

THE EFFECT OF LONG AXIS MANIPULATION OF THE THIRD METACARPOPHALANGEAL JOINT ON ARTICULAR SURFACE SEPARATION, PERI-ARTICULAR SOFT TISSUE MOVEMENT AND JOINT CAVITATION

By

WILLIAM PETER FOGWELL

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Durban University of Technology

I, William Peter Fogwell, do hereby declare that this dissertation is representative of my own work in both conception and execution (except where acknowledgements indicate to the contrary)

Date: _____

William Peter Fogwell

Approved for Examination

Date: _____

Dr. J. Shaik

M. Tech. Chiro., M. Med. Sci. (SM), MCASA

Supervisor

DEDICATION

I dedicate this dissertation to my Lord Jesus Christ, my all.

I also dedicate this dissertation to my incredible wife and best friend, Lise-Marié Fogwell and our beautiful children, Olivia and Thomas. Thank you for the unconditional love and support.

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ABSTRACT

Aim: To determine the effect of long axis manipulation of the third metacarpophalangeal joint (MCP) on articular surface separation, peri-articular soft tissue movement and joint cavitation.

Participants: Forty two right-handed healthy individuals between 18 and 28 years of age from the Durban University of Technology campuses, KwaZulu Natal.

Methodology: Written informed consent was obtained from each participant. A case history, physical examination and a hand and wrist orthopaedic assessment was conducted for each participant. Study specific data, such as sex, age, height and weight were recorded. A diagnostic ultrasound (US) scan was done to the left third MCP joint for each participant while distractive manipulation was applied to the joint. The presence or absence of audible release was noted and the tension levels applied to the joint was measured with a digital tension meter. Joint surface separation (JSS), synovial membrane position (SMP), gas bubble presence and location were assessed on the US recordings at baseline, just prior to cavitation, at maximum traction and in the post-traction resting joint.

IBM SPSS version 20 was used to analyse the data. Independent sample t-tests were used to compare the means between the two groups and the associations were compared using Pearson's chi square tests. A p value <0.05 was considered as statistically significant.

Results: Long axis manipulation resulted in audible release in 22 of the participants (Group 1) and no audible release in 20 of the participants (Group 2). No significant difference in joint surface separation or the synovial membrane position could be established between MCP joints that cavitated and MCP joints that did not cavitate at the baseline, as well as in maximum traction and in the post-procedure resting joint ($p > 0.05$; t-test). Hyperechoic gas bubbles were present in 21 of the 22 participants of Group 1 and no gas bubbles could be visualised in the participants in Group 2. The presence of intra-articular hyperechoic gas bubbles was highly associated with audible release ($p < 0.001$; Pearson's chi square test).

Due to the predefined features of cavitation, gas bubble inception was could not be detected in the Group 1 participants prior to cavitation. In Group 1, 95.5% of the gas bubbles were present in the middle third of the joint at maximum traction. At the post traction resting joint evaluation, no gas bubble was evident in 42.9% ($n = 9$) of the joints; 42.9% ($n = 9$) indicated bubbles were present only in the dorsal third, whilst 9.5% ($n = 2$) presented bubbles in the middle and dorsal third; and in one case gas bubbles were seen in the dorsal, middle and ventral thirds of the joint space. The mean manipulative force recorded in participants in

which gas bubble inception took place during manipulation was 5.7 kg, and in those with no gas bubble inception was 12 kg. There was a significant difference between the mean traction force applied to those with and to those without a gas bubble appearance ($p < 0.001$; t-test).

Conclusion: No significant differences were observed between the cavitation and non-cavitation groups for the joint surface separation and synovial membrane movement at various stages of manipulation. A significant association was established between the audible release of a joint that was manipulated and the appearance of intra-articular gas bubbles or micro-bubbles. The mean traction force that was required to cause cavitation was significantly lower than the force to which joints with no cavitation were tensioned. The findings concur with those of previous studies that cavitation is a necessary component of joint manipulation.

