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The helical biotensegrity model

A visual qualitative study of the continuous 3D movement of the head

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The purpose of this thesis was to raise more interest towards the biotensegrity model in education and practice of osteopathy and other bodywork and movement therapies since traditional biomechanics fails to consider the complexity of living organisms when applied on humans and human movement.

The method of the study was visual auto-ethnography that illustrated the multiplanar and continuous movement patterns of the head. The hermeneutic exploration included cognitive observations of the embodied experience during the performance of the movement sequence.

The results demonstrated different movement patterns for the neurocranium and viscerocranium respectively during the three-dimensional movement sequence of the head. Focusing on the helical patterns enhanced the interoception and internal perspective in the movement generation. The embodied experience reflected previous findings on how internal perspective induces a significantly higher excitation of muscles in comparison to external perspective during the performance of the movement.

To conclude: understanding the fundamental scale free helical motion in the living tissues may aid the osteopathic or other health care practitioners in helping their patients move better and thus improve their various health and pain conditions. Visualization of helicality can aid the performance of tensegrity-like movement which could be utilized in rehabilitation and prevention of different chronic and fascia-related conditions. Biotensegrity provides interesting frontiers in health care that can point new directions beyond the paradigm of traditional reductionist biomechanical approach.

Keywords	fascia, body awareness, mental imagery, hermeneutics

List of abbreviations

CKC Closed kinematic chain

ECM Extra-cellular matrix

FNC Fascia Nomenclature Committee

FEP Free energy principle

FMI Fascial mental imagery

HA Hyaluronan

KT Kinetic transmission

MI Mental imagery

TEM 3D electroanatomic mapping

VMB Ventricular myocardial band

Contents

1 Introduction

The educational curriculum of an osteopathic practitioner includes the study of biomechanics and kinetics (WHO 2010; CEN 2015). Currently taught biomechanics is mostly based on the Newtonian laws of physics. It is known that these laws do not apply on small scales and therefore do not consider the complexity of living organisms when applied on humans and human movement. (Kerr and Rowe 2019; Levin in Hutson and Ellis 2006; Sharkey 2015) Traditional biomechanics mostly considers a movement happening only on one cardinal plane at a time and often focuses on one body part at a time, e.g. an elbow joint (Neumann 2010: 5, 87; Levin, Lowell de Solórzano and Scarr 2017). Natural movement, however, is not mechanistic and machine-like (Levin in Hutson & Ellis 2006; Scarr 2020).

A growing body of researchers question the mechanistic and reductionist model of traditional biomechanics in the light of new research and discoveries (Levin et al. 2017; Scarr 2020; Sharkey 2021; Banton & Vogel, 2023). Traditional biomechanics makes assumptions regarding biologic tissues that are not valid (Sharkey 2015) thus bringing forth a concern that the adoption of traditional biomechanics has negative implications on the perception, thinking and reasoning when incorporated into a holistic approach such as osteopathy (Scarr 2020; Esteves, Cerritelli, Kim, and Friston 2022; Thomson and MacMillan 2023).

Osteopathy is a holistic approach to patient care and healing. It emphasizes the integrity of structure and function and the intrinsic capacity for self-healing. Osteopathic manual therapy seeks to improve physiological function and support homeostasis. The underlying concept by which an osteopathic practitioner operates is to consider a human being as a functional unit, in which all parts are interrelated. Osteopathy is a health care modality that relies on manual contact for diagnosis and treatment. Osteopathic health care includes an array of manipulative techniques combined with other treatments or advice, for example on diet, exercise, self-care activities, or counselling. (WHO 2010; CEN 2015).

Traditional biomechanic view often overlooks the underlying biological etiology and pathogenesis of chronic pain as it is diagnosed as “nonspecific” due to disregarding the role of the facial system. However, fascial tissues have been demonstrated to play a significant role in the pathogenesis of chronic neck pain and overuse syndrome. (Stecco 2015:

viii, 95, 138.) Other chronic fascia-related conditions are e.g. fibromyalgia, low back pain, Dupuytren disease, and adhesive capsulitis (Abraham et al. 2020). It is likely that an osteopathic practitioner encounters patients with chronic pain conditions since it is the leading cause of disability worldwide (Calatayud, Perelló-Romero, Núñez-Cortés, López-Bueno, Clausen, and Andersen 2024).

The fascial system has been addressed by osteopathic practitioners since the times of Andrew Taylor Still – the founder of osteopathy (Findley and Shalwala 2013) but it is only recently that the fascial system has received wider interest across research and practice domains (Guimberteau in Schleip et al. 2012: 143-145). Interaction of disciplines and translating fascia research into practical applications can inform and support traditional osteopathic treatment methods (Chaitow 2012). The development of imaging tools that has enabled the study of living tissue in micro and nano scales (Ingber 2003a; Edlin et al. 2018) and indeed, it is now recognized that even the quantum scale is relevant in the self-organization of the biologic organism (Bettinger and Friston 2023; Torday, Klein, and Maimon 2024).

The biotensegrity model is a structural system that examines the fundamental rules of physics first and recognizes that everything else must be derived from them. Therefore, the biotensegrity model more accurately describes the structure and function of the human cells and tissues on multiple scales from nano to micro to macro (Ingber 2003a; Levin in Hutson & Ellis 2006; Swanson II 2013; Scarr 2020; Sharkey 2021).

The biotensegrity principles have already been applied by osteopaths and other professionals in bodywork and movement therapies (Swanson II 2013; Hohenschurtz-Schmidt et al. 2016; Scarr 2020). The model of biotensegrity has been viewed to serve the osteopathic attempt to have a holistic approach in their clinical reasoning, decision making and patient management. The biotensegrity model offers a concept for structure-function relationships at all size scales in the human body. Additionally, it can provide practical models for visualizing the living tissues, for example according to the subjective findings in palpation (Swanson II 2013; Hohenschurtz-Schmidt et al. 2016.)

Even more osteopathic practitioners, and other manual and movement therapists might utilize biotensegrity model, but it has received criticism for having poorly defined nomenclature, not being generally accepted as an alternative to the “traditional lever-based biomechanics” and lacking mathematical models and applications at macroscopic scale (Hanaor 2012; Hohenschurtz-Schmidt et al. 2016; Scarr 2020).

In fact, new mathematical approaches have been generated that look beyond the linear Newtonian mechanics such as closed kinematic chains (CKC) Levin et al. 2017 and predictive processing models such as free energy principle (FEP) that considers the self-organizing and dynamic nature of a living organism (Friston et al. 2023).

Soft Logic mathematics are applicable to biological organisms and have been developed based on the “First Principles of Physiology”. The unicellular state giving rise to the cell-cell signaling is seen as the basis of physiology. Soft Logic mathematics allow the conversion between the Cartesian 2D plane onto the “soft Mobius map”. The simplest topography – a mobius strip – with its one edge and one surface provides a model of scale free helical motion present in a living organism. This connects the infinitely small size and the function in the real-world size. (Torday 2021; Torday et al. 2024.)

Helicality can aid the performance of tensegrity-like movement which could be utilized in rehabilitation and prevention of different fascia-related conditions by improving interoception and benefitting fascial mobility and movement in general (Abraham et al. 2020). Physical activity has been acknowledged to improve chronic pain with improvement in overall mental and physical wellbeing and thus improvement in quality of life (Stecco 2015: 64; Calatayud et al. 2024.) This is interesting to osteopaths and other health care practitioners who put emphasis on the quality of movement (Hohenschurz-Schmidt et al. 2016).

This auto-ethnographical thesis explores helical biotensegrity and visualizes multiplanar and continuous movement patterns in the region of the head hypothesized to be tensegral and thus fascia friendly. The phenomenological approach of this study sees the human body as a process (‘motion’). Motion is primary, form is secondary, and the form arises out of motion. (Van der Wal 2013.)

This thesis is intended to clarify the concept of biotensegrity and its related topics and to generate discussion regarding the scientific framework in osteopathic and other health care settings. The topic of the thesis might interest health care educators and practitioners who emphasize the quality of movement in patient management and who are in search for strategies to improve and maintain good health of their patients beyond traditional biomechanics.

2 Fascia research

Fascia is considered a body-wide mechanosensitive signaling system that contributes to motor (i.e. movement), sensory-cognitive and wound regulation functions (Stecco & Schleip 2016; Zügel et al. 2018; Abraham, Franklin, Stecco, and Schleip 2020). It is an interconnected matrix that adapts its fiber arrangement, length, and density according to the tensions in the internal environment. Indeed, the connective tissue system could also be viewed as a metasystem enabling all body systems to operate in an integrated manner (Langevin 2006).

Fascia was neglected for several decades in the domains of anatomy and physiology since the traditional cadaver dissecting method is to “clean” structures from their covering of connective tissue due to thinking that it is meaningless packing material and only has a passive function in force transmission. The properties of fascia in vivo and in vitro differ significantly. The development of imaging tools now allows the study of fascial tissue in vivo. (Findley and Shalwala 2013; Schleip, Findley, Chaitow and Huijing 2012, xv.) A greater interest in fascia research grew after 2005 due to the release of in-vivo endoscopic videos by Dr Jean Claude Guimberteau that showed the microscopic microvacuole structure of fascia. The videos illustrated the living microstructure of the connective tissue fibers that enables sliding, gliding, and adaptation of fascia thus allowing the overall movement of all other structures (Guimberteau in Schleip et al. 2012: 143-145). Since 2005, the fascia related articles have increased from approximately 100 articles per year to over 4000 articles listed annually in PubMed and resulting in over 26000 publications in total to date (PubMed 2024). Fascia research has been claimed valuable in the field of sports medicine, providing better understanding and improvements in injury prevention, sports performance, and sports-related rehabilitation (Zügel et al. 2018).

Fascia has been a concept of interest in osteopathic profession from the very start. According to Findley and Shalwala (2013), the founder of osteopathy, Andrew Taylor Still (1899: 163) wrote that fascia sheaths, permeates, divides and sub-divides every portion of all animal bodies, surrounding and penetrating every artery and every fiber. A.T. Still conceptualized the role of fascia as vital for an organism’s growth and support and considered its role as the birthplace of disease (Findley and Shalwala 2013). Also, Lee

(1849: 324-325) was convinced that fascia was significant from a pathological point of view and how for example inflammation in the fascia later resulted in other diseases. More recent research indicates that connective tissue has a role in pathogenesis (Langevin 2006; Abraham et al. 2020).

Fascial tissue within the cardiac structure has also been recognized a long time ago. Lee (1849: 323-325) described his notions of cardiac fascia crediting it for providing firmness that makes the heart muscle the strongest muscle in the body.

> The cardiac fascia is obviously one of the principal causes of the firmness and strength of the central organ of the circulation of the blood, as it binds together into one mass, and gives support to, the muscular fibres, like the fasciae investing other muscles. (Lee 1849: 324.)

One of the main properties of fascia is the adaptability e.g. to the volume variations of muscle tissue. The adaptability is credited to the gliding property of the collagen fibers and layers over one another. Hyaluronan (HA) is the lubricant providing the normal gliding in fascia and confers motility to the cells. HA-secreting cells in fascia are called fasciacytes. The HA-rich loose connective tissue between aponeurotic fascia and muscle seems to provide protection to the muscle and support recovery from injury and intense activity. This layer apparently plays a role in the inflammatory processes as HA is prevalent during the earliest stages of wound healing and opens spaces through which cells can travel. (Stecco 2015: 60-64.)

Changes in the HA-rich matrix contribute to pain, inflammation, and loss of function. An abnormal accumulation of water, salts or waste products may alter the gliding properties of loose connective tissue and can cause myofascial dysfunction and alteration in proprioception (Stecco 2015: 60, 95, 138; Wilke, Schleip, Klingler and Stecco 2017). Accumulation of waste products such as lactate in the loose connective tissue increases its acidity. Normal acidity of pH 7.4 in the muscle is associated with normal viscosity of 3.8 Pa·s. At pH 6.6 a muscle reaches a state of exhaustion and the viscosity of HA that is present in the endomysium and perimysium significantly increases and approaches 5 Pa·s. The effect of increased viscosity can explain the post exercise stiffness that normally disappears with rest. The failure to restore the gliding in the fascial system occurs in cases of overuse syndrome, trauma, and surgery. (Stecco 2015: 60, 95, 138.) Excessive loading of fascial tissues modifies tissue function and may also contribute to pathological changes leading to compromised function of healthy tissue. Effects may become systemic, and thus not limited to the injured or loaded tissues (Zügel et al. 2018.)

