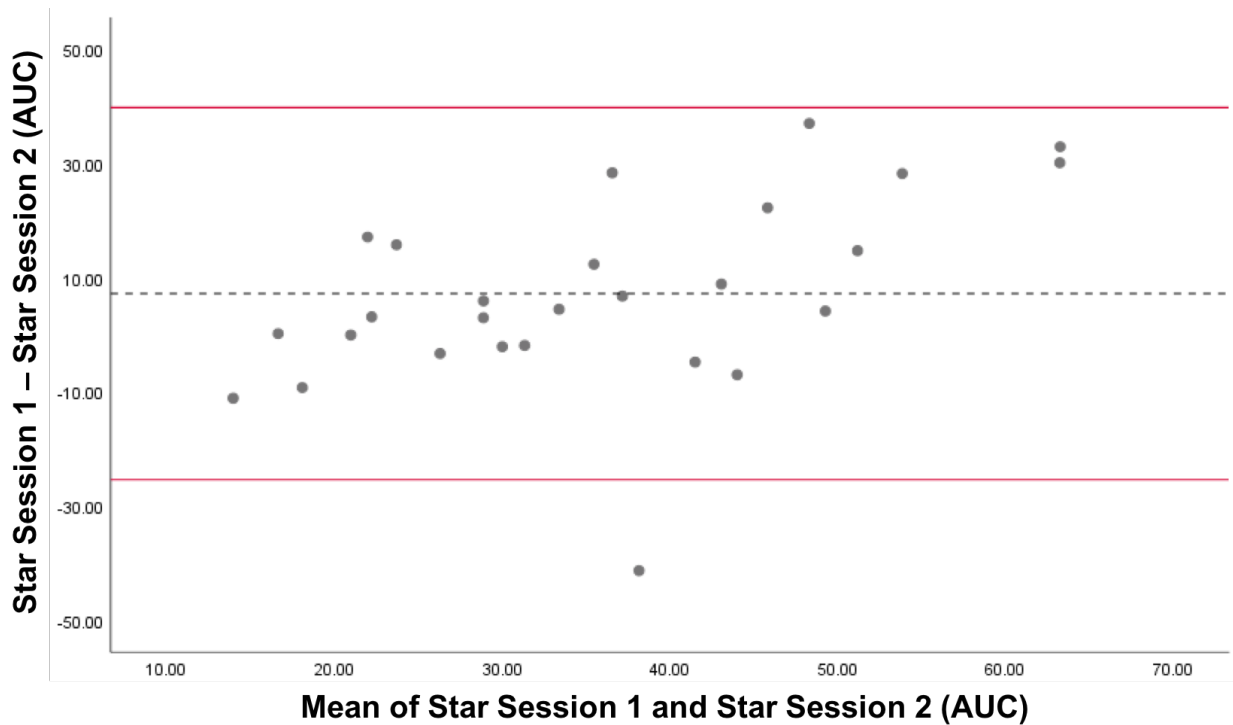
Figure 20. Bland Altman plot of agreement between session 1 and session 2 for the Star task. The dashed horizontal line represents the mean difference (7.21), and the red lines represent the lower and upper limits of agreement (-15.95 to 39.78).