LIST OF SYMBOLS AND ABBREVIATIONS

>:	greater than
<:	less than
°:	degrees
~:	approximately
±:	plus-minus
µm:	micrometre
3D:	three dimensional
A-P:	Anterior to posterior
BMI:	Body mass index
CDC:	Chiropractic Day Clinic
cm:	centimetre
CT:	Computed tomography
DUT:	Durban University of Technology
etc.:	and so on
g:	grams
HA:	Hyaluronic acid
Ha:	Alternate hypothesis
IBM:	International Business Machines Corporation
i.e.:	namely
JSS:	Joint surface separation
kg:	kilograms
kg/m²:	kilograms per metre squared

lb:	pound
m:	metres
MCP:	Metacarpophalangeal joint
mg/ml:	Milligrams per millilitre
MHz:	Megahertz
min:	Minutes
mm:	Millimetres
MRI:	Magnetic resonance imaging
ms:	milliseconds
<i>n</i>:	Sample size or count
N/A:	Not applicable or Not available
PA:	Posterior to anterior
SD:	Standard deviation
sec:	seconds
SF:	Synovial fluid
SMP:	Synovial membrane position
SOAPE:	Subjective, Objective, Assessment, Plan and Education
SPSS:	Statistical Package for the Social Sciences
US:	Ultrasound
USA:	United States of America
viz:	Namely
yrs:	Years

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CHAPTER ONE

INTRODUCTION

1.1. INTRODUCTION TO THE STUDY

Joint manipulation is a therapeutic intervention utilised by chiropractors and other manual therapists in the treatment of musculoskeletal disorders (Bergmann and Peterson, 2011). It is typically a passive manual manoeuvre with a specifically directed impulse to a joint near or at the end of the joint physiological range of motion and is regularly associated with an audible crack or pop (Sandoz, 1976).

The audible release i.e. the audible crack heard during joint manipulation is thought to be due to synovial fluid (SF) cavitation in the joint (Unsworth et al., 1971), a phenomenon which is commonly believed to signify that a technically successful manipulation has been administered to a joint (Sandoz, 1976; Mierau et al., 1988; Brodeur, 1995; Reggars, 1999). It has been suggested that joint cavitation may be the only truly distinguishing feature that differentiates manipulation from other forms of manual therapy (Evans and Breen, 2006). The effects of joint manipulation are thought to be both mechanical and neurophysiologic (Pickar, 2002). Joint manipulation is reported to cause relaxation of hypertonic muscle by stimulating sensory nerve endings in the joint capsule and musculotendinous structures and the disruption of articular or peri-articular adhesions because of its effects on articular and peri-articular soft tissue structures (Shekelle, 1994; Evans, 2002). However, there is a paucity of literature on the behaviour of the synovium, joint capsule and the surrounding peri-articular soft tissue during joint manipulation and its associated SF cavitation. Some models propose that once the manipulative force overcomes the elastic limit of the capsular ligament of the joint, the capsule snaps away from the SF resulting in cavitation (Sandoz, 1976; Brodeur, 1995). To date his model has not been verified experimentally, but radiographic studies by Roston and Haines (1947) and Mierau et al. (1988) indicate that there might be merit to this theory.

Experimental investigations have shown that distractive manipulation of the metacarpophalangeal (MCP) joint is a reliable method to cause cavitation and that joint cavitation is associated with an audible release, which is considered to be an abrupt separation of the joint surfaces and gas bubble formation within the joint (Roston and Haines, 1947; Semlak and Ferguson Jr, 1970; Unsworth et al., 1971; Mierau et al., 1988; Watson and Mollan, 1990). After successful cavitation the joint enters a refractory period during which no further cavitation can be elicited. This period, which can last up to 30 minutes in the MCP

joint, is thought to be related to the time required for residual gas micro-bubbles to be reabsorbed into the SF (Roston and Haines, 1947; Unsworth et al., 1971). The gas present in the joint space due to cavitation is visible as a radiolucent space in plain film radiographs and as hyperechoic foci in diagnostic ultrasound images (Mierau et al., 1988; Malghem et al., 2011). Diagnostic ultrasound can be used to visualise the joint capsule, synovium, soft tissue structures and the superficial cartilage of the MCP joint that is theoretically affected by joint cavitation (McNally, 2008).