HA is also present in the heart. HA reduces muscle friction and enhances the sliding of the myocardial segments. A capillary network with HA-rich plasmatic fluid has been found between cardiomyocytes. The finding has been considered crucial in understanding cardiac dynamics. Traiani et al (2021) conclude that this finding adds to the understanding of the lubricating role of hyaluronan in the rest of the organism.

One of the recognized effects of manual treatment, e.g. massage is a local and temporary increase in the temperature of the tissue. It has been demonstrated that the increase in the temperature leads to decreased viscosity in the loose connective tissue that is present within and beneath deep fascia and muscles. The decrease in viscosity is due to the progressive breakdown of the intramolecular water bridges that sustain the three-dimensional superstructure of HA chains. This mechanochemical reaction within the connective tissue therefore suggests a possible therapeutic mechanism underlying the restoration of normal function of the fasciae. (Stecco 2015: 64.)

Several researchers have expressed that the indiscriminate use of the term “fascia” often leads to confusion, complicating the comparing of the research results. All fascia is connective tissue, however not all connective tissue is fascia. (Stecco and Schleip 2016; Schleip, Hedley and Yucesoy 2019). In Findley and Shalwala (2013) A.T. Still (1899: 166) described fascia as the covering substance and drew attention to the common embryological origin of individually named parts of the fascial system stating that all organs have a covering of this substance, though they may have names to according to the organs, surfaces, or parts spoken of. Connective tissue provides a structural framework for growth through its organizing role during embryologic development. The mesoderm emerges in between the ectoderm and the endoderm and is the origin of the primordial connective tissue: mesenchyme. (Findley and Shalwala 2013; Sharkey 2021.)

Connective tissue includes bones, cartilage, blood, and lymph which are derivatives of the embryologic mesenchyme (Schleip et al. 2012, xviii). Connective tissue is one of the four major classes of tissue (the others being epithelial, muscle, and nerve tissue) (Stecco 2015: 1). According to the broad definition, fascia is a connective tissue continuum throughout the body which unites and integrates different regions (Findley and Shalwala 2013). As prompted by the Fascia Nomenclature Committee (FNC) “a fascia” should be distinguished from “the fascial system”. The FNC proposes that “the fascial system” refers to a network of interacting, interrelated, interdependent tissues forming a complex whole, all collaborating to perform a movement. (Stecco and Schleip 2016.)

Fascia is a subcategory of connective tissue and for example morphological variations of collagen have been used to give it descriptions and definitions. For histological or morphological analyses an anatomical definition of “a fascia” is a sheath, a sheet, or any number of other dissectible aggregations of connective tissue that forms beneath the skin to attach, enclose and separate muscles and other internal organs. (Stecco and Schleip 2016.)

The proposed narrower anatomical definition excludes the interconnections of fascial tissues with joint capsules, aponeuroses, tendons, ligaments, and intramuscular connective tissue which are interesting to manual practitioners and other clinicians who are interested in the functional aspects of the tissues (Stecco and Schleip 2016). To some authors fascia is restricted to muscular connective tissues and the visceral fasciae are often excluded. Indeed, the narrower definition of fascia is yet to be resolved. (Schleip et al. 2012, xvi). It is hypothesized that is impossible to find a definition for fascia that is fully descriptive and would suit all interested medical agencies, researchers, and fascia-focused disciplines (Hedley 2012; Stecco, Adstrum, Hedley, Schleip and Yucesoy 2018; Sharkey 2019).

It has become evident that the most suitable nomenclature of fascia depends on the type of investigation or perception of it. If the focus is morphological, then narrower fascia definition seems to be in order. However, if the focus is on the functional aspects - such as force transmission, sensory capacities, and wound regulation – then a wider definition is more helpful. (Stecco and Schleip 2016.)

In the beginning of anatomy as a scientific discipline, the criteria for naming were anatomical, topographical, and morphological. Understanding anatomy functionally led to the development of functional names and notions. In fact, the confusing act might be the commitment of a categorical error when talking about ‘fascia’. Anatomist and embryologist, Jaap van der Wal (2020; 2015), draws attention, along with Stecco et al. (2016) and Adstrum (2017), to the growing body of evidence that supports moving away from focusing on discrete anatomical elements and think about fascia as a system of continuity and connectivity hence focusing on functional category instead of anatomical one. (Van Der Wal 2015; 2020.)

3 The tensegrity model

Tensegrity is a scale-free structural system that has evoked interest e.g. in architects, engineers, space engineers, scientists, and biologists (Hanaor 2012) as well as movement and manual therapy practitioners (Scarr 2011; Swanson II 2013; Hohenschurz-Schmidt, Esteves and Thomson 2016). The tensegrity model has the potential to elevate the traditional mechanistic model to meet the current deficiencies of its postulates (Ingber 2003a; Ingber 2003b; Swanson II 2013; Levin et al. 2017; Scarr 2020; Sharkey 2021).

The model of tensegrity originates in arts and architecture and was formerly developed in the 1960's. The word ´tensegrity´ is a combination of two words: *tension* (or *tensile* by Hanaor 2012) (or *tensional* by Swanson II 2013) and *integrity* that describe tensioned or pre-stressed structure and its architecture that follows certain mathematical rules. (Ingber 2003a.) The same fundamental mathematical rules describe the closest packing of spheres (Connelly and Back 1998; Ingber 2003; Levin in Hutson and Ellis 2006).

A technical definition where "tensegrity" stands for systems in a stable self-equilibrated state comprising a (discontinuous) set of compressed components and inside a continuum of tensioned components (Rhode-Barbarigos 2012). This definition is designed for engineers, architects, and artists. Most manmade structures are stabilized by gravitational compression. In contrast, tensegrity systems are self-stabilized through force triangulation and would maintain their shape in the absence of gravity (Swanson II 2013).

The critique towards the ambiguity of the tensegrity model by Hanaori (2012) may be justified as the field is in its early stages and the nomenclature is not established in further detail. This was also pointed out in the response to Hanaori's article by Rhode-Barbarigos (2012).

Biotensegrity is the application of tensegrity principles to biological structures (Levin in Hutson and Ellis 2006; Swanson II 2013). The biotensegrity model tackles the complex nature of a biological organism that consists of multiple nested and hierarchical systems within systems - from microscopic to macroscopic. Since the 1970's the concept of biotensegrity has expanded markedly and is applied at the molecular, cellular, organ, and organ-system level. (Ingber 2003b; Swanson II 2013).

As a result of the emerged ideas of the tensegrity principles together with the technological developments, many discoveries have been made such as in cellular biochemistry (Ingber 2003a, b), cardiology (Buckberg 2002; Torrent-Guasp 2005), and fascia research (Guimberteau in Schleip et al. 2012: 143-145; Sharkey 2015; Stecco 2015) The insights have expanded from the scientific research into the fields of different bodywork and movement therapies (Swanson II 2013; Hohenschurtz-Schmidt et. al 2016).

Hohenschurtz-Schmidt et. al (2016) identified four main approaches to apply tensegrity model within manual therapy practitioners. The modalities in the study included osteopathy, Rolfing, and massage therapy. Four distinguished tensegrity model-based approaches arise from the synthetization of the research data. The four approaches were: ‘a theorist’, ‘a biomechanist’, ‘a manual therapist’ and ‘a movement therapist’. These four approaches relate to practical use of the tensegrity model. Each one is characterized by a different conception of the model and a different implication for practice. ‘Theorist’ examines the physical principles underlying tensegrity and their relevance in understanding the human body. ‘Biomechanist’ is mainly concerned with force-transmission via the body-wide fascial network. For ‘manual therapist’ the tensegrity model informs treatment decisions by providing scientific basis for phenomena experienced in practice and aids in palpation and visualization of tensional patterns in tissues. ‘Movement therapist’ is concerned with the quality of body movement, which when effective is deemed to be tensegrity-like or ‘tensegral’. (Hohenschurtz-Schmidt et. al 2016.)

3.1 Helicality

Helical and tensegrity structural systems complement each other. They share common origins geometrically which serves as an energy-efficient solution for biologic organisms. In molecular biology this is referred to as close-packing and the mathematical models concern its spherical nature. The geometry and principles of symmetry of close packing at an atomical level is revealed in crystals. The structures of crystals form tetrahedrons, octahedrons, cubes, and hexagons. The icosahedron tensegrity structure is considered most apt for sustaining life due to its closest-packing ability and surface to volume ratio (Levin 1995; Ingber 2003a; Scarr 2011; Sharkey 2021).

It is well known that many patterns in Nature appear in helical arrangement from micro to macro. Helixes are observable in the growth patterns of flowers, seashells, and the antlers of a ram. At large scales the helical patterns can be seen in hurricanes and galaxies. (Buckberg 2002). Helicality is also a palpatory phenomenon observed for example within the soft tissues of the limbs which current anatomical knowledge has not been able to explain (Scarr 2011).

In humans, the helical arrangement of “tubes within tubes” appears at organ-system and organ level (e.g. urinary system, cardio-vascular system) and cellular and molecular level (e.g. DNA, collagen) (Buckberg 2002; Scarr 2011; Swanson II 2013; Sharkey 2021.) Collagen is the most wide-spread structural protein surrounding virtually every cell in the body and being a major component of the extra-cellular matrix (ECM). The fascial net is a ubiquitous, three-dimensional network of double and triple helical folds (Scarr 2011; Levin et al. 2017; Sharkey 2021).

Helical tensegrity emerges in structures from micro to macro and is present in embryo-development, organ-development and in the movement patterns of living organisms, humans included. Helical movement is natural in closed kinematic chains that connective tissue forms. (Scarr 2011, Buckberg 2002; Levin et al. 2017; Sharkey 2021)

3.2 Tensegrity model in cellular biochemistry

Before the tensegrity model was coined, a cell was pictured as a balloon in the field of cellular biochemistry. To understand biological processes responsible for cell behavior as integrated, hierarchical systems rather than as isolated parts, Donald Ingber (2003a) brought forth a more educated perception of a cell regarding its structure and function. Rather than being filled with a liquid “protoplasm”, as imaged a century ago, eukaryotic cells contain an intricate molecular framework, the cytoskeleton, composed of interconnected microfilaments, microtubules, and intermediate filaments within their viscous cytosol. (Ingber 2003a.)

Cellular mechanochemical behavior is an emergent property that results from collective interactions among intricate filament systems of the cell, connections to the extracellular matrix (ECM) and other cells. The complementary tensegrity-based force interactions between focal adhesions and microfilaments can be passed to microtubules at distant sites via mechanotransduction. Additionally, to the ability to change in size and shape, the individual filaments can have dual function and alternate between bearing either tension or compression depending on the size scale and structural context (Ingber 2003a; Findley and Shalwala 2013; Sharkey 2021).

Focal adhesions are cell member sites for transmembrane proteins, such as integrins. Together the links connecting the cytoskeleton, extracellular matrix and other cells form a pre-stressed tension matrix. The reciprocal transfer of forces is likely to orchestrate cellular growth and other behavior through changes in enzymes and substrates. (Scarr 2011; Findley and Shalwala 2013; Sharkey 2021) Without cells connection to the ECM, they cannot stabilize their specialized shapes. In the same way “as one cannot describe the stability of a spider web without considering the tree branches to which is it tethered.” (Ingber 2003a.)

3.3 The helical heart

> Heart should be considered as self-regulating functional system, which is greater than the sum of its constitutive parts. (Kresh and Armour 1997.)

The human heart expresses a helical tensegrity in its structure and function (Torrent-Guasp et al. 2005; Scarr 2011; Swanson II 2013; Trainini et al. 2021). It is the first organ in the vertebrate embryo to develop (Liebling et al 2006) and Nature seems to have produced the formula of the helical heart as a basis of the circulatory system at least 400 000 years ago. In the 1400s, Leonardo da Vinci made observations and drawings of anatomic dissections and described the helical form of the heart. His notion was that the apex was important for the proper function of the heart and comprises the left ventricle. Furthermore, Leonardo observed the clockwise and counterclockwise spirals within the aortic structure as well as in the flow of the blood as it moves through the aortic valve in reciprocal coils. (Buckberg 2002.)

The cardiac helix muscle fibers going from outside in and inside out forming an apical vortex was described in the 1660’s by Richard Lower (Buckberg 2002; Trainini et al. 2021). More recently, the helical structure and function of the heart have been confirmed for example by magnetic resonance imaging and computational fluid dynamics (Edlin et al. 2018). 3D electroanatomic mapping (TEM) has been used to demonstrate the helical electrical activation of the heart (Trainini et al. 2021).