3.2 Objective 2

Results of the Pearson correlation indicated there was a significant correlation for areas where overlap did exist between degrees of motion from the EMTS and capacitance change from the C-Stretch® ($r= 0.90 – 1.00$, $p < 0.01$). Figure 21 is a representative figure for the line of fit for C-Stretch® on the left side of the neck against the EMTS sensor for rotation after a regression analysis for the mid-range segment of motion. The average RMSE score obtained from the first session and the second session were 5.06° (SD 2.52°), and 5.34° (SD 2.82°), respectively. Each session provided an average RMSE score from the two C-Stretch® sensors for the five left rotations and five right rotations. Table 3 lists the mean error and standard deviations of errors from each session. Figure 22 is a representative display of rotational motions observed as a result of angular displacement from the EMTS and capacitance from C-Stretch® from a representative participant.
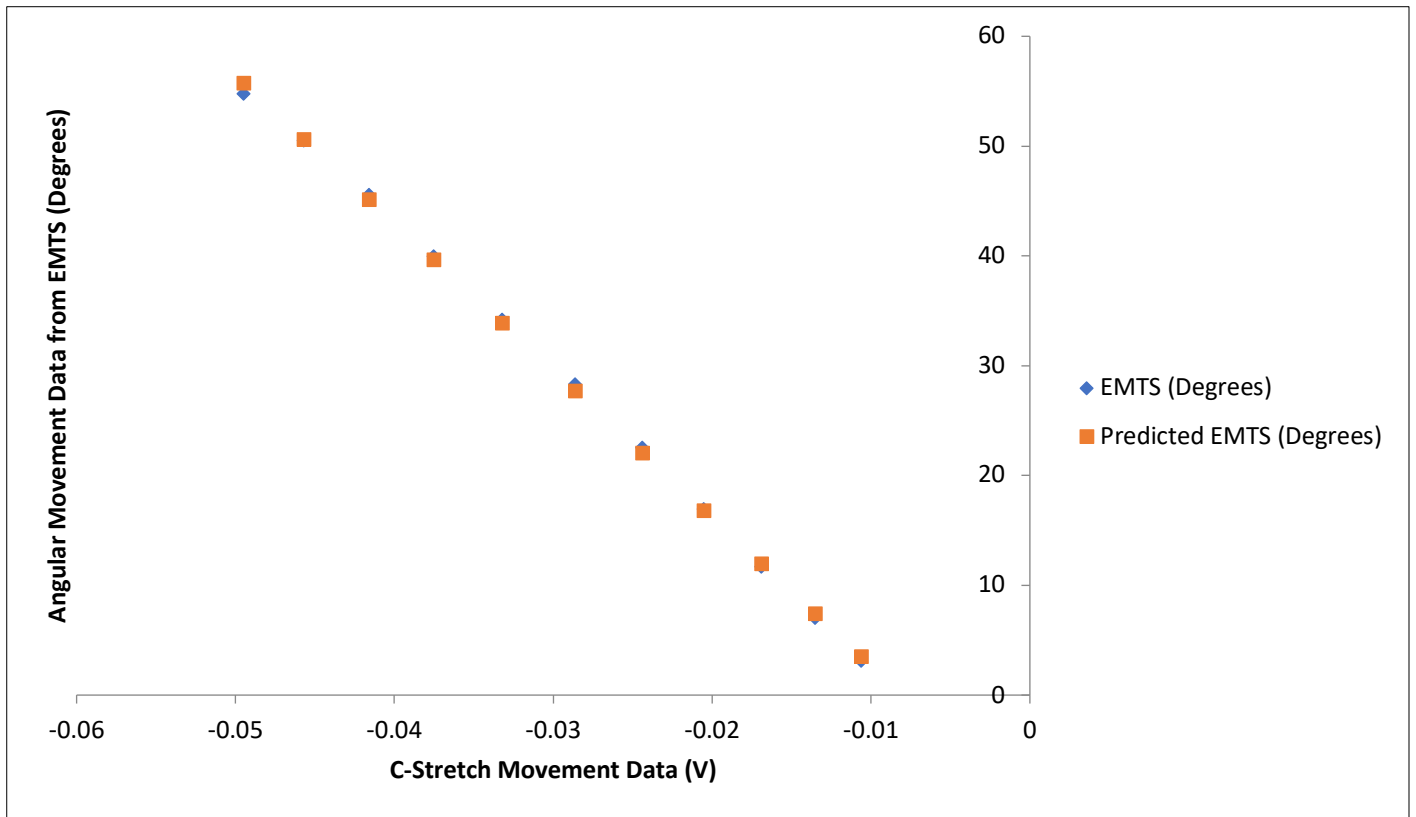
Figure 21. Line of fit plot from the left side of the neck for predicted movement from capacitance (independent) to degrees (dependent) using EMTS after performing linear regression.

Table 3. Average RMSE from both sessions for left and right rotations from all participants.

RMSE	Session One	Session Two
Average	5.07°	5.34°
SD	2.52°	2.82°
95% C.I	0.12° to 10.01°	-0.20° to 10.88°
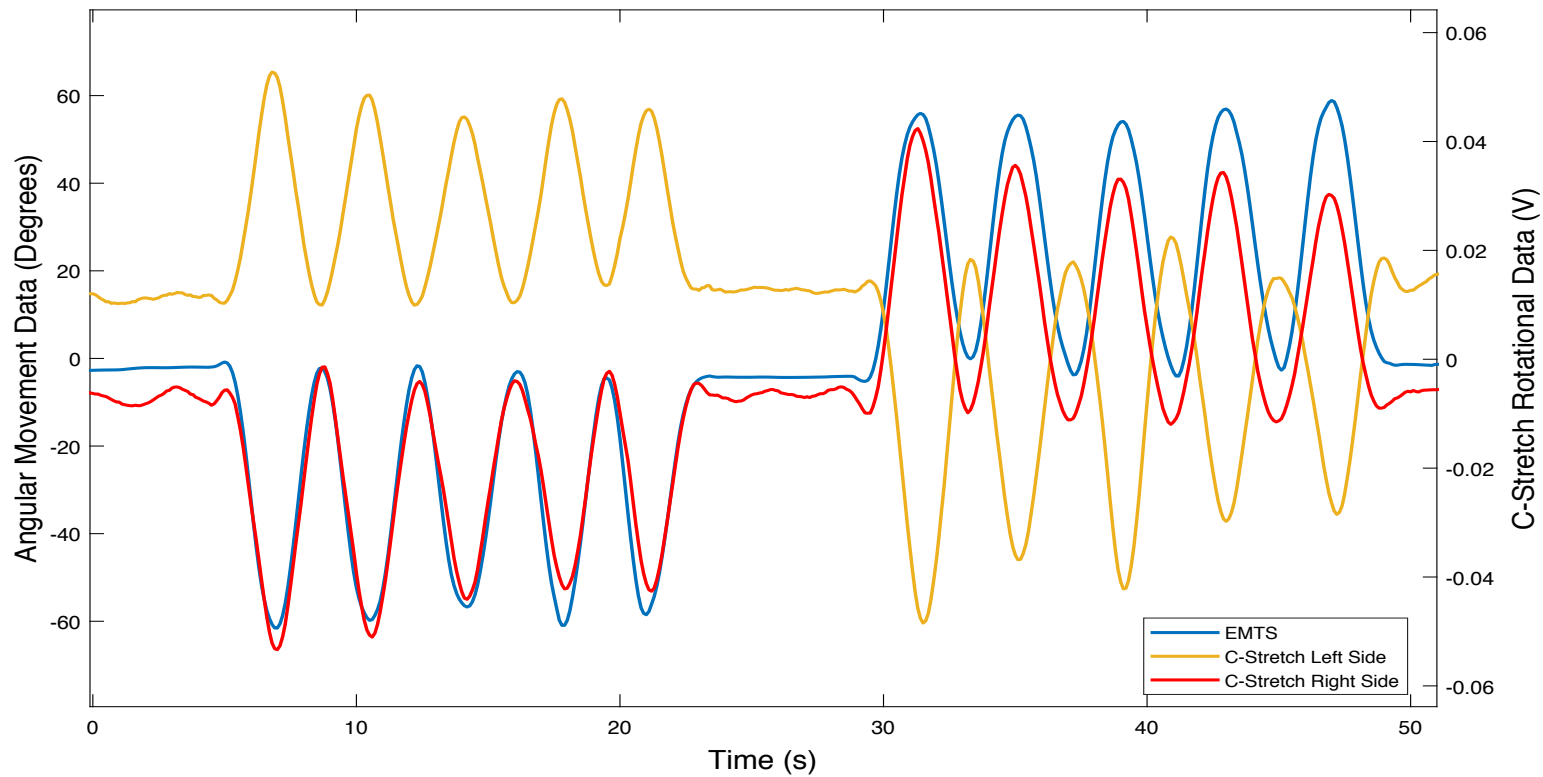
Figure 22. Representative rotational movement data from one participant for both C-Stretch® sensors and the EMTS sensor. The valleys are maximum ROM for left turns with 0 degrees being neutral (head facing forward) and peaks representative of maximum ROM for right turns.