There is growing evidence that joint manipulation is an effective therapeutic modality in the treatment of non-pathological low back pain and neck pain (Gross et al., 2010; Rubinstein et al., 2011). Even though joint manipulation is gaining popularity with physiotherapists, medical practitioners and podiatrists (Fryer et al., 2002), the level of acceptance remains low among orthodox primary health care practitioners (Sewitch et al., 2008). Joint manipulation as an intervention is closely associated with the chiropractic profession and acceptance of joint manipulation has been marred because of the historic philosophical differences between the medical and chiropractic professions; and because of perceived dangers associated with joint manipulation (Leach, 2004). A better understanding of the anatomical effects of joint manipulation can improve the acceptance of this therapeutic intervention by the scientific and healthcare communities; and it may also help to improve the rationale for using joint manipulation by manual therapists in certain clinical conditions. Current literature is very old and a fresh approach is required to further the knowledge base related to the possible mechanical effects of manipulation. Contemporary ultrasound allows for a better evaluation of joint, thus facilitating innovative research in the area. Therefore, the aim of this study is to determine and measure the effect of long axis manipulation of the third MCP on articular surface separation, peri-articular soft tissue movement and joint cavitation.

1.2. AIM AND OBJECTIVES OF THE STUDY

1.2.1. Aim of the Study

The aim of this study is to describe and measure the effect of long axis manipulation of the third MCP joint on articular surface separation and soft tissue movement, and to determine the effect of long axis manipulation of the third MCP joint on joint cavitation.

1.2.2. Objectives of the Study

- 1 To determine and compare the effect of long axis manipulation of the third MCP joint on articular surface separation in participants who experienced joint cavitation and in those who did not.

- 2 To determine and compare the effect of long axis manipulation of the third MCP joint on synovial membrane movement in participants who experienced joint cavitation and in those who did not.
- 3 To determine the effect of long axis manipulation of the third MCP joint on joint cavitation
 - 3.1 To determine the association between gas bubble formation and audible release in the third MCP joint in participants who experienced joint cavitation
 - 3.2 To determine the gas bubble location and movement during long axis manipulation in participants who experienced joint cavitation
- 4 To determine the association between the long axis manipulation force and the gas bubble appearance in the third MCP joint.

1.3. HYPOTHESIS OF THE STUDY

The general hypothesis (Alternate Hypothesis (Ha)) was set for this study which stated that: There would be a significant difference in the articular surface separation and soft tissue movement between those that cavitated and in those who did not cavitate and there will be a significant effect of the long axis manipulation of the third MCP joint on joint cavitation.

Specifically the Ha stated that:

- 1.3.1. Long axis manipulation of the third MCP joint would result in greater articular surface separation in participants that experienced joint cavitation, versus participants that it did not experience cavitation.
- 1.3.2. Long axis manipulation of the third MCP joint would result in greater synovial membrane movement in participants that experienced joint cavitation, versus participants that it did not experience cavitation.
- 1.3.3. There will be a significant association between gas bubble formation and audible release in the third MCP joint in participants who experienced joint cavitation.
- 1.3.4. There will be a significant association between the long axis manipulation force and the gas bubble appearance in the third MCP joint.

1.4. SCOPE OF THE STUDY

The results of 42 healthy participants between the ages of 18 to 28, who met all the inclusion criteria of this study, are reported in this dissertation. These participants were recruited from the Durban campuses of the Durban University of Technology (DUT), KwaZulu Natal, using a purposive sampling technique. The participants were given an explanation of the nature of the study and each of them signed an informed consent form. Each of the participants underwent a case history, a physical examination and an orthopaedic examination of the hand and wrist.

A B-mode ultrasound scan, using a high frequency linear transducer, was done of the dorsal aspect of the third MCP joint of each participant's left hand while the joint was manipulated using long axis traction. Joint surface separation, synovial membrane position, gas bubble presence and location were captured on ultrasound recordings of the joint at various stages of traction.

1.5. LIMITATIONS OF THE STUDY

The sample size was limited to 42 healthy asymptomatic individuals. As a result of time and budgetary constraints, as well as limited human resources the reliability of US transducer placement and anatomical landmark location in the third MCP joint could not be established. Due to the nature and design of the study, the neurophysiological aspects of joint manipulation could not be determined.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter provides an overview of the available literature pertinent to joint cavitation. A review of the relevant bony and soft tissue anatomy of the MCP joints provides the basis to understanding the physical process of joint manipulation and cavitation. The concepts of manual therapy and its sub-divisions, joint mobilisation and joint manipulation, are explained to provide insight into the physiological mechanisms of joint manipulation. The mechanical effects of joint manipulation are presented and brief explanations of the neurophysiological effects are presented. Cavitation as a physical phenomenon in fluids is explored and a detailed review of previous research on synovial joint cavitation is presented. Diagnostic ultrasound (US) as an imaging modality and investigative tool for joint cavitation is finally discussed and reviewed.