The structure and function of the heart is the same and interdependent on the size-scale. Perhaps the smallest heart examined by scientists belongs to a zebrafish. Its heart is only a third of the width of a human hair. Regardless of the microscopic size, the scientist discovered the same spiraling flows in the aorta and the clockwise and counterclockwise beating of the heart. (Buckberg 2002.)

The shape of the heart correlates with its function. A healthy heart has a spiral orientation. The clockwise and counterclockwise muscle fibers form approximately a 60-degree angle in a healthy heart. (Buckberg 2002; Scarr 2011; Trainini 2021) The epicardial fibers take an oblique course, the intermediate fibers a transverse one and the endocardial fibers also an oblique course but contrary to that of the epicardial plane. The predominant course of the cardiac fibers is defined with sliding planes, which together form the myocardial muscle. In addition to the orientation of the fiber bundles according to their respective plane, collateral fibers are present. (Trainini 2021.) A malfunctioning heart dilates and adopts a more spherical than elliptical orientation in heart conditions such as ischemic, valvular, and nonischemic cardiomyopathy. With that it loses as much as half of the power of ejecting the blood. (Buckberg 2002; Torrent-Guasp 2005; Trainini 2021.)

Curiosity towards the function of the heart led to the discovery of the ventricular myocardial band (VMB) by Francesco Torrent-Guasp. Torrent-Guasp developed a dissection method to illustrate that the cardiac structure is a unity that folds itself in spiraling formation. The VMB both expresses the embryological growth pattern and the reciprocal contracting pattern of the clockwise and counterclockwise fibers. (Buckberg 2002; Torrent-Guasp 2005) The discovery of the ventricular myocardial band received criticism for being too simplistic and not following the Newtonian laws of dynamics (Criscione, Rodriquez and Miller 2005). The geometric approach to the structure and function of the heart led to the development of new surgical methods to aid patients with various cardiac failures. In the surgical solutions a more elliptical configuration of the left ventricular chamber is restored. (Buckberg 2002; Torrent-Guasp 2005.) Indeed, a cardiac surgeon Buckberg (2002) announces:

> Restoration of the helix is our goal. (Buckberg 2002.)

Trainini et al. (2021) describe in more detail the motions of the heart: narrowing, shortening-twisting, lengthening-untwisting and left ventricular expansion. In the narrowing phase (at the beginning of systole) there is a consecutive contraction of the right and left segments representing the basal loop. The overlapping shortening occurs as the base descends and twists longitudinally. The activation of the left ventricle begins in the endocardial descending segment which is almost simultaneously occurring axially and radially. The narrowing and shortening of the basal loop constitute the outer shell or ring within which the apical loop is to contract. The activation from endocardium to epicardium spreads at the crossover point of descending and ascending segments. A twisting motion like “wringing a wet towel” is achieved and the highest amount of blood is ejected during the first fifth (20%) of the systolic phase. The depolarization of the apical loop occurs in two simultaneous wave fronts from the descending and from the ascending segments.

The untwisting motion increases the circumferential and radial axes. The stimulation ends in the ascending epicardial segment and produces the active isovolumic phase and generates a suction mechanism (“suction cup”). The apex remains fixed as the base descends in systole and ascends in diastole providing fulcrum for the helicoidal torsion. (Trainini et al. 2021). Purkinje (1843) observed and called it a ‘punctum fixum’ according to Torrent-Guasp et al (2004). At the apex, the fibers of subepicardium become subendocardial around a tunnel which is closed by the endocardium in the inside and by the epicardium on the outside as a transverse cut of several dissected muscular layers reveals (Torrent-Guasp, Buckberg, Clemente, Cox, Cesil Coghlan and Gharib 2001).

Since the 17th century it has been commonly taught that during the diastolic phase of the heart the blood passively fills the heart due to negative pressure followed by an active systolic phase when the blood is squeezed out in the aorta. However, contrary to being passive the diastolic phase is equally active as the heart sucks the blood in. (Torrent-Guasp et al. 2001; Buckberg 2002; Trainini et al. 2021). This was first written about by a Greek Physician Erasistratus of Chios (304-250 BC). Later, during the Roman Empire AD 180, the doctor of the gladiators, Galen of Pergamon (129-210 AD), saw a gladiator with an open chest would and observed the blood being sucked into the heart. “The overlying heart, at each diastole, robs the vena cava by violence of a considerable quantity of blood.” Galen suggested that to understand how the heart works, one should look at waves in the ocean. The father of anatomy, Vesalius, supported Galen’s ebb-and-flow thinking. (Torrent-Guasp et al. 2004; Buckberg 2002).

This concept of suction was denied by William Harvey (1578-1657) and for some reason became the generally accepted explanation for how the heart is filled with blood (Torrent-Guasp et al. 2001; Torrent-Guasp et al. 2004; Buckberg 2002). Surely enough, 2000 years after Galen, the electrical stimulations of the heart muscle contractions are called waves. According to the electroanatomical mapping the untwisting of the heart during the first 100 milliseconds of diastole generates a negative force intraventricularly that draws the blood into the left ventricle. In fact, it has been suggested that the heart cycle consists of three stages: systole, suction, and diastole. Furthermore, Trainini et al. (2021) emphasize that the left ventricular suction is the link between the pulmonary and the systemic circulations.

Suction and ejection are observable already on embryonic heart before its complete maturation. Embryonic research has revealed that the heart first forms a beating tube that causes a unidirectional flow of the blood even without the help of the valves. The observed minimal backflow is probably caused by impedance mismatches between the inflow tract and the outflow tract, resulting in *a suction pump*. (Liebling et al 2006.)

In hemodynamic studies 4D flow MRI allows measurement and visualization of spatial and temporal changes of 3D volume. It provides data of blood velocity in all dimensions rather than a given plane. Hemodynamic research that studies the patterns of blood flow has revealed several variables such as flow eccentricity, helicity, flow displacement, systolic flow angle and wall shear stress. In the systematic review by Edlin et al. (2019) It is suggested that abnormal blood flow predates aortic dilatation. In the past, the diameter of the aorta has been thought to be an indicator of an acute aortic event such as an aneurysm. Now the entire geometry and valve morphology are held important and hemodynamic parameters are considered useful in predicting disease progression. (Edlin et al. 2019.)

4 The problematics with traditional biomechanics

Despite the advancements in fascia research, the descriptions of “passive collagen” that “passively transmit forces” still dominate the textbooks. Traditional biomechanics uses a lever-theory that describes e.g. bones as levers and joints as ‘pin-joints’ that provide a fixed fulcrum for movement (Kresh and Armour 1997; Kerr and Rowe 2019: 157; Levin et al. 2017). In traditional biomechanics ‘a musculoskeletal system’ is responsible for moving (locomotion) (Scarr 2011). Traditional biomechanics imply that bones are compressed across their articular surfaces and that the synovial joints act as levers. In traditional biomechanic approach a muscle gets narrower when it lengthens thus expressing positive Poisson ratio. (Scarr 2011; Levin et al. 2017; Scarr 2020; Sharkey 2021.)

The so called ‘musculoskeletal system’ is an example of a system that has been studied in isolation from the rest of the body (Langevin 2006). Jaap van der Wal (2020) suggests that the term ‘musculoskeletal system’ should be abandoned since it represents inherently reductionist and mechanistic view that has no functional meaning without an organizing nervous system. Living structures do not move around fixed fulcrum as proposed in traditional lever-based biomechanics. Bones follow more complex helical pathways with all the other tissues. (Levin et al. 2017.)

It has been demonstrated that normal joint surfaces in the knee are not touching each other. This removes the notion that cartilage or meniscus would act as a shock absorber. Furthermore, shear stresses that levers would generate are considered impossible to occur in developing biological tissues without causing serious damage. (Levin et al. 2017; Scarr 2020; Sharkey 2021.) Poisson ratio is positive in most of man-made materials. However, negative Poisson ratio is a common in biological structures (Scarr 2011), such as the heart. When observed from an anterior perspective, the motions of the heart include narrowing and shortening and then lengthening and widening ie. expanding thus expressing negative Poisson ratio (Torrent-Guasp et al. 2001; Buckberg 2002; Traiani et al. 2021.)

Sharkey (2015) noted the error of traditional biomechanics:

> --initial premise that muscles, fascia and indeed, any biologic material can be bound by the rules of hard matter physics. (Sharkey 2015.)

Hard matter physics rules that the volume of the solid stays the same which is referred to as Hookean material and visualized in a linear stress/strain curve anagram. Unlike man-made elastic materials, biological tissues like muscles and fascia have non-linear stress/strain curve. Non-hookean material is omnidirectional. Biological structures have non-linear visco-elastic properties, with fluid-like movements. (Scarr 2011; Sharkey 2015; Scarr 2020.) This is not to say that the mechanistic approach and schematic images don’t have value, for example, in education (Van der Wal 2015; Levin et al. 2017; Sharkey 2021).

Sir Isaac Newton established the field of mechanics and introduced “Law’s of Motion” that govern the relationship between forces and motion. These laws were taken as absolute laws governing all motion in the universe. (Kerr and Rowe 2019: 234.)

Cartesian coordinate system by René Descartes is most frequently employed to describe motion in traditional biomechanics. The Cartesian coordinate system divides the body into three cardinal (principle) planes of the body: sagittal, frontal, and horizontal. The sagittal plane divides the body into left and right sections, the frontal plane divides the body into front and back sections and the horizontal plane divides the body into upper and lower sections. The Cartesian system uses coordinates for locating a point on a 2D plane. The location of the point is at the intersection of two axes (X, Y) that are arranged perpendicularly. A 2D reference frame is used when the motion is described to be planar (i.e. in one plane). (Neumann 2010: 5, 87.) 2D Cartesian coordinate system combines geometry and algebra. Algebra is characterized by symbols that embody the unknown. Geometry is a much older discipline than algebra and mostly concerns properties of shape, space, distance, size, and position. These two mathematical disciplines were developed independently until brought together by René Descartes. (Study.com 2024.)

Applying mathematics to modeling and measuring human movement can be subcategorized in kinematics and kinetics. Kinematics seeks to describe motion and concerns its geometry. Kinetics is a branch of mechanics that seeks to explain the causes of motion, e.g. pushing and pulling forces attempting to change the motion of objects. (Kerr and Rowe 2019: 227-228). Osteokinematics describes the motion of bones relative to the three cardinal planes of the body (Neumann 2010: 5).

The lever-theory can be traced back to a Greek mathematician and engineer, Archimedes of Syracuse and further established by a French philosopher, René Descartes (Sharkey 2021). Traditional biomechanics uses Newtonian mechanics to calculate human movement (Levin et al. 2017) – although it knowingly does not provide accurate solutions. Einstein demonstrated in his times that the Newtonian laws do not apply at very high speeds. The human movement in traditional biomechanics is calculated using linear methods due to the belief that this mismatch “can be ignored without any loss of accuracy”. (Kerr and Rowe 2019: 234). There is nothing “wrong” with classical mechanics but to apply it to biology is out of date (Sharkey 2015; Scarr 2020).

It has very much been the case that human tissues such as bones have been perceived as wooden planks or bricks (Scarr 2011). Yet, biomechanic nomenclature often predominates interprofessional communication. Scarr (2020) ponders if having adopted the vocabulary of the traditional biomechanics influences how we practice osteopathic profession (and other health care modalities). It has been acknowledged that within osteopathic profession a set of descriptive words have been replaced with biomechanical potentially leaving out essential aspects of osteopathic approach therefore affecting one's professional identity (Shaw et al. 2022, Thomson and MacMillan 2023, Grech 2023: 25-30).

In addition to fascia and tensegrity focused researchers there are other groups of thinkers who have also recognized the limitations of rigid and mechanistic approach predominating the health care arena and diminishing psychological, sociocultural, and environmental aspects. These groups aim to advance and reframe research methods and other healthcare practices highlighting patient-centered approach in osteopathy (Esteves et al. 2022; Shaw, Abbey, Casals-Gutiérrez and Maretic. 2022; Banton and Vogel 2023; Horta Moragas 2023: 37; Nicholls 2024) and physiotherapy (Nicholls et al. 2023). However, these topics are not the main scope of this study. Nevertheless, they are not seemingly in conflict with the biotensegrity model.