3.3 Objective 3

All 30 participants responded to the post-session survey. Participants response frequencies, mode, median and range are reported in Table 4.

Table 4. Response frequency of users experience and comfort using C-Stretch®.
(0 = 'Not at all', 1 = 'A little', 2 = 'A lot' and 3 = 'Extremely

Questions	Frequency				Median
	0	1	2	3	
I found the adhesive used to keep C-Stretch on irritating	23	6	1	0	0
I found C-Stretch interfered with the tasks I was performing	18	12	0	0	0
I would be willing to wear the C-Stretch during an exercise session	0	6	12	12	2
I was aware of C-Stretch the entire time I was wearing it	1	15	12	2	1
I would wear C-Stretch during a normal daily routine	4	17	7	2	1
I found it easy to perform the tasks while wearing C-Stretch	0	5	9	16	3
I felt discomfort when C-Stretch was removed	16	14	0	0	0
I found C-Stretch sweaty	28	2	0	0	0
I would be willing to wear C-Stretch for an entire day	4	15	9	2	1
I felt the C-stretch secured on my neck	2	2	14	12	2

All 30 participants responded to all questions on the post-session survey. The overall response indicated participants tolerated the C-Stretch® well and found it to be secured on their necks well, but only a few would be willing to wear such a device for longer than an exercise session, even though the majority surveyed did not find the C-Stretch® to be irritating when performing the functional tasks.

Chapter 4

In this section, the findings of the three objectives of this thesis are discussed. A conclusion is also presented to summarize the results of this thesis. Finally, a future direction is laidout reflecting on the current results.

Discussion

Traditionally, a protractor with adjustable arms with one-degree increments or other analog methods have been used to quantify the cervical range of motion. This thesis aimed to investigate the feasibility and preliminary measurement properties of a novel stretch-sensitive wearable adhesive for quantifying neck motion in a healthy population. The first analysis indicated that test-retest reliability for each of the performance tasks was poor to moderate. The results of the second analysis showed that C-Stretch® and the EMTS are highly correlated in the linear mid-range portions of the motion curve with acceptable errors between the residuals of the predicted variable (Degrees from C-Stretch) in comparison to the observed variable (Degrees from EMTS). Further analysis between sessions for cervical rotational movements indicated that residual error (RMSE) between sessions are in agreement with one another, suggesting further stability of the measurement from session one to session two. Lastly, the results from the third objective indicated that participants tolerated the C-Stretch® without discomfort and with some participants willing to wear the stretch-sensitive wearable sensor during regular daily routines or for longer durations with the majority suggesting they would wear C-Stretch® during an exercise session to monitor their neck motions.

The first objective of this thesis set out to identify whether the stretch sensitive adhesive (C-Stretch®) provides reliable measurements between sessions and whether the total motion envelope during functional movement tasks between the sessions agree. From the intraclass correlation estimates and their 95% confidence intervals, it is evident the first performance task (Bag-Lift) was the only estimate to provide moderate reliability. Where 95% of the data if drawn from many random samples would lie between reliability coefficients of 0.2 and 0.8 with a point estimate of 0.57. This suggests that this movement, in particular, might be useful for identifying change over time, though even here considerable change would be required to overcome random noise. Whereas the second and third tasks (Bag-Slide and Star) demonstrated reliability estimates that were poor with confidence intervals between 0.0 to 0.6. Examining Figures 15 through 17, it is apparent that the average movement data captured from C-Stretch® from the right side of the neck between session one and session two for each performance task were in sync, both session data had the same displacement with respect to peaks and valleys at certain intervals of movement during session one and session two. It is also apparent that there was movement overlap between the mid-ranges before the peaks and valleys of the sinusoidal curves as well as at the end-ranges of the sinusoidal curves. Graphically, this suggests that between session (test–retest) the movement data obtained from C-Stretch® are in agreement although the movement between the sessions demonstrates wide 95% confidence intervals. This is further complemented by the Bland Altman plots (figures 18-20) illustrating that the majority of data points are within the limits of agreement with a small bias for the area under the curve with 5.03, 5.68, and 7.21 for each task, respectively. The ICC was calculated for the average of both sensors together from session one to session two. The rationale for this was based on an exploratory analysis comparing each sensor on the side of the neck to itself across testing sessions. The results of that exploratory analysis, although not presented, demonstrated poor reliability across all performance tasks for each sensor from session one to session two. Therefore, having two sensors averaged per session rather than one sensor per session shows an increase in reliability. Two likely explanations for the poor agreement can be identified; one, although conditions were kept as consistent as possible from session one to session