2.2 OVERVIEW OF THE RELEVANT ANATOMY OF THE METACARPOPHALANGEAL JOINT

2.2.1 Bony Anatomy of the Metacarpophalangeal Joint

The MCP joint is a condyloid-type synovial joint between the metacarpal proximally and the proximal phalanx distally. The metacarpal is a small long bone with a proximal expanded base, a shaft and a distal head. The metacarpal head is convex, but slightly flattened from medial to lateral and extends further to the volar surface. The head is also wider on its volar aspect resulting in increasing bony stability as the MCP joint approaches maximal flexion and greatest laxity in its extended position. The proximal phalanges are also long bones (Gray et al., 2005). The metacarpal heads are adapted to the shape of shallow concavities on the volar aspect of the proximal phalangeal bases, thus making the joint near bicondylar (Gray et al., 2005; Moore et al., 2009).

2.2.2 Soft Tissue Anatomy of the Metacarpophalangeal Joint

The skin on the dorsal surface of the hand varies considerably from that on the volar surface. The skin on the dorsal MCP joint is thin and pliable. It overlies the dorsal fascia and dorsal venous plexus of the hand and is attached to these structures with loose areolar connective tissue. The volar skin is thick, hairless and is less pliable than the dorsal skin. It is strongly

attached to the volar fascia and volar aponeurosis by numerous minute fasciculi (Moore et al., 2009).

Upon emerging on the dorsum of the hand, the extensor digitorum tendon splits into four parts; which then travel to the second to fourth digits. Each tendon splits over the MCP joint into two lateral bands; which pass to the base of the distal phalanx and a median band that passes deep to the extensor hood to the base of the middle phalanx (Moore et al., 2009). The extensor hood is a triangular fibrous expansion wrapped around the dorsal and collateral aspects of the MCP joint of each digit. The extensor digitorum tendon blends with the extensor hood along its central core and it is separated from the MCP joint by a small bursa (Lee and Healy, 2005). The extensor hood keeps the extensor tendons centred and anchors on each side of the volar plate. The extensor indices and extensor digiti minimi cause independent extension of the second and fifth digits respectively. Their tendons run on the ulnar side of the extensor digitorum tendon and insert on the extensor hoods of the respective fingers (Moore et al., 2009).

On the volar surface of digits two to four, one finds the flexor digitorum profundus and superficialis tendons. They are enclosed in the common flexor sheath and bound to the phalanges by a fibrous digital sheath composed of strong annular and weaker cruciform pulleys. These tendons pass the MCP joint through the A1 annular and C1 cruciform pulleys that are attached to the deep volar plate. The flexor digitorum superficialis lies superficial and splits to attach on either side of the middle phalanx. The flexor digitorum profundus lies deep and attaches to the base of the distal phalanx (Moore et al., 2009).

The MCP joints have a fibrous joint capsule that blends with the volar plate and its collateral ligaments (McVay and Deune, 2011). The MCP joint cavity is lined with synovium that consists of a thin, highly vascular synovial intima deep to the thicker, loose connective tissue layer of subsynovium (Young et al., 2000; Gray et al., 2005). The proximal recess is located between the metacarpal neck and the joint capsule; and is an intra-articular area. It is deep to the overlying tendon and is filled with intra-capsular, but extra-synovial fat. This layer of fat keeps the two layers of the synovium closely approximated and the proximal recess is larger on the dorsal aspect of the joint (Sharma and Sharma, 2009; McNally, 2008). The distal recess is much smaller to allow the extensor tendon to conform to the shape of the proximal phalanx (McNally, 2008).