5 Beyond traditional biomechanic

There is a lack of mathematical models of biotensegrity - as requested by Hohenschurz-Schmidt et al. (2016). Unlike linear mechanics, the dynamics of tensegrity structures are very complicated to analyze mathematically (Scarr 2020). However, the algorithms of tensegrity structures are widely used in engineering (Skelton and de Oliveira 2009, xii-xiii, Song, Scarpa and Schenk 2023) and computational models exist for complex analysis of flow dynamics (Edlin et al. 2019). Indeed, such mathematical tools of macroscopic biotensegrity are yet to enter the undergraduate curriculum of osteopathy thus also reflecting the current curricula in health care and rehabilitation more widely. Kristyanto, Nugraha, Pamosoaji and Nugroho's (2015) work to simulate head and neck movement was created using the anthropometrics of the cervical spine in flexion, extension, rotation, and lateral flexion. The model illustrates the limitations of the 2D thinking of linear movements where cardinal movements are studied in isolation thereby lacking focus in helicality, complementary movements (e.g. translation) and arthrokinematics.

Levin et al. (2017) provide a bridge to gap between traditional lever-theory and biotensegrity by drawing attention to multi-bar kinematics that both allow simplified 2D schematics that is in harmony with non-linearity of biotensegrity structures. Tensegrity structures allow movement, with the minimum of energy expenditure, without compromising stability. Closed kinematic chains provide a geometrical solution that offers more accurate schematic modeling than single-plane and linear calculations used in traditional biomechanics. CKCs are oriented in many different planes and increase the number of degrees of freedom. Closed kinematic chains (CKCs) seem to be an energy-efficient solution that nature has applied to generate rapid and powerful movements which are needed e.g. to catch prey. CKCs are well-researched and described in animal kingdoms but are less recognized in human movement. (Levin et al. 2017.)

Closed-kinematic chains are demonstrated to be present in fascia/extra-cellular matrix in a body-wide ubiquitous manner. The integration of different parts into a more comprehensive sensing and moving system is fully compatible with the concept of biotensegrity. The structural design that emphasizes the *distribution of the mechanical forces* is at the heart of the stability and ease of the movement instead of oversimplified strength factor. Biotensegrity highlights the dynamic stability of the living organism which balances out complex force vectors and enables the change shaping with the minimum effort and returning into stable equilibrium. Movement can be stabilized through a system of multidirectional motion and control possibilities. (Levin et al. 2017)

According to Levin et al. (2017), a classification prompted by Muller (1996), considers the inherent complexity of biological systems by comparing the effect of changes in the relative lengths of the component bars and overall geometry. According to Muller’s system a graphic representation of a 4-bar mechanism shows the non-linear relationship between the changing input and output angles relative to a reference bar. The kinematic transmission curves vary according to which bar is taken as reference. The graphics demonstrate how the motion of each bar is controlled by the relative positions of all the others. The input and output angles on either side of the reference bar define the mechanical property which is called kinematic transmission (KT). The changing shape (morphology) of a 4-bar system maps non-linearly to the emergent property of KT thus leading to disproportionate responses because of shape changing therefore enabling sometimes even extreme amplification in force, speed, and kinetic energy. (Levin et al. 2017.)

Replacing the idea of solid bars used in traditional biomechanics with a concept of a strut offers another way to update be ‘the man as a machine’ approach with a more biologically based tensegrity model one. Connelly and Back (1998) provide a mathematical explanation: unlike a solid bar with fixed length, a strut can get either longer or shorter mostly without sacrificing stability. The same fundamental mathematical rules describe the closest packing of spheres (Connelly and Back 1998; Ingber 2003; Scarr 2011).

Differentiating between pre-stressed and geodesic - the two broad classes of tensegrity structures, can further assist in conveying the tensegrity concept. According to Connelly and Back (1998) the same mathematical rules define both classes. Pre-stressed tensegrity structures consist of two discontinuous elements: compression-resistant element that is held within a web of continuous tension elements. Geodesic structures are also under pre-stress but differ as the elements of geodesic structures can alter between generating tension of resisting compression hence stabilizing the structure through force triangulation. (Swanson II 2013.)

The use of the abovementioned classification of pre-stressed tensegrity structure has led to mechanistic and reductionist conclusion. Generally, it has been taught that when applying tensegrity model on a human at a macro level – the bones act as struts and resist compression and the fascia, in most parts, is the tension-bearing element (Hohenschurtz-Schmidt et. al 2016). However, in tubular structures the radial pressure pushing outwards provides the compressional element, such as in arterial walls which are pre-stressed. The helical array of the fibers balances both longitudinal and circumferential stresses allowing smooth bending and resistance against torsional deformations. When looked at microscopically, at one level the struts organize themselves in tension cables with differing orientations. Mathematically the structural elements handle tension and compression in straight lines to form a stable equilibrium - true linearity does not exist in biology. (Scarr 2011; Scarr 2020.) Instead of “pre-stressed”, the more appropriate property of biotensegrity would be “geodesic”.

5.1 Spinors and mobius strips

As stated in chapter 5 there has been a rip between mathematics and physiology. A possible remedy may lie in spinors that are mathematical objects that describe rotations in abstract state space such as in particle physics. The concept of spinors joins together geometry, algebra, and quantum mechanics (Coddens 2017). Applying the related mathematics to biological organisms is based on the “First Principles of Physiology” (Torday et al. 2024).

Euclidean linear vectors in 2D Cartesian coordinate system can be described as arrows or “pointed sticks”. When rotated 360 degrees they end up in the starting position. An analogue of this could be a pointer of a clock making a full circle. However, true linearity does not exist in biology (Scarr 2011; 2020).

A spinor, instead, needs 720 degrees of rotation, or 2 full turns (4 π), to return to its starting point. This is demonstrated by "Dirac's belt trick" or the "Balinese plate/cup trick" (Rahul and Murugesh 2019). Making one turn by turning the arm holding a cup returns the cup to its starting position but leaves the arm twisted. A second turn untwists the arm returning a cup again to the starting position. A visual analogue of a spinor is called a mobius strip (or a Möbius strip). A mobius strip is the simplest topological system with one side and one edge. (Saha and Maiti 2016.) A recent mathematical conversion method allows the mapping of the 2D Cartesian plane on a "soft Mobius map" (Torday et al. 2024).

Soft Logic mathematics represents both consciousness and unconsciousness/subconsciousness as the fundament of life. Soft Logic links mathematics to Nature and physiology using both a real number axis and a zero axis. The continuum model of evolution of physiology consists of the real world that is represented by real numbers and inner world or consciousness that is represented by zero which is composed by multiples of the number zero which express the infinitely small sizes. Soft Logic mathematics describes the relationship by a new type of number called "soft numbers" which are part real and part multiples of zero. Soft Logic mathematics allow the conversion between the Cartesian 2D plane onto the "soft Mobius map". This creates a bridge between the infinitely small size and the function itself in the real world. (Torday 2021; Torday et al. 2024).

It has been hypothesized that cell membrane is like a mobius strip in that it forms a continuous topologic surface between the outer and inner environments of the cell, having given rise to the 'inside' and 'outside'. The cells were preceded by lipids aligning with one another reducing the surface tension of the surrounding waters leading to the formation of micelles that gave rise to eukaryotic cells. It has been proposed that the unicell is the primary state of being. (Torday 2021.)

Furthermore, it has been hypothesized that the cell behavior and cell-cell signaling assimilate a functional mobius strip. Cells evolved the capacity to communicate with one another mediated by soluble growth factors and their receptors to generate physiology. The cell-cell signaling mechanisms are the basis for all of physiology and have been used to trace evolution back to the unicellular state (Torday et al. 2024).

The mobius strip-like unicellular knotting takes place during embryonic development forming the complete embryo. It has been suggested that the organism can return to its unicellular state over the course of the life cycle. This is constituted by organized loss of cell-cell signaling mechanism and finally the loss of consciousness. (Torday et al. 2024)

A Trefoil Knot is associated with mobius strip and a homologue of a cell (Torday 2021). Interestingly, the heart has been called the Gordean knot of anatomy since its function cannot be explained by the traditional approach of biomechanic. (Torrent-Guasp et al. 2001, Torrent-Guasp et al. 2005). It seems like a coherent idea that the twisted cardiac form, the VMB, signifies that the heart is a mobius strip -like structure.

The topology of mobius strips has been a topic of intense research since it is related to physics of quantum rings and has the potential to be utilized in information processing and other nano-electronic devices. Saha and Maiti 2016.) For instance, carbon materials twisted in a mobius strip-like manner have unique optoelectronic properties and are used e.g. as nano-conducters, sensors, magnetic materials, and catalysts (Zhang, Tian, Zhen, Li, Wu, and Lu 2017).

To fully understand the mathematical theory of spinors (and mobius strips) one must be familiar with complex numbers, matrix algebra, vector spaces, the Hermitian norm, and the definition of a group (Coddens 2017). However, it can be argued that it should be possible to form a conceptual mental image of a spinor (or mobius strip) this motion was inherently a fundamental physiological property of a living tissue. This would be in harmony with Banton & Vogel's (2024) statement of the embodied capacity to create, experience, and understand concrete and abstract concepts without verbal expression. Mental imaging is recommended also to those with mathematical training. This allows the underlying ideas to become clear in the form of "visual" geometrical clue. (Coddens 2017.)

5.2 Predictive processing models

Affective neuroscience aims to link subjective experience with neural activity. Early neuroscience models searched for specific brain regions that uniquely carried out the computation that underlie subjective experiences such valence. However, research has failed to identify these circuits. New direction for research leans on predictive processing models which suggest that the activity underlying an affective experience may span throughout the neural hierarchy. (Lee, Ferreira-Santos, and Satpute 2021.)

Predictive processing models are increasingly adopted in cognitive and affective neuroscience. They originate in computer science research about predictive coding which is an efficient technique for data compression. Predictive processing models view the brain as an active stakeholder that is continuously making predictions about the future instead of only passively waiting for and receiving stimulation. (Lee et al. 2021)

The free energy principle (FEP) is a predictive processing model that considers the self-organizing and dynamic nature of a living organism by bringing quantum, statistical and classical mechanics together (Friston et al. 2023). Social, psychological, and environmental factors are considered together with the brain-body dynamic within the predictive model conceptualization. (Bettinger and Friston 2023)

> In summary, predictive coding represents a biologically plausible scheme for updating beliefs about states of the world using sensory samples. (Friston and Frith 2015.)

Following the principles of free energy and self-organization, “homeostasis” has been contextualized within a broader class of “allostatic” dynamics. “Homeostasis” is described as “stability through constancy” whereas “allostasis” is viewed as “stability through change” and the physiological ability to stabilize and regulate processes (i.e. physiological resilience). This is also called the action to restore health when the normal state of the organism has been disturbed. (Bettinger and Friston 2023.)

The energy-conserving idea of FEP is consistent with energy-efficiency of the tensegrity model as the pre-tensioned tensegrity structures automatically assume a position of stable equilibrium (Scarr 2011). The tensegrity model may similarly integrate anatomy from molecular level to the entire body (Scarr 2011; Scarr 2020) as well as the fascial system (Levin et al. 2017).

Research on chronic pain suggests that treatment should be guided by the awareness of the complexity of chronic pain which is always influenced by social, emotional, and biological factors. Models such as biopsychosocial model and enactivist framework have been proposed to address the patient holistically. (Esteves et al. 2022, Banton and Vogel 2024; McDonald and Lowe 2024.)

A holistic approach means considering the patient as a person and the attempt to understand their unique lived experience (Shaw et al. 2022). Enactivist theory that incorporates the FEP has been proposed as a holistic framework for osteopathic and other health care practitioners. (En)active inference is the process by which dynamical systems autonomously adapt to the environment to meet the expectations. Enactivist theory provides an explanatory model that considers an individual as a whole person – inseparable into systems or into physical and mental components. Enactivism is a concept of embodied cognitive science suggesting that mental processes are embodied, embedded, enacted, and extended, known as the 4E approaches. (Esteves et al. 2022, Banton and Vogel 2024.)

5.3 Embodiment and mental imagery

It has been argued that conscious experience is shaped by active inference and rooted in embodied activity (Esteves et al. 2022). Embodiment is a phenomenological concept that rejects mind-body dualism suggesting that the sense of self arises through perception and engagement with the world. Embodiment conveys that understanding and sensemaking of the world is phenomenologically done through the body. Embodied cognition suggests inseparable interconnectedness between the mind, body, and environment. The process of making sense of interoceptive, exteroceptive and proprioceptive information through embodied experience leads to perception. (Shaw et al. 2022.)

Exteroception relates the person to the outer world whereas interoception is the awareness of internal bodily experiences that pre-dates language. Interoception is generated through neuroanatomical pathways and ongoing neurophysiological processes that transmit information of visceral and metabolic processes from organs and tissues to the brain, and vice versa. The brain and the body are not sensed separately but sensing the “self” is a whole-body phenomenon. (Van der Wal in Schleip et al. 2012: 81; Casals-Gutiérrez & Abbey 2020; Shaw et al. 2022.) According to Suksasilp & Garfinkel (2022) Khalsa et al. (2018) present a contemporary definition of interoception as conscious and unconscious levels of sensing, interpreting, and integrating of signals across multiple dimensions (e.g. neural, attentional, and behavioral).