two, it is was difficult to hold a pre-stretch at the estimated 1 volt after application as the stretch sensitive fabric tended to compress to its original state naturally. This was avoided as much as possible by securing one end using another piece of tape perpendicular to the SCM to hold the tape at the estimated 1 volt from session one to session two and then taping the lower part of the tape to firmly secure C-Stretch®. The second rationale is the potential for variation between sessions as the researcher visually estimated the position of adhesion for both sessions without visually marking the neck to aid in locating previous adhesion sites of the stretch sensitive sensor on the neck. The eye estimation of applying the C-Stretch® was performed to mimic real-world clinical assessment. A possible solution to this is likely in the form of a garment or textile with the sensors embedded within to be worn on the neck, as seen with pressure sensor socks and leggings.

Furthermore, due to the sensitivity of the tape, movements that required quick neck movements as performed during task two and three (Bag-Slide and Star) could have added undesirable noise to the data. The first task, Bag-Lift saw participants on average spend 2 seconds per bag lift, whereas the Bag-Slide saw participants quickly moving their necks back and forth from the center in the same amount of time.

Similarly, this was the case during the Star task. It is worthwhile to mention that all objectives in this study did not control for anthropometrical measures. Although not reported, an anecdotal difference was observed across participants for neck girth and neck length during application of the sensor systems. Variation in neck size with respect to length and circumference as well as underlying tissue are factors that may have potentially contributed to movement artefacts, and as a result, lower intersession agreement. Although the ICCs in this thesis are reported to be poor to moderate, it is worth noting that the ICCs performed in this study were based on the total motion envelope (AUC) rather than the range of motion in degrees. Therefore, when reviewing the current literature, we cannot make a direct inference between the AUC with respect to the range of motion since both are quantifying different metrics.

The second objective of this thesis was a proof of concept to determine the feasibility of extracting degrees from raw capacitance data and compare the observed motion data

from the EMTS as a reference (gold standard) to the estimated motion data predicted from the C-Stretch®. The Pearson's correlations indicated near-perfect agreement between the two modes of evaluation (r >0.90) suggesting that a linear regression model could be used on the chosen mid-range segments to extract degrees of motion from capacitance. Figure 16 is a visual representation of the linear relationship between the observed and predicted degrees from the EMTS. The main findings in this objective are based on the errors estimated between the two systems. The average RMSE for the first session in comparison to the second session saw an agreement with a reliability coefficient of ($ICC_{2,1}$ = 0.65) between the two sessions. This suggests that the errors are consistent from one session to the next for the left and right rotations. Furthermore, the average RMSE score obtained from the first session and the second session were 5.04° (SD 2.56°), and 5.34° (SD 2.82°), respectively. RMSE, in this context, is related to the degree of agreement or error that exists between the two systems. An RMSE value of 0 is an indication of a perfect agreement between the two systems. In this proof of concept, the error between the C-Stretch® and the EMTS between sessions can be considered small, with a mean difference of only 0.30° apart. The RMSE values obtained in this proof of concept are similar to other findings in the literature that use stretch sensitive fabrics for motion and angle estimate measurements (range 1.20° – 9.50°) for the wrist, knee, back and neck [72–75]. Based on a systematic review of the literature on reliability of three-dimensional gait measurements by McGinley et al., (2009) errors less than 2° are widely accepted, whereas errors between 2° and 5° are acceptable with careful interpretation considering context and the proposed use of the application. This is also echoed in studies that use inertial measurement units to measure cervical spine ROM. Theobald et al.,(2012) obtained four RMSE values when comparing different sensor positions for axial rotations. All values were above the error value observed in this thesis, but still comparable (range 7.50° – 8.91°) to this proof of concept for axial rotational movement [76]. It is inconclusive whether there is an acceptable level or a threshold for what is an acceptable error of the measuring application in comparison to a gold-standard when it comes to cervical ROM using stretch-sensitive fabrics. Finally, comparing a similar study by Maselli et al., (2018) that assessed a commercially available

wearable sensor Electrolycra (Mindsets Ltd, United Kingdom) against a reference system, Vicon Bonita (Vicon Motion System Ltd, United Kingdom) for measurement of single planes of movement from the neck. The authors reported an average RMSE value of 10.16° for axial rotation for five trials obtained from five subjects, which is twice the error compared to this study. The difference in findings between that study and mine could potentially be the methodology adopted to obtain neck measurements. For one, the pre-stretch obtained in this proof of concept was approximated to 1 V, which is about 25% strain. Whereas Maselli et al. pre-stretched their wearable sensor to 200%. Secondly, the position of the sensors differs for axial rotation, Maselli et al., positioned the sensors from the angle of the mandible towards the scapulae insertion of the trapezius muscle, whereas in this thesis, the positioning of the sensors was aligned along the mid-ranges of the SCM muscles. Although the RMSE achieved in this study may be clinically acceptable with interpretation. It is necessary to take precaution when assessing commercially available wearable sensors since many come packaged with their software and processing algorithms that may have not been validated and are not available to the user. Furthermore, the method employed in this thesis for fitting the movement obtained from C-Stretch® heavily relied on a linear fitting of the mid-ranges without accounting for the curvilinear nature at the end-ranges of movement instead of peak measures as seen in Theobald's 2012 study. This may have allowed for a more thorough comparison between the wearable sensor, C-Stretch®, and the EMTS. Therefore, a more robust fitting could have been used to account for the sinusoidal curve observed. Concerning group means for errors obtained between the two sessions in this study, a moderate agreement was observed. This suggests that mean session one errors were consistent with mean session two errors. Regarding limitations for this objective, it is necessary to point out that both systems were not synchronized for a start and stop. The EMTS was placed on a five-second delay to ensure the researcher has enough time to press start and initiate data collection from the C-Stretch® software at the same time the EMTS system reached zero and started collecting data. This was corrected for in post-processing based on the visual exploration of the data for the initiation of movement. While movement initiation was