The ligaments of the MCP joint include the volar plate, proper and accessory collateral ligaments, the deep transverse metacarpal ligament, the natatory ligaments, and the retaining ligaments (McVay and Deune, 2011). The volar plates are specialised fibrocartilaginous thickenings that form part of the joint capsule (McVay and Deune, 2011). They lie on the volar aspect of the MCP joint between the collateral ligaments (Gray et al.,

2005). The volar plates also blend with the deep transverse metacarpal ligaments and are grooved for the flexor tendons (Gray et al., 2005). Their distal aspect attaches firmly to the volar surface of the proximal phalanx. The proximal attachments are via two elongations called check rein ligaments. These ligaments have the ability to tuck under the metacarpal head during flexion and become taut with extension. The volar plate serves to limit hyperextension of the MCP joint, which may be varied between individuals (McVay and Deune, 2011).

Each MCP joint has a radial and ulnar collateral ligament (Moore et al., 2009). Each collateral ligament consists of a round, cord-like proper ligament and a fan-like accessory ligament. The proper ligament is a strong cord that originates on the posterior tubercle of the metacarpal head slightly dorsal to the mid-axis of the shaft. It inserts into the base of the proximal phalanx. The proper ligament becomes taut under MCP joint flexion, due to the elliptical shape of the metacarpal head (Gray et al., 2005) and the eccentric attachments of the ligaments to the metacarpal head (Moore et al., 2009). As flexion takes place, the base of the proximal phalanx moves away from the centre of rotation and the supporting structures tighten (McVay and Deune, 2011). The accessory ligament is more fan-shaped. It originates from the sides of the metacarpal heads, near the centre of rotation, runs volarly to attach to the volar plate and to the deep transverse metacarpal ligament (second to fourth digits). The volar orientation of the accessory ligament helps the volar plate to limit hyper-extension (McVay and Deune, 2011). The deep transverse metacarpal ligaments are three short, flat, wide bands that connect the volar aspects of the second to fifth MCP joints (Moore et al., 2009). These ligaments limit abduction of the MCP joints, preventing the fingers from splaying, but still allowing for some flexion and extension of adjacent fingers in relation to the other (McVay and Deune, 2011).

The key arteries and nerves to the MCP joints are shown in **Tables 2.1** and **2.2** respectively.

Table 2.1 Arterial supply to the metacarpophalangeal joints

Reference	Artery	Joint supplied	Origin	Course
Gray et al. (2005)	Dorsal metacarpal artery	2 nd , 3 rd and 4 th MCP joint	Arises from the dorsal carpal arch	Runs dorsal to the 2 nd , 3 rd and 4 th dorsal interossei and bifurcates into dorsal digital arteries
	Volar metacarpal artery	2 nd to 5 th MCP joint	3 or 4 arise from the convexity of the deep volar arch	Runs distally on the interossei and anastomoses with the common digital branches of the superficial volar arch
	Ateria princeps pollicis	1 st MCP joint	Arises from the radial artery	Passes between the 1 st dorsal interosseous and adductor pollicis obliquus and runs on the ulnar side of the 1 st metacarpal
	Arteria radialis indicis	2 nd MCP joint	Arises from the ateria princeps pollicis	Passes on the radial aspect of the entire 1 st digit

MCP = metacarpophalangeal joint

Table 2.2 Innervation of the metacarpophalangeal joints

Reference	Nerve	Origin	Course
Gray et al. (2005)	Volar digital branches of the median nerve	Two common volar digital nerves arise from the larger medial division of the median nerve and three proper volar digital branches arise from the smaller lateral division	2 branches of the common digital branch. The 1 st branch runs in the cleft between the 2 nd and 3 rd digits and the 2 nd in the cleft between the 3 rd and 4 th digits. Both terminate by dividing into proper digital nerves. Two branches of the proper volar digital nerves supply the thumb and the 3 rd runs on the radial aspect of the index finger
	Deep terminal branch of the ulnar nerve	Arises from the ulnar nerve	Runs between the muscles of the hypothenar eminence to pass deeply across the palm with the deep volar arch

MCP = metacarpophalangeal joint

2.2.3 Movements of the Metacarpophalangeal Joints

The MCP joints of the second to fifth digits allow for flexion, extension, abduction, adduction, circumduction and limited rotation (Gray et al., 2005). The movement of the MCP joint of the thumb is limited mainly to flexion and extension (Moore et al., 2009).