Interoceptive assessment has clinical value since decreased interoception has been discovered in a variety of health problems such as anxiety and chronic pain. Research findings suggest that altered interoceptive processing precedes neurological sensitization leading to inappropriate activity in the autonomous nervus system. This is followed by hypersensitization of the peripheral tissues accompanied by metabolic and neurological processes that underpin chronic pain. Current research proposes that interoceptive processes may be distinguishably mapped across dimensions and bodily axes. Furthermore, interoceptive assessment can inform about the nature of interoceptive deficit (Casals-Gutiérrez & Abbey 2020; Suksasilp & Garfinkel 2022.)

The neurophysiologic definition for proprioception is the ability to sense the position, location, orientation, and movement of the body and its parts. In the past ‘proprioception’ has been more strictly defined as the control of joint position and movement (Van der Wal in Schleip et al. 2012: 81.) There is debate whether proprioception should also be considered interoceptive (Brewer, Murphy, and Bird 2021). Interoception and proprioception are sometimes used interchangeably although differences with the associated neural pathways have been detected. Interoceptive sensations with proprioceptive, exteroceptive, and cognitive aspects are usually associated with anterior insular cortex. The posterior insular cortex is the primary sensory center for interoceptive signals. (Schleip in Schleip et al. 2012: 78, Casals-Gutiérrez & Abbey 2020.) In this study ‘interoception’ includes ‘proprioception’ and both are combined under a broader term of ‘body awareness’ that also carries psychological meaning (Van der Wal in Schleip et al. 2012: 81).

Mental imagery (MI) is a cognitive process meaning mentally envisioning a motor task. MI has been shown to enhance motor and cognitive performance and it is associated with increased body awareness. MI elicits similar brain activation than an overt physical execution of the task. Mental imagery utilizes mainly visual or kinesthetic images in the mind. Visual MI involves mental pictures or scenes associated with the task from either a first-person (i.e. internal) or a third-person (i.e. external) perspective whereas kinesthetic images involve mental images of sensations. It seems that internal perspective induces a significantly higher muscle excitation when compared to external. (Abraham et al. 2020.)

Mental imagery (MI) has primarily focused on muscle tissue but recently a suggestion for fascial mental imagery (FMI) subcategory has been proposed. Fascia-focused motor patterns and mindful movement could specifically facilitate fascial sliding by potentially changing fascial and muscular activation patterns and stimulating the lubrication between fascial fibers and layers. MI offers images to illustrate fascial composition and three-dimensional movement. Furthermore, a fascia-focused movement may have neuro-sensory effects by enhancing neural activation and improving proprioceptive signaling from fascia. Understanding fascial structure may have psychological effects of improving one's internal attention leading to better body awareness. (Abraham et al. 2020.)

Chronic pain is the leading cause of disability worldwide. Physical activity has been acknowledged to improve chronic pain with improvement in overall mental and physical wellbeing and thus improvement in quality of life. (Calatayud et al. 2024.) Movement and increased temperature stimulate the hydration of the tissues (Stecco 2015: 64). Helical movement can potentially aid the visco-elastic properties of connective tissue by creating gentle strains that follow the natural pathways of bones and fascial layers.

Visualization or mental imagery (MI) of helicality can aid the performance of tensegrity-like movement. The combination of mental imagery (MI) and fascial-targeted movement may benefit fascial mobility and thus movement in general. Such an approach could be of relevance for rehabilitation and prevention of different fascia-related conditions, such as fibromyalgia, low back pain, Dupuytren disease, and adhesive capsulitis. (Abraham et al. 2020.)

Combining perception and action usually provides the best outcome. Increasing body-awareness by becoming more aware of the internal states may help the patient change expectations of their physical capacities (Shaw et al. 2022). Enabling and empowering the individual with the realization of their own health potential through tensegral movement. The phenomenological approach can yield great insight and renewal to the study of the human form and body. For it reveals that the body is an instrument of the soul. (Van der Wal 2013.)

6 Purpose, aims, and research objectives

The problem we are currently facing is the complex nature of a biologic organism that consists of multiple nested and hierarchical systems within systems - from microscopic to macroscopic (Ingber 2003b). The biotensegrity model acknowledges the structure and function of a living organism and fits with the holistic view of human body. Despite the increasing acceptance among the professionals in bodywork, movement, and other forms of therapies, there are many who are puzzled about how to meaningfully apply it, perhaps due to lack of practical models. (Swanson II 2013; Hohenschurtz-Schmidt et. al 2016; Scarr 2020.)

The purpose of this thesis is to raise more interest towards the biotensegrity model in education and practice of osteopathy and other bodywork and movement therapies hypothetically for the benefit of the patients' wellbeing.
The aim of this study is to introduce the reader to the knowledge base and explore possible future concepts of the biotensegrity model in health care, focusing on a movement therapist (Hohenschurz-Schmidt et al. 2016) point of view.

Hohenschurz-Schmidt et al. (2016) describe in their qualitative study how the idea of tensegrity can inform a manual therapy practice such as osteopathy. In their analysis four main approaches of how to utilize the tensegrity approach were identified. According to that categorization, a movement therapist is a practitioner who applies (bio)tensegrity principles and takes on an interest in the quality of movement. A movement therapist ponders on what a tensegrity-like movement pattern could look like. However, Hohenschurz-Schmidt et al. (2016) point out that the (bio)tensegrity model - when applied in a clinical setting - lacks models at a macro level.

Since the abovementioned question has received little to none research attention to date, the purpose of this study is to apply biotensegrity principles from a movement therapist perspective and develop a tensegrity-like macro-movement model. The approach of a 'movement therapist' links "fascia-friendliness" with tensegrity-like movement patterns. This approach sees the important role of connective tissue matrix in human posture and locomotion and seeks to take it into account in practical applications. (Scarr 2011; Hohenschurz-Schmidt et al. 2016.) Although categorized to belong more to a 'manual therapist' approach (Hohenschurz-Schmidt 2016), it can be argued that visualization of tensional patterns in tissues is a major interest also in a 'movement therapist' point of view.

The technical research question of the study is: What could a tensegrity-like movement of the head look like? The topic of this study follows the author's personal interests in the structure and function of the cranio-cervical complex and resonates with her background in dance. This study is hypothesized to interest health care practitioners and educators who are curious of the biotensegrity model and its potential applications and implications on the overall scientific base of health care practices.

7 Materials and Methods

This auto-ethnographical thesis explores helical biotensegrity by visualizing multiplanar and continuous movement patterns in the region of the head hypothesized to be tensegral and thus fascia friendly.

Qualitative approaches have been accepted as empirical methods capturing phenomena which would be poorly understood through quantitative methods (Poulos 2021). Qualitative studies are explorations on “how?” and “why?” questions that are related to social or human problems or phenomena. Qualitative studies seek to understand and make sense of them by generating theories about new or poorly understood processes or situations. (O’Brien et al. 2014.)

The phenomenological approach sees the human body as a process (‘motion’). Motion is primary, form is secondary. The form arises out of motion. Mind and body are an inseparable two-folded entity created by the triune of mind-motion-matter. The whole body is an act of mind and consciousness. (Van der Wal 2013.) Van der Wal (2013) and Banton & Vogel (2024) suggest taking a phenomenological stance against the Cartesian mind-body dualism as well as the modern monism that reduces human experience into brain activity. The phenomenological stance takes on the role of a participant instead of an observer. According to the phenomenological approach the sensed experience is the primary reality. Phenomenologically ‘being’ is embodied participation in the Lifeworld which is the phenomenal world experienced as a matrix of meanings (Banton & Vogel 2024).

Auto-ethnography is a phenomenological qualitative research method that uses the researcher’s personal lived experience to describe and critique cultural beliefs and practices. By balancing intellectual and methodological rigor, emotion and creativity auto-ethnography interprets lived experience and merges the insights of the researcher into a larger context. Auto-ethnography is an observational, participatory, and reflexive method of data-driven narrative research. (Schroeder 2017, Poulos 2021.)

From a phenomenological standpoint, being human is being hermeneutic: for humans, participation in the world is a form of sense-making which is said to create meaning. The process of sense-making and the resulting emergence of meaning is conveyed by the concept of hermeneutics. (Banton & Vogel 2024.) Originally the term hermeneutics refers to the art of interpreting written texts such as holy scriptures. The interpretation considers the era when the text was written and the influence current languages and cultures. The key problem of hermeneutics is to decide whether the interpretation is correct. The hermeneutic process includes the evaluation of the interpretation by developing a criterion to guide the decision making (Friston & Frith, 2015).

Gadamer (1979, 350) states that all understanding is interpretation, and all interpretation takes place in the medium of a language which would allow the object to come into words. Understanding happens in the interpreter's own language. However, research from the fields of clinical psychology, psychotherapy, dance, and architecture, has proposed that language has evolved from the embodied capacity to create corporeal concepts of how we map the world on our bodies. Therefore, both concrete and abstract concepts can be created, experienced, and understood with and through the body even without verbal expression which is to follow Husserl's and Merleau-Ponty's phenomenological approach. (Banton & Vogel 2024.)

7.1 Visual methods

Human movement is a complex phenomenon that involves multiple autonomic and voluntary neural circuits that are associated with motor, sensory, and cognitive functions. Movement is therefore at the juxtaposition of conscious and unconscious actions. (Abraham et al. 2020.)

Banks and Zeitlyn (2015: 14) suggest that visual methods are indicated when the subject of research is image-based or otherwise inherently visual. They argue that visual methods are especially adapted for investigations involving particularly visual or embodied practice, such as dance, sport, or craft activity. As presented in the work of Cleland Silva & Fonseca Silva (2022: 28-29), Victor & Boynton (1998: 22) state that tacit knowledge is easier to show than explain. Craftspeople with tacit knowledge rely on the holistic process of the mind and body in their work. The inherent sense of “knowing” is more a reflection of their tacit knowledge than the ability to reason why they know. This is in harmony with the abovementioned notion by Banton & Vogel (2024) of how understanding is possible without verbal expression.

Visual methods can be used to tell a story, to elicit a story or as the story itself. Visual methods include a direct analysis of the things we see (van den Scott 2018). According to Richard & Lahman (2015) visuals can be used as a representation of inherent meaning. In contemporary qualitative research, visual methods are a means to elicit emotional and cognitive information.

7.2 Data gathering

Using visual methods was considered to best serve the attempt to create a visual model in exploring the research question: What could a tensegrity-like movement of the head look like? The method of this study was visual hermeneutic auto-ethnography that incorporated embodied mental imagery of helical movement to aid interoception and proprioception.

The study began by using MI for visualizing each movement pattern attempting to focus on the internal (first-person) perspective. The visual data was produced by recording the movement patterns by a smart phone. The video recording captured movement in the three cardinal planes: sagittal, frontal, and transverse/horizontal.

Single plane movements (flexion, extension, and lateral flexions) were first recorded and analyzed for the comparison of the multiplanar movements that were the main focus of the study. The recording of the movement patterns was done from the side, from the front or from behind and from the above representing three cardinal planes: the sagittal, the frontal and the horizontal. The trajectories of the top of the head (vertex) and the jaw (occlusal plane) were followed representing the neurocranium and the viscerocranium. To aid the movement tracking of the viscerocranium, a thin object was held between the front teeth.

To explore the three-dimensional continuous movement of the head through all three cardinal planes was performed in upright seated position. The movement sequence began with a lateral flexion to one side leading into flexion and was followed by lateral flexion to the opposite side finishing with extension, and again into a lateral flexion movement looping through the whole sequence approximately three times.