easily identifiable on the traces, use of something like a time marker across the data collection systems may have improved synchronization.

In recent years, wearable sensors have garnered much attention for their ability to monitor, record and detect changes without being invasive or interfering with the user's daily activities. In order for wearable sensors reach clinical use, they first need to be perceived positively by those who use it. Therefore, the third objective of this study was to descriptively asses user's comfort and experience concerning the wearable stretch sensor, C-Stretch®. The overall response indicated participants tolerated the C-Stretch® well and found it to be secured on their necks, with only a few people willing to wear the wearable sensors for a period longer than an exercise session, even though the majority surveyed did not find the C-Stretch® to be irritating when performing the functional tasks. A majority of those surveyed also reported they would be willing to wear the stretch sensor during an exercise session with some indicating they would be ready to wear the C-Stretch® for an entire day. Those who did not find the wearable sensor to be irritating also reported that they felt like the sensors did not restrict their ability to move their necks. The overall perception of the thirty participants was positive. This is reiterated by Papi et al.,[77] who looked at perceptions of a wearable sensor to monitor the knee with those living with osteoarthritis. After conducting focus groups on 21 patients (age 45-65), they determined that wearable technology is acceptable by this patient group and the group recognized their benefits as tools to monitor performance, help with adherence, and a tool to inform and improve outcomes with the help of their clinicians.

In comparison, my study relied on the perceptions of a younger and asymptomatic group of people (19-34) who may already have positive attitudes on wearable technology. Therefore, I am unable to comment on the degree to which older participants or those with neck pain would tolerate the sensor. The results of the survey suggest that there is potential for users to adopt wearable stretch sensitive sensors as part of their daily routines.

Chapter 5

Conclusion

The neck is a complex structure with complex motions with three degrees of freedom and plays a crucial role in our day-to-day lives, keeping the head stabilized concerning gravity and responding to external stimuli. Evaluation of impaired neck motion is however difficult, potentially being one explanation for suboptimal evidence of neck pain treatment effectiveness. Therefore, the goals of this thesis were threefold. One, to assess the reliability of the commercially available stretch sensitive sensor, for functional cervical motion in the transverse plane. Two, to determine whether axial rotation, a traditionally difficult movement to quantify can be measured from raw-capacitance data and converted to degrees of motion using an electromagnetic tracking system as a reference. Finally, to explore the user's experience with C-Stretch® with regards to usability, comfort, and adhesion. Overall, the C-Stretch® was moderately reliable across testing sessions separated by 5 to 7 days when performing the Bag-Lift task but was poor during the second and third tasks (Bag-Slide and Star). The C-Stretch® along the SCM muscles of the neck provided good estimates for degrees of motion from the linear portions for axial rotations (left and right rotations along the transverse plane). The results from the second objective for between-session agreement indicated that mean error approximation were in agreement between the testing sessions. Overall, the participants received C-Stretch® positively. Many indicated that they did not find the C-Stretch® to interfere with the functional tasks, to be sweaty, or uncomfortable. Some participants even reported that they would be willing to wear C-Stretch® for an entire day. Moreover, it is precieved that the use of stretch sensitive fabrics for monitoring CROM is feasible as they may provide an alternative approach to CROM measurement. In order for this to be realized, further development and future studies to investigate the limitations proposed.

5.1   Future Directions

To better evaluate wearable sensors for human joint motion tracking, future studies are encouraged to address the positioning and the placement of the sensors regarding each person. In   this   study,   the   placement   of   the   sensors   were   based   on   the

sternocleidomastoid muscle. This was identified by palpating the boundaries of the SCM and applying the C-Stretch® along the length of the muscle with the wire end closer to the clavicle. In this context, the underlying tissue needs consideration as it may potentially be a source of movement artefcats (source of error) when estimating joint angles since motion-captured from these sensors is attributed to either elongation or compression of the sensor elements on top of the skin. Therefore, capturing anthropometric variables such as neck girth (circumference of the neck) and neck length (along the SCM) might provide useful information for understanding measurement properties of the stretch sensitive sensor on a per user basis. Future studies that involve stretch-sensitive sensors for estimating neck ROM will need a robust method for fitting the curvilinear nature at the end ranges to allow for direct comparison for the entire motion envelope. This study focused on a linear relationship between the mid-range of motion from the reference system to the wearable sensor. As a result, the entire ROM, in particular the end ranges (maximum CROM) was not accounted for.

Furthermore, when working with any measurement device within in vivo work, systematic error (bias) may lead to over-or under-estimation of the angles based on improper calibration or improper sensor positioning. Therefore, it is best to keep the environment fairly consistent across tests sessions as well as keeping the person in charge of application and measurement consistent. Keeping the person who performs the protocol consistent allows for increased reliability across the testing sessions. A possible direction for this tool in the future would be to embed the stretch sensitive sensors into a customizable garment that fits nicely and wraps around the neck to reduce any inconsistency with application and measurement of the wearable sensors to provide for a more reliable measure across sessions.

5.2 Contributions

The work in this thesis has contributed to the literature on the use of stretch senstitive sensor and their ability to sense and capture body movements. The focus of this study was on the reliability and feasibility of C-Stretch sensors to monitor cervical range of motion. A secondary focus was on criterion validity of the sensor with respect to a gold standard,

an electromagnetic tracking system. It is to the best of our knowledge that this is the first use of commercially available stretch-sensitive sensors were used to capture perofmrance tasks in a lab setting to investiage whether they are a feasible alternative for monitoring CROM movements.

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Appendix A

Protocol for adhesion sensor positioning:

1. Ask the participant to sit back fully in a chair in an upright manner facing forward, so as to completely allow their back to rest freely against the back of the chair.
2. Ask the participant to rotate the neck to the left/right as possible while sitting in the upright manner.
3. Palpate for the side of the neck to feel for the sternocleidomastoid muscle that runs from the clavicle to behind the ear (mastoid process). Once identified;
   i. Using eye-estimation, trace to the sternum and feel for the clavicle head of the SCM. Once identified;
   ii. Place (#2477P Medical Speciality Tape, 3M™, London ON) double sided adhesive tape strips; one from the clavicle insertion towards the occiput, along the mid-range of the SCM.
   iii. Repeat steps i and ii for the opposite SCM.
4. Place the stretch-sensitive sensors on top of double-sided adhesive.
   i. Use of kinesiology tape can be used to keep the sensors in place as needed.

Appendix B

<u>Performance Metrics:</u>
All participants will complete the following performance adapted protocol of the Functional Impairment Test-Head, and Neck/Shoulder/Arm (FIT-HaNSA) protocol (McMaster University, Hamilton, ON, Canada) that will provide validated measures in functional performance of the neck while wearing the C-Stretch.

1. <u>"Bag-Lift"</u>
   a. Two shelves are placed in front of the participant. The first shelf is directly above the participants eye level and a second shelf is 30 cm below it. On the shelf just above eye level are seven bean-bags placed 10 cm apart.
      i. <u>Order and placement:</u>
         Using the left arm first, the participants will reach to the far left most bean-bag on the shelf just at eye level. The bean-bag is lifted to the same position onto the shelf directly 30 cm below it. When the participant reaches the bean-bag directly in front of them they will switch to their right arm to coincide with the bean-bags on the right side and continue placing each bean-bag directly below. When all bean-bags are on the lower shelf, the participant will then start from the right side and begins to return the bean-bags directly above to their starting position.
      ii. <u>Participant position:</u>
         The participant will stand with their feet shoulder width apart, flat on the ground. When elbow is tucked at their side, their fingertips should line up with the end of the shelf that is closest to their waist.

<u>Test 1 Instructions:</u> For the first test, the participant will be asked to move each bean-bag from the shelf at waist level to the shelf directly above it. The test will be performed at a speed of 60 beats per minute, controlled by a metronome (beat #1 – grab, beat #2–lift and place). This will allow each participant to look at the bean-bag (extending and rotating the head as much as possible in the direction of the movement needed to complete the task). The participants will be asked to perform the task for a maximum of 5 minutes.

2. <u>"Bag Slide"</u>
   a. One shelf placed in front of the participant at chest level. On the shelf directly in front of the participant is one 1 bean bag.
      i. <u>Order and placement:</u>
         Using the left arm first, the participants will reach out and hold onto the bean bag directly in front of them. The bean-bag is then to be slid from the center of the shelf as far left as possible. When the

participant reaches as far left as possible, they will slide the bean bag to the center and grasp the bean bag with their right hand and slide the bean bag as far right as possible.

    ii. <u>Participant position</u>:
The participant will stand with their feet shoulder width apart, flat on the ground. When elbow is tucked at their side, their fingertips should touch the shelf at waist level.

<u>Test 2. Instructions (Bean-Bag Slide)</u>: The participant will be asked to use both hands, their left or right hand to slide the bean bag from the center (direction will correspond the hand that will assist in the movement) as far left or right as possible while their head follows the movement of the bean bag. The speed of movement will correspond to 60 beats per minute controlled by a metronome (beat #1 – grab bean bag at center position, beat #2 – slide bean bag far left with left hand, beat #3—slide bean-bag to middle and switch hand, beat #4 – slide bean-bag far right with right hand). The participants will be asked to perform the task for a maximum of 5 minutes.

    3. <u>"Star"</u>
        a. A whiteboard/wall placed in front of the participant that extends from waist level to just beyond eye level. Drawn on the board/wallpaper is a large star with 5 points.
            i. <u>Order and placement</u>:
Using a head mounted laser pointer, the participants will guide the laser along the star as to trace the path of a pre-drawn star on the whiteboard. There are 10 individual points that make up the trace of the star.
           ii. <u>Participant position</u>:
The participant will stand with their feet shoulder-width apart, flat on the ground. Participant should be far enough to see the entire star in front of them.