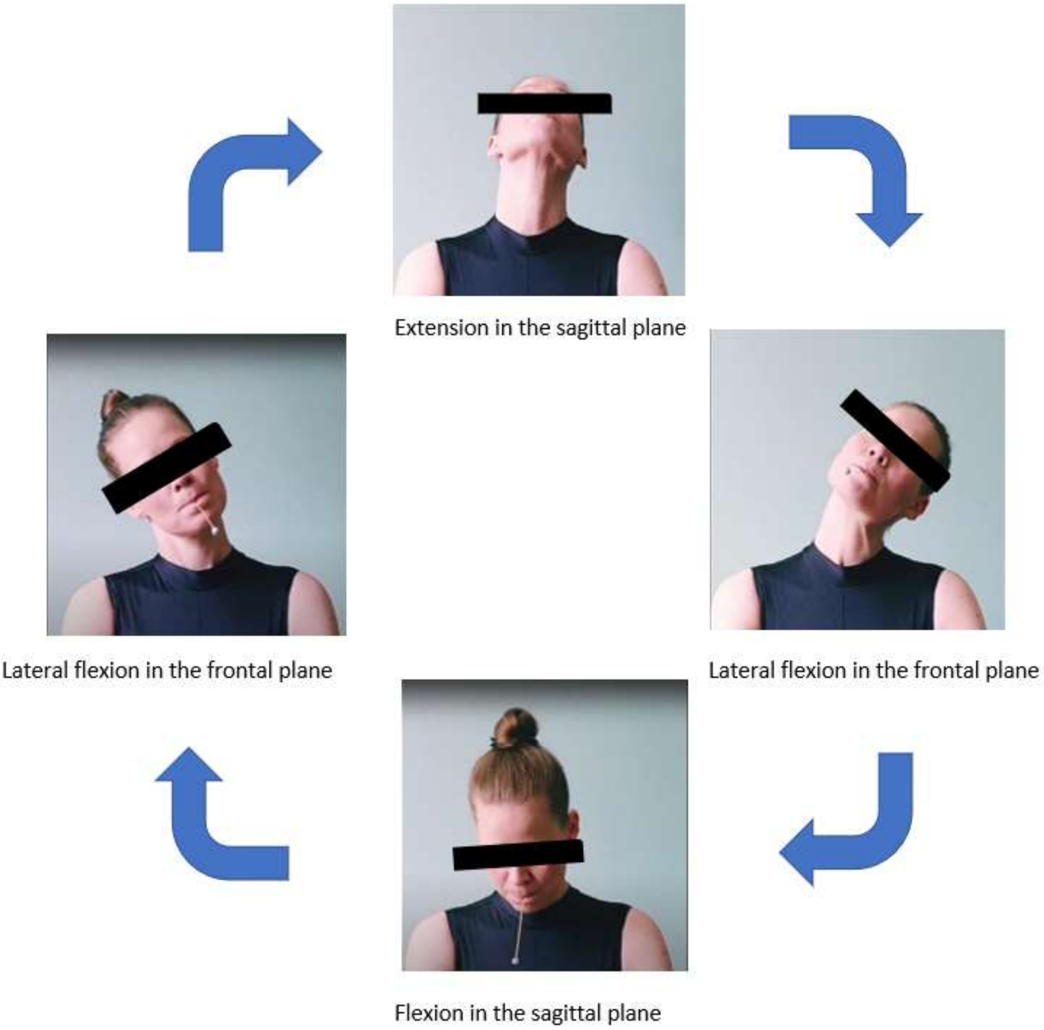

Figure 1: A movement pattern sequence of the cranio-cervical complex through three cardinal planes.

The visual data was further processed using a video editing program. To better track the neurocranium (top of the head/vertex) a marker was added. Still frames were captured from the videos, labeled, and printed on paper. The prints of the still frames were then placed on a glass board one by one with a light shining from below. The movement of the neurocranium and viscerocranium (jaw) was tracked and drawn on representing the continuum of the movement through each cardinal plane a separate sheet of paper.

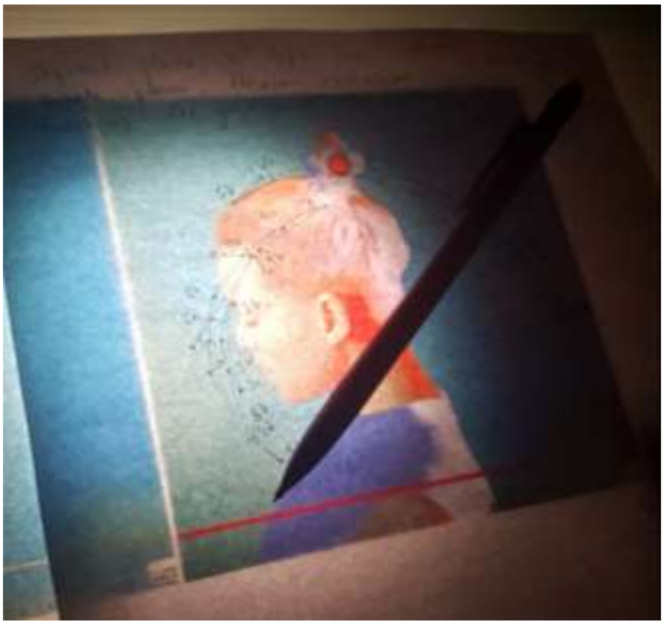

Figure 2. The analyzing process of the single plane movement of flexion in the sagittal plane.

Labeling the reference points according to the label of the still frame along aided in identifying the correct path forming the overall pattern. For example, “8b” is the 8. point along the trajectory of the second loop of the movement sequence.

After the creation of the multiplanar movement pattern drawings, the insights were applied in the video production where both trajectories of the viscero and neurocranium were illustrated.

8 Results

The main results of visual representations of the continuous multiplanar movement patterns in the craniofacial region are presented here. The visual data of the single plane movement patterns are presented in Appendix 1.

The representations of multiplanar movement patterns of the neurocranium were created in frontal, sagittal and horizontal planes. The neurocranium shows elliptical movement pattern in both sagittal and frontal view. The trajectory was tracked using 39 and 38 reference points.

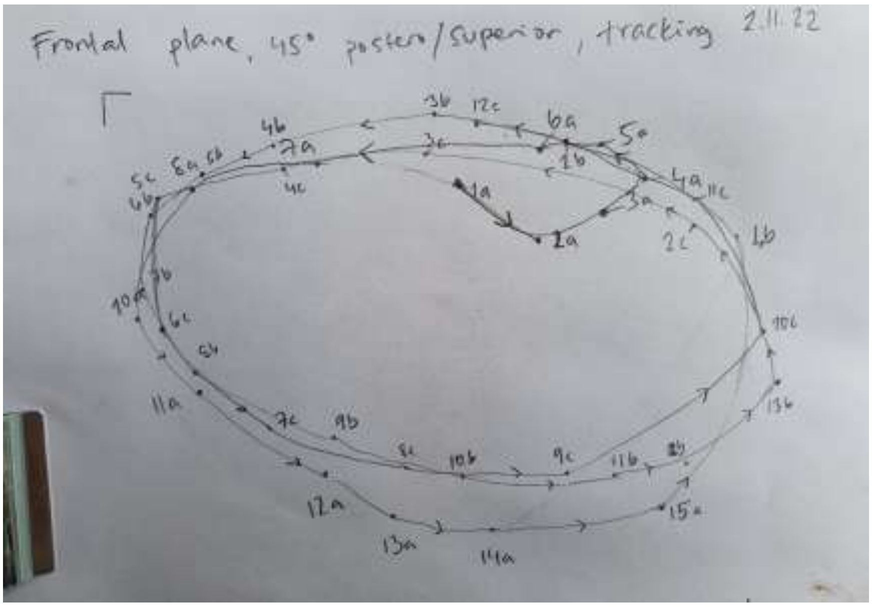

Figure 3. A visual representation of the multiplanar movement of the neurocranium in the frontal plane.

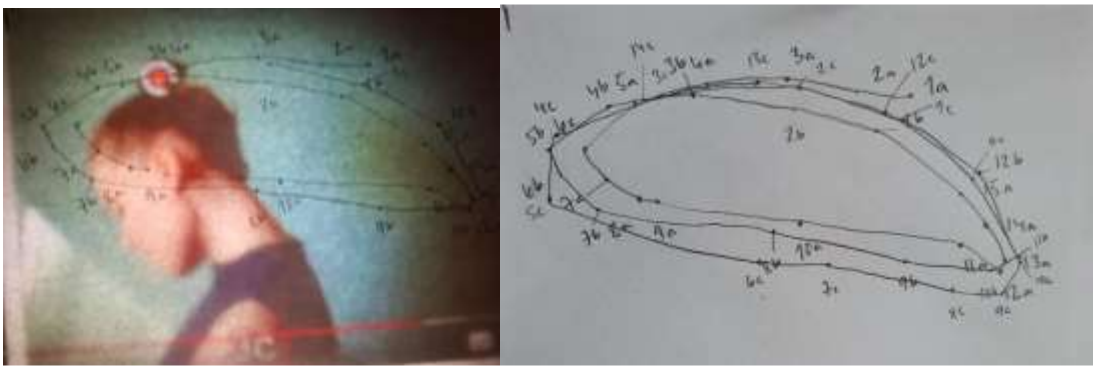

Figure 4. Visual representations of the multiplanar movement pattern in the sagittal plane.

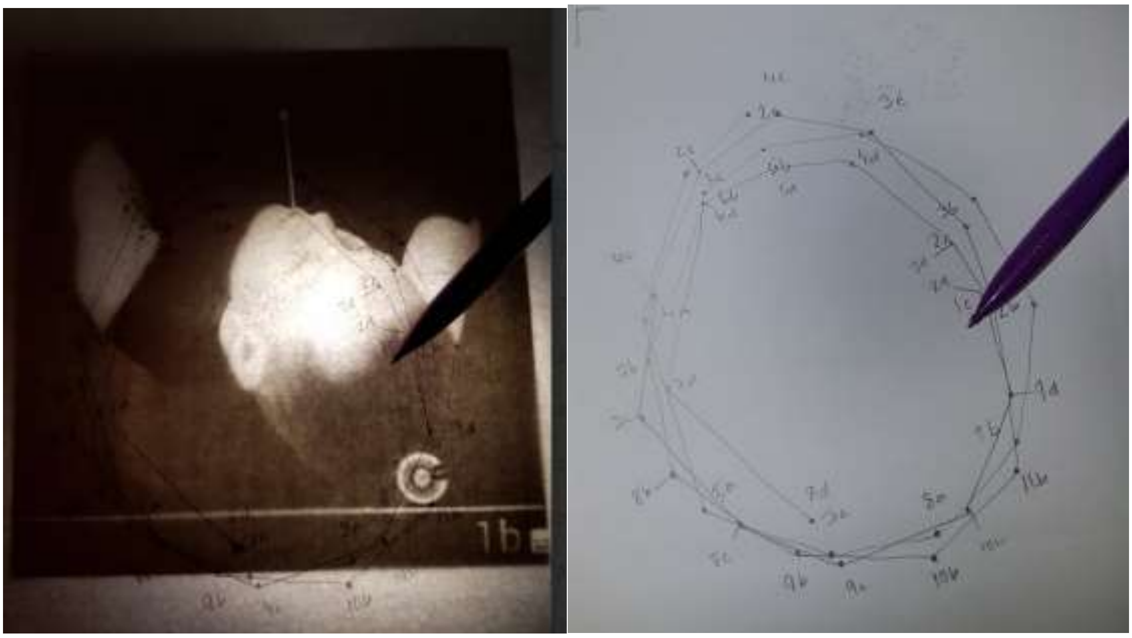

Figure 5. Visual representations of multiplanar movement of the neurocranium in the horizontal plane.

The multiplanar movement pattern of the neurocranium in the horizontal plane using 31 reference points approximated a circle. The multiplanar movement of the viscerocranium in the sagittal plane showed crossing of the movement lines in the middle of the pattern when 39 reference points were used.

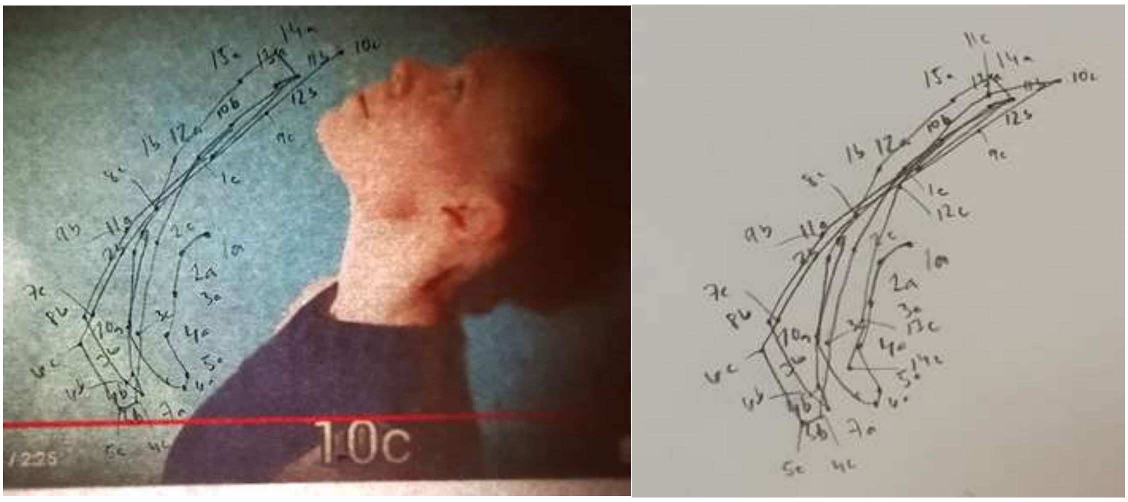

Figure 6. Visual representations of the multiplanar movement of the viscerocranium in the sagittal plane.