<u>Test 3. Instructions (Star)</u>: The participants will be asked to trace a path following the outline provided of the 5-point star at a speed of 60 beats per minute, controlled by a metronome (beat #1 – start from the top of the star, beat #2—trace to second point counter-clockwise, beat #3 continue to next point...etc.). This will allow each participant to extend, flex, and rotate their head as they follow the trace of the star (rotating the head as much as possible in the direction of the movement needed to complete the task). The participants will be asked to perform the task for a maximum of 5 minutes

Appendix C

Western HealthSciences
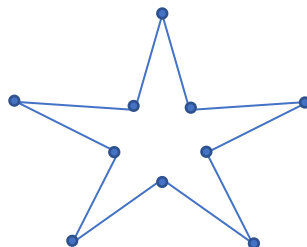
Health and Rehabilitation Sciences

C-Stretch Survey

Participant ID: _____

We would like to better understand what you thought of C-Stretch® by completing the survey below. Circle what applies most to you. Please pay close attention to what the question is asking.

1. I found that the <u>adhesive</u> used to keep C-Stretch on irritating.

Not at all	A little	A lot	Extremely

2. I found that C-Stretch interfered with the tasks I was asked to performed.

Not at all	A little	A lot	Extremely

3. I would be willing to wear the C-Stretch during an exercise session.

Not at all	A little	A lot	Extremely

4. I was aware of the C-Stretch the entire time I was wearing it.

Not at all	A little	A lot	Extremely

5. I would wear the C-Stretch during a normal daily routine.

Not at all	A little	A lot	Extremely

6. I found it easy to perform the tasks while wearing the C-Stretch.

Not at all	A little	A lot	Extremely

7. I felt discomfort when C-Stretch was removed.

Not at all	A little	A lot	Extremely

8. I found the C-Stretch sweaty.

Not at all	A little	A lot	Extremely

9. I would be willing to wear the C-Stretch for an entire day.

Not at all	A little	A lot	Extremely

10. I felt like the C-Stretch was secured on my neck.

Not at all	A little	A lot	Extremely

Version Date: November 21, 2018

Ethics Approval

Western Research

Date: 7 January 2019

To: Dr. Dave Walton

Project ID: 112806

Study Title: Evaluating a commercially-available stretch-sensitive adhesive for quantification of neck mobility with a focus on validity and reliability.

Application Type: HSREB Initial Application

Review Type: Delegated

Full Board Reporting Date: 29January2019

Date Approval Issued: 07/Jan/2019 09:26

REB Approval Expiry Date: 07/Jan/2020

Dear Dr. Dave Walton

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above mentioned study as described in the WREM application form, as of the HSREB Initial Approval Date noted above. This research study is to be conducted by the investigator noted above. All other required institutional approvals must also be obtained prior to the conduct of the study.

Documents Approved:

Document Name	Document Type	Document Date	Document Version
Advertising Recruitment Email	Recruitment Materials	16/Dec/2018	2
Aurora EMTS data collection form	Other Data Collection Instruments	19/Nov/2018	1
C-Stretch data collection form	Other Data Collection Instruments	19/Nov/2018	1
C-stretch survey	Paper Survey	21/Nov/2018	1
Email Script	Email Script	16/Dec/2018	2
LOI and Consent	Written Consent/Assent	04/Jan/2019	3
Recruitment Poster	Recruitment Materials	16/Dec/2018	2
Research Plan	Protocol	21/Nov/2018	1

No deviations from, or changes to, the protocol or WREM application should be initiated without prior written approval of an appropriate amendment from Western HSREB , except when necessary to eliminate immediate hazard(s) to study participants or when the change(s) involves only administrative or logistical aspects of the trial.

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University HSREB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Please do not hesitate to contact us if you have any questions.

Sincerely,

Nicola Geoghegan-Morphet, Ethics Officer on behalf of Dr. Philip Jones, HSREB Vice-Chair

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).

Photo Release Form

Western 🛡️

MEDIA PERMISSION   **Project Lead:** _Iyad Al-Nasri_

On _____, a photographer and/or videographer acting on behalf of the University of Western Ontario ("Western") may be taking photographs and/or videos at _____ (the "Event").

Permission: I grant permission to Western and its representatives to photograph and video me, and otherwise capture my image, and to make recordings of my voice at the Event.

Grant: I grant to Western and its representatives, the right to use, reproduce, distribute, and broadcast my image, including my name, voice, likeness and affiliation with Western captured in such recordings in any media now known or later developed as well as my name for promoting, publicizing or explaining Western and its activities and for administrative, educational or research purposes. This right also extends to any of the contents performed, created or provided by me which are captured in any recordings, such as my performances, artwork, compositions or similar materials. This right is irrevocable, royalty-free, worldwide, non-exclusive and transferrable.

Ownership. I acknowledge that Western owns all rights to the images and recordings.

Waiver: I waive:

    i.   any right to inspect or approve the use of the images or recordings or of any written copy;
    ii.   all moral rights; and
    iii.   any right to royalties or other compensation arising from or related to the use of the images, recordings or materials.

Other: I am not a member of any performers union or guild and I am of the age of majority.

Mohamad Fakhareddin   _Aug 20, 2019_
Name of Participant (Please Print)   Date

██████████████████████████
Signature

Privacy Statement: Western collects personal information under the authority of the *University of Western Ontario Act, 1982,* as amended. The information is related directly to and utilized by Western for the purposes of recruitment, program development, administration, and other related activities. The information may be used by Western in its publications including, but not limited to, printed publications, poster displays, electronic publications and websites, external media or other promotional media that supports Western's education initiatives and programs. Questions about this collection, use, or disclosure of personal information should be directed to the Associate Vice-President, Department of Communications and Public Affairs, Western University, Westminster Hall, Suite 360, London, ON, N6A 3K7, tel: 661-2111, ext. 85469.