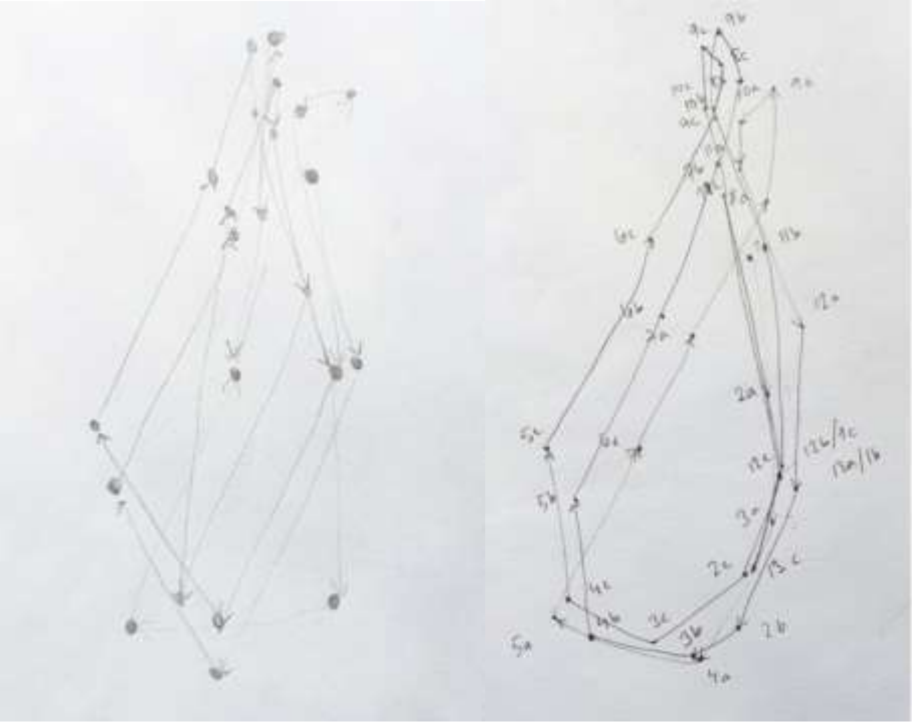

Figure 7. Visual representations of the multiplanar movement of the viscerocranium in the frontal plane with 25 and 36 reference points.

At first the multiplanar movement pattern of the viscerocranium seemed a vertical ellipse but with higher resolution a figure eight emerged. Next, the camera angle was changed from a 90-degree angle to a 45-degree angle giving a more superior viewpoint and to better capture the movement of the top half of the figure eight since it seemed to be associated with the extension part of the movement sequence. Another change in the parameters was shortening of the marker allowing less contraction from the temporo-mandibular joint making it easier to maintain the stability of the marker throughout the movement sequence.

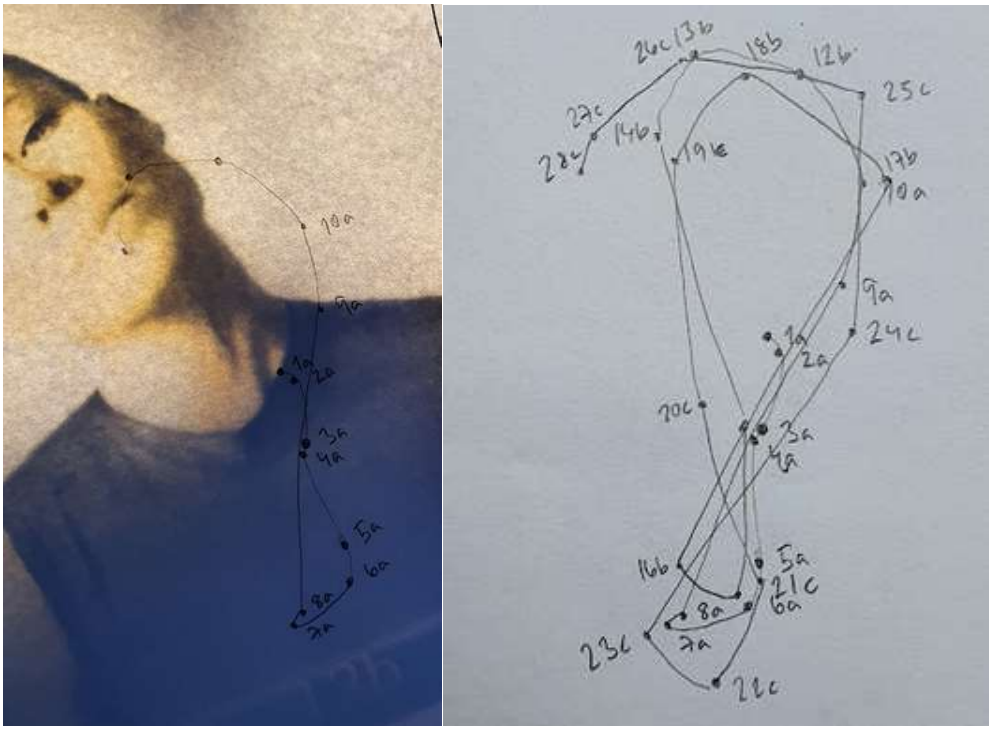

Figure 8. Visual representations of the multiplanar movement of the viscerocranium from the fronto-superior view.

The analysis of the fronto-superior plane was done using 28 reference points that resulted in more symmetrical figure eight pattern of the viscerocranium.

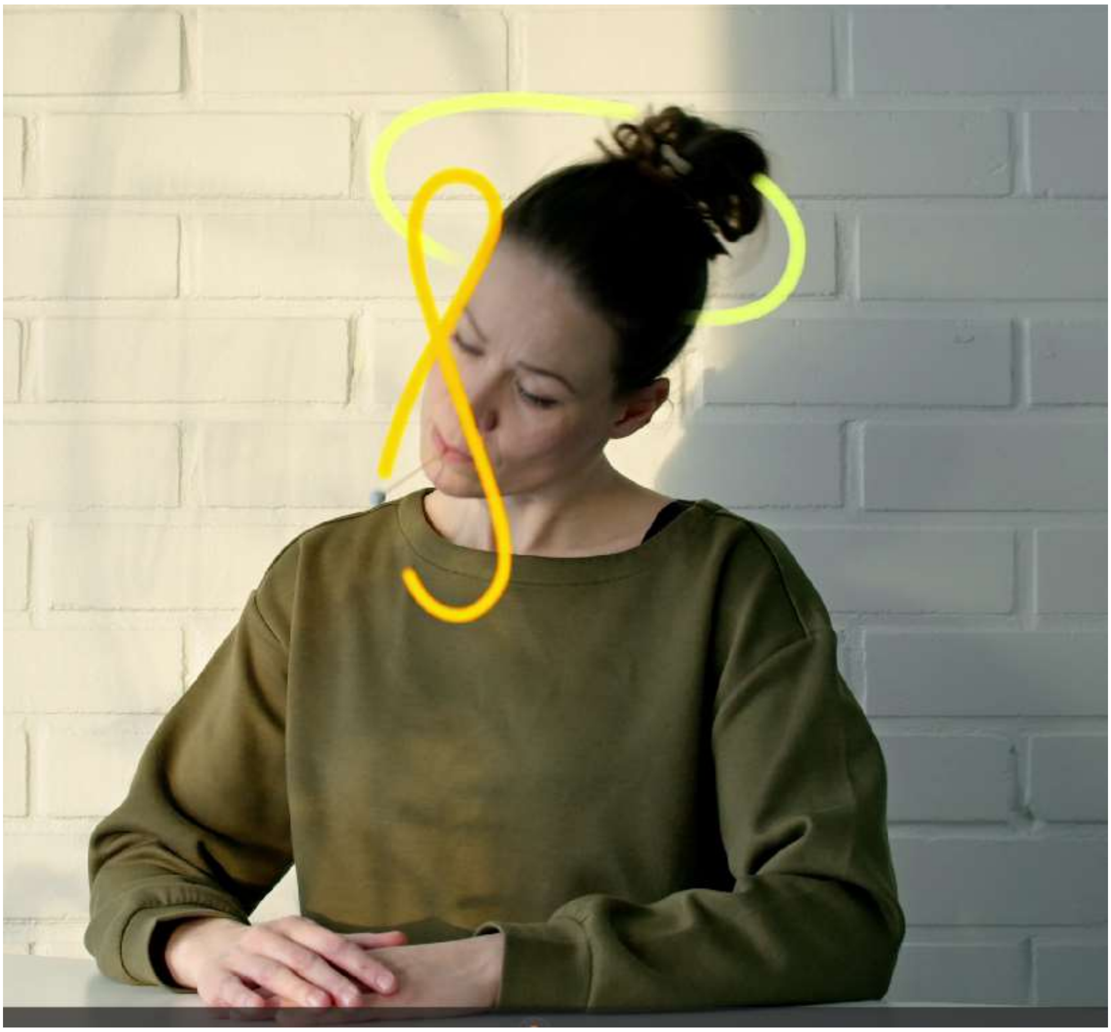

Figure 9. Helicoid movement pattern of the head (Newell 2024).

The visual exploration of the multiplanar movement of the head resulted in a video production illustrating the circular movement pattern of the viscerocranium and the figure eight movement pattern of the viscerocranium.

9 Discussion

The hermeneutic exploration of tensegrity-like movement included cognitive proprioceptive and interoceptive observations of the embodied experience during the performance of the movement sequence. Performing the 3D movement pattern involved both sensing and sense-making to navigate the unknown in the attempt to map the tensegral helical pathway on the body.

When attempting to perform the continuous multiplanar movement sequence smoothly it was noted that initially the focus was more directed at the top of the head (the vertex) using external perspective. When repeating the circle of the head more than two times the focus then shifted to the tip of the chin and the helical pattern of figure eight became easier to visualize internally. Furthermore, when focusing on the movement of the chin it was felt to activate and incorporate a larger portion of the ventral structures superficial to the sternum and the hyoid. A helical movement by focusing on the chin created a lifting effect that increased smoothness when moving through different movement planes. This seemed to have a positive effect on breathing. The ease of breath further benefited the engagement with the internal perspective. The embodied experience seems to be in line with the proposition by Abraham et al. (2020) that internal perspective during the movement performance induces a significantly higher excitation of muscles in comparison to external perspective. Visual methods enable people to see things they have always known in a new way (Banks and Zeitlyn 2001: 95). Shifting the inner focus on the helical movement felt very natural and enhanced the sense of embeddedness in the movement creation.

Figure eight is more complex form than a circle allowing 720 degrees of rotation compared to 360 degrees of a circle. Figure eight movement is hypothesized to localize internally at the cranial base which is likely considering the arthrokinematics of the four articular surfaces of occipito-atlantis junction (Schuenke, Schulte, and Schumacher 2011: 11). It is assumed that space in the joint gap allows fluid-like movement like demonstrated in the knee joint (Levin et al. 2017).

Abraham et al. (2020) suggest the combination of mental imagery (MI) and fascial-targeted movement may benefit fascial mobility and thus movement in general. Reflecting on the observations during the exploration of tensegrity-like movement leads into a thought of mental imagery of the helical movement.

Considering embryologic development aids to further explore the pathways provided by the bones of the skull. A human skull can be divided into two main parts: neurocranium (the cranial vault that holds the brain) and viscerocranium (facial bones and hyoid bone) This division is a close representation of the embryonic origin of the craniofacial bones. The bones of the neurocranium origin mostly from the somitic mesoderm and the bones of the viscerocranium are derived from the neural crest mesenchyme. The ossification of cranial bones can be formed by intramembranous ossification or endochondral ossification or by the combination of them. Sphenoid bone, occipital bone, and temporal bones that for the midline of neurocranium and viscerocranium are derived from both embryonic origins and are formed by both intramembranous and endochondral ossification. (Schuenke et al. 2011: 3.)