I Y A D   A L - N A S R I

EDUCATION

2017–2019 **Master of Science, Health and Rehabilitation Sciences**
University of Western Ontario

Thesis: Feasibility and Reliability of a commercially available stretch-
sensitive sensor for neck range of motion.
Supervisor: Dr. Dave Walton

2015 **Bachelor of Science, Honours Biological Sciences**
University of Windsor

RESEARCH EXPERIENCE

2017–present **Researcher,** Pain and Quality of Life Integrative Research Lab (PIRL)
University of Western Ontario
- Conducting research in augmented (wearables)in rehabilitation for clinical utility
- Contributing to the development and assessment of a novel wearable device for cervical spine rehabilitation

2014-2015 **Laboratory Volunteer,** Developmental Genetics
University of Windsor
- Assisted Master students with experimental procedures such as nano-injecting frog embryos, PCR reactions, extracting DNA and RNA
- Assembled and stocked solution needed for experiments
- Captured images of experimentally injected frog embryos
-

TEACHING EXPERIENCE

Sept. 2017– **Graduate Teaching Assistant**
May. 2018 *University of Western Ontario*
- Facilitated and delivered aid in introductory course 'Systemic Approach to Functional Anatomy
- Set up weekly office hours to aid students in identifying gross anatomy and the major physiological systems of the body

Dec. 2015 **Pedagogy of Speech Communication Mentor**
University of Windsor
- Identified and differentiated teaching strategies for students taking the course
- Constructed lesson plans for lab instruction and critiqued student's speech communication and speech pedagogy
-

VOLUNTEER EXPERIENCE

May. 2019   **Grant Reviewer,** Canadian MSK Rehab Research Network
                   University of Western Ontario, London
- Scored grant proposals based on quality, feasibility, impact and potential to leverage external funding

2014-2017   **Physiotherapist Assistant,** Complex Palliative Care & Inpatient Rehabilitation
                   Hotel Dieu Grace Healthcare, Windsor
- Checked patients list and reviewed exercises for the patient during rehabilitation exercises
- Assisted patients independently throughout their exercises
- Assisted physical therapists in preparation of equipment for treatment
- Effectively communicated the type of exercise and how to accomplish the exercise safely

2014-2015   **Communication Executive,** Muslim Students' Association
                   University of Windsor
- Managed the club's social media and email account sending out mass emails, compiling and distributing weekly electronic newsletter advertising events, activities and initiatives

2012-2014   **Head Coach,** Tecumseh Recreational Soccer Club
                   Tecumseh
- Developed and trained technical skills to under 12 athletes
- Coached and implemented basic soccer drills
- Conditioned and trained athletes with set plays and formations

PUBLICATIONS, PEER REVIEWED

Lee JY, Guy SD, Lukacs MJ, Letwin ZA, Fakhereddin MF, **Al-Nasri IJ**, Salim S. Management of Fibromyalgia Syndrome: Cognitive-Behavioural Therapy (CBT) for healthcare professionals. University of Western Ontario Medical Journal. 87(1). 34-37. Mar. 2018.

Walton DM, Elliott JM, Salim S, **Al-Nasri I.** A reconceptualization of the pain numeric rating scale: Anchors and clinically important differences. Journal of Hand Therapy, 31(2), 179-183. Feb. 2018.

Al-Nasri I, Salim S. Using gamification to break barriers to adherence in physical therapy. University of Western Ontario Medical Journal. 87(2). 9-11. Sept. 2018.

Abu Shammeh R, **Al-Nasri I,** Walton DM, Trejos AL, Price AD. Low-cost and scalable fabrication of wearable soft sensor for neck mobility measurement. Proc. SPIE 10966, Electroactive Polymer Actuators and Devices (EAPAD) XXI, 109661V. Mar. 2019.

Al-Nasri I, Price AD, Trejos AL, Walton DM. A commercially available capacitive stretch-sensitive sensor for measurement of rotational neck movement in healthy people: Proof of concept. Proc. IEEE-RAS-EMBS International Conference Proceedings on Rehabilitation Robotics (ICORR)July 2019.

ABSTRACTS, PEER REVIEWED

Iyad Al-Nasri, Rami Abu Shammeh, David Walton, Aaron Price, Ana Luisa Trejos. Fabrication and Preliminary Evaluation of a Flexible Wearable Sensor to Capture Ecological Momentary Assessment of Neck Function. Canadian Bone and Joint Conference 2018. London, ON, Canada.

Iyad Al-Nasri, David Walton, Aaron Price, Ana Luisa Trejos. Testing the Potential of Adhesive 'Smart Tape' to capture Ecological Momentary Assessment of Neck Function. Health and Rehabilitation Sciences Graduate Research Conference 2018. London, ON, Canada.

LECTURES / PRESENTATIONS

Feb 1, 2018 – Annual Graduate Research Conference – Oral Presentation (London, ON)

May 11, 2018 – 3rd Biennial Canadian Bone & Joint Conference – Poster Presentation (London, ON)

May 16, 2019 – Ontario Physiotherapy Association, London Chapter – Invited Oral Presentation (London, ON)

June 3, 2019 – Innovation in Motion: Health Sciences/Biomedical Engineering Collaborative Research Day – Invited Oral Presentation (London, ON)

Aug 16, 2019 – Validation and Synchronization of Sensors with Motion Capture. UBC-KIN OBDAF Cluster – Group presentation (Vancouver, BC).

AWARDS

Sept. 2017 –Western Graduate Research Scholarship – ($2,000 x 6)

May, 2018 – Natural Sciences and Engineering Research Council award – (2018-2019) - $17,500