Bones are said to follow complex helical pathways with all the other tissues (Levin et al. (2017). There may be a connection linking the observed helical movement of the head and the forces underlying embryonic development of the craniofacial bones thus illustrating the scale free manifestation of helical movement pattern as a fundamental phenomenon that seconds Van der Wal's (2013) notion that form is secondary to motion. The biotensegrity model explains the embodied experience of orienting interoception where the leader of the movement is not the top of the head but in fact the tip of the chin.

9.1 Critical assessment of the study

The goal of this interpretivist auto-ethnographic study was not to claim objectivity, nor should the results be considered generalizable per se. The development of evaluation criteria for autoethnographies has met resistance since objective criteria for subjective work is seen to be a by-product of the positivist research paradigm. Nevertheless, Schroeder (in Deitering et al. 2017) suggests possible criteria for review and evaluation of autoethnographies: Revealing the self (auto), Exploring culture/society (ethno), Storycraft (graphy), Ethics, Unclassified Criteria.

This study uses the author's personal experience and observations as a starting point for further exploration. The personal embodied experience as described in the methods and results sections seeks to bring value to people in similar situations when they might struggle to find meaning in a movement pattern.

This study explored the helical biotensegrity model in the context of healthcare practice and the development of related ideas and concepts over time. The knowledge base of helical biotensegrity for this study was gathered mostly using ScienceDirect and PubMed databases representing professions in many fields. The search strategy was not standardized. The articles were sampled based on purposefulness and conveniency. Research examples were drawn for example from engineering, medicine, architecture, and osteopathy while maintaining the focus on the research questions. The author does not claim expertise in any of the fields, nor that the theoretical background presented here is all-encompassing. The manuscript may have internal contradictions and tensions due to possible misconceptions and misunderstandings. Future work is needed to improve the descriptions, definitions and classifications based on feedback and further exploration.

The emphasis on the storycraft in this study is ‘showing’ more than ‘telling’ long personal stories. The visual data of movement pattern reflects the theoretical framework and is complemented with an interoceptive interpretation. The checklists and guidelines SRQR (O’Brien, Harris, Beckman, Reed and Cook 2014) and COREQ (Tong, Sainsbury and Graig 2007) for qualitative research were used when applicable to the design of this study to ensure good research integrity.

One common goal that autoethnographies share is to give momentum to prompt action both in the author and in the readers by awakening understanding, motivation, and transformation (Schroeder in Deitering et al. 2017). For the author this study satisfied the goal and furthermore anticipated the potentiality and value of the new paradigms in health care arena. It is only the readers who can say if this autoethnographic exploration made sense for them or brought up any valuable meanings.

9.2 Implications for policy and further research

Further research and systematic literature reviews about biotensegrity would be needed to further establish the relevance of the concept in varying fields. Utilizing technological solutions would allow more accurate kinematic analysis of the helical movement and development of more detailed movement models and applications.
Biotensegrity can provide interesting frontiers in health care that can point new directions beyond the paradigm of traditional reductionist biomechanical approach that probably requires adjustments considering osteopathic standards and guidelines in education and practice.

10 Conclusion

It seems that the current traditional biomechanical approach that is also part of osteopathic training (WHO 2010; CEN 2015) does not accurately consider the complexity of a biologic organism with its multiple nested and hierarchical systems (Ingber 2003b; Sharkey 2021). This has led to inaccurate and insufficient research and health care practice methods jeopardizing the holistic approach and professional identity of osteopathy (Scarr 2020; Shaw et al. 2022; Esteves et al. 2022; Thomson and MacMillan 2023).

Newtonian mechanics that underlie traditional biomechanics serve as an educational starting point. However, traditional biomechanics disregard e.g. the active role of the fascial system rendering too reductionist and simplistic model on its own and should be complemented with concepts such as the biotensegrity model and the fascial system that are more applicable to living biological organisms (Van der Wal 2015; Levin et al. 2017; Sharkey 2021). The fascial matrix is a system of continuity and connectivity. According to functional definition it can be viewed as a metasystem enabling all body systems to operate in an integrated manner. (Langevin 2006; Van Der Wal 2015; 2020.)

This thesis intended to clarify the nomenclature of biotensegrity, and present examples of related mathematical and macro level models requested by Hanaor (2012), Hohenschurtz-Schmidt et al. (2016) and Scarr (2020) and could be applied in osteopathy and other health care practices. The focus was to understand the underlying physiological processes, especially in the connective tissue matrix that can improve the quality of movement (Stecco 2015: 60, 95, 138; Wilke et al. 2017). The method of this thesis was a visual auto-ethnography that looked at continuous and multiplanar movement patterns of the head. The visual and phenomenological exploration on biotensegral movement illustrated the helical movement pattern of the viscerocranium during three-dimensional movement sequence together with the expected circular motion of the neurocranium supporting the theory of underlying biotensegrity structure.

Biotensegrity is a structural system that serves as an energy-efficient solution for biologic organisms. Biotensegrity model acknowledges the connective tissue as a vital member of the sensorimotor system. (Levin 1995; Ingber 2003a; Scarr 2011; Sharkey 2021.) Biotensegrity and fascial system consider the properties of biological structures like continuity, non-linearity and helicality that are in harmony with the physics of self-organization and self-preservation. (Scarr 2011; Torday et al. 2024).

Understanding the fundamental scale free helical motion in the living tissues may aid the osteopathic or other health care practitioners in helping their patients move better and thus improve their various health and pain conditions. (Levin et al. 2017; Hohenschurtz-Schmidt et. al 2016; Calatayud et al. 2024.) Chronic pain, adhesive capsulitis, and overuse syndromes and other non-specific pain conditions are fascia-related and can harmfully alter the body-wide mechanosensitive signaling system that contributes to motor (i.e. movement), sensory-cognitive and wound regulation functions (Stecco & Schleip 2016; Zügel et al. 2018; Abraham et al. 2020).

Human movement is a complex phenomenon that involves motor, sensory, and cognitive functions at conscious and subconscious level (Abraham et al. 2020). Movement and increased temperature stimulate the hydration of the tissues (Stecco 2015: 64) and improve chronic pain (Calatayud et al. 2024). Helicality as a property seems to be a phenomenon affecting human movement at all levels (Scarr 2011; Torrent-Guasp et al. 2005; Torday et al. 2024). Helical movement can potentially further aid the visco-elastic properties of connective tissue by creating gentle strains that follow the natural pathways of bones and fascial layers. Visualization of fascial-targeted, helical, and tensegrity-like movement may enhance interoception and benefit fascial mobility thus improving movement in general (Abraham et al. 2020).

Emerging research - that technological imaging speeds up - has revealed new insights in the microstructure of human anatomy. These insights suggest that the rapid physiological processes in the microstructure are fundamental in supporting the homeostasis of the organism. (Langevin 2006; Guimberteau in Schleip et al. 2012: 143-145; Saha and Maiti 2016; Torday et al. 2024.) All efforts should strive to enhance the allostasis which is the body's ability to adjust to perceived and interpreted stressors.

Osteopathic health care approach is to focus on health and the healing potential. An osteopathic practitioner should be able to counsel and provide advice on exercise and self-care. (WHO 2010; CEN 2015). The holistic approach should remain constant throughout the osteopathic reasoning and decision making and not shift into biomedical and reductionist approach (Thomson and MacMillan 2022). The application of the helical biotensegrity model in osteopathy is in harmony with its tenets that human being possesses an intrinsic capacity for self-healing. The human body is a functional unit with interrelated parts, structure, and function at all levels. (WHO 2010; CEN 2015.)

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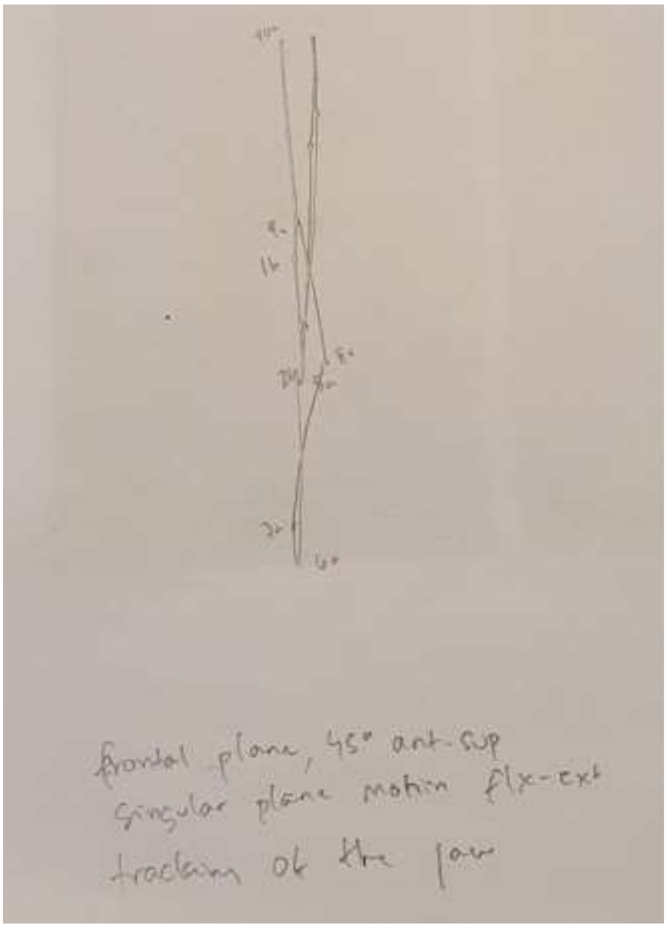
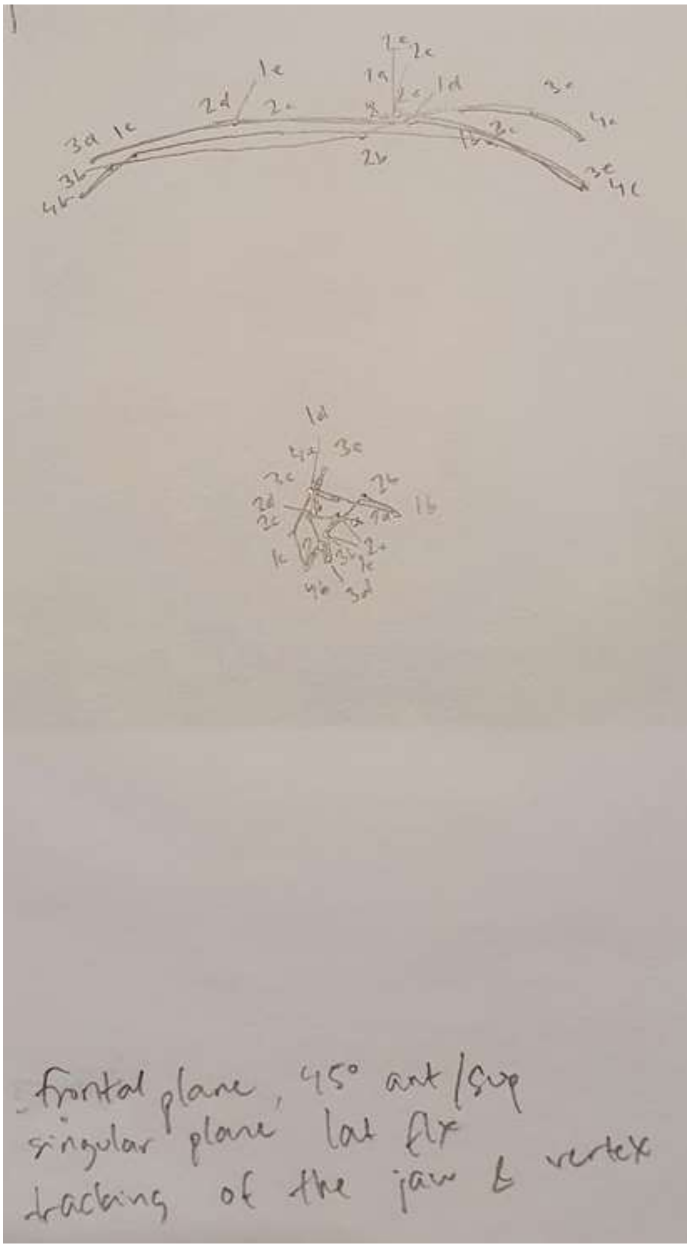
The visual representations of the single plane movement patterns

Tracking the single plane movement of the jaw (neurocranium) in flexion and extension along the frontal plane using 10 reference points.



Movement pattern of lateral flexion along the frontal plane tracking the neurocranium (top) and viscerocranium (bottom) using 12 reference points.



Single plane movement of flexion and extension along the sagittal plane using 30 reference points. On the left is the trajectory of the jaw (viscerocranium) and on the right the top of the head/vertex (neurocranium).