Maximum flexion is at almost 90° and is often terminated by the resistance of a grasped object. The principal muscles producing flexion at the MCP joint are flexor digitorum superficialis and profundus, which are assisted by the lumbricals and interossei. Flexion in the fifth digit is aided by flexor digiti minimi brevis, and in the thumb, flexion is attained by the flexor pollicis longus and brevis and the first volar interosseous. Flexion of digits three to five is accompanied by slight lateral rotation and flexion of the index finger with minimal lateral, no rotation or even a slight medial rotation (Gray et al., 2005). Extension is very variable, but is generally limited to a few degrees. The muscle responsible for extension of the MCP joint is extensor digitorum. It is assisted by the extensor indices in the index finger and extensor digiti minimi in the fifth digit. The thumb is extended by the extensor pollicis brevis and longus muscles (Gray et al., 2005).

The maximal abduction in the MCP joints is 25°. Extended fingers rely on the dorsal interossei with assistance from the extensor digitorum (except in the third digit), extensor indices in the index finger, and extensor digiti minimi; and abductor digiti minimi in the fifth digit to abduct the MCP joint. If the interphalangeal joints are flexed, only passive abduction of the MCP joint is possible. This is possibly due to shortening of the dorsal interossei and abductor digiti minimi with the interphalangeal joint in this position (Gray et al., 2005). Adduction is achieved through the volar interossei with the fingers extended and through the long flexors during flexion. Limited adduction is possible in the MCP joint of the thumb via the action of adductor pollicis and the first volar interosseous (Gray et al., 2005).

2.2.4 Anatomy of the Synovium

The joint cavity of a synovial joint is delineated by the articular cartilage and by the synovial membrane; which lies on the intra-articular surface of the fibrous joint capsule. The synovial membrane is a bilaminar structure composed of the synovial intima and the sub-synovium. The synovial intima is the thin lining (~50µm) that forms folds and smaller villi directly adjacent to the joint lumen (Young et al., 2000; Blewis et al., 2007). It is a discontinuous layer containing Type A synoviocytes (tissue macrophages), Type B synoviocytes (fibroblast-like cells), and a rich network of capillaries (Young et al., 2000; Pascual and Jovaní, 2005; Blewis et al., 2007). The intimal capillaries allow for the production of SF due to the capillary fenestrations orientated toward the joint cavity (Levick, 1995). The sub-synovium is a thicker layer (~100µm) of loose connective tissue on which the synovial intima lies and contains an

extensive network of lymphatic vessels responsible for the removal of fluid, particles and macromolecules that have escaped the joint cavity. The cellular constituents of synovium are invested in an extracellular matrix containing Type I, III and V collagen, chondroitin phosphate, proteoglycans, fibronectin and hyaluronic acid (HA) (Blewis et al., 2007).

2.2.5 Composition and Properties of Synovial Fluid

Normal SF is a clear, straw-coloured and viscous fluid; which functions as a biological lubricant between articular surfaces and in transporting nutrients to the avascular joint cartilage (Brannan and Jerrard, 2006). The amount of SF in normal joints varies from a few drops in small joints to several millilitres in larger joints (Brannan and Jerrard, 2006). It is unique, in that, it connects the articular cartilage and the synovium without an intervening intact cellular layer on a basement membrane i.e. an epithelium (Denton, 2012). Therefore, SF is considered a specialised, fluid form of synovial extracellular matrix rather than a true secretion (Young et al., 2000). Synovial fluid consists of a plasma transudate filtered from a dense network of fenestrated capillaries in the synovial intima (Levick and McDonald, 1995). It can be distinguished from plasma by the presence of the proteoglycan molecules, HA and lubricin, which is secreted by Type B synoviocytes into the plasma ultrafiltrate (Blewis et al., 2007).

Hyaluronic acid consists of repeating disaccharide units D-glucuronic acid and D-N-acetylglucosamine. The mean HA concentration in normal SF varies from 3.2 to 4.1 mg/ml which indicates that physiological differences exist between individuals in the absence of arthritis or joint trauma (Hui et al., 2012). At low concentrations (i.e. <1 mg/ml) HA exists in freely-moving random coils, but at concentrations found in SF, HA coils form an entangled network stabilized by hydrogen bonding and non-covalent intermolecular associations. The network formation with high concentration of HA in SF is crucial for normal joint function and endows SF with its viscoelastic properties and pronounced non-Newtonian behaviour (Fam et al., 2007; Brujan, 2010). Hyaluronic acid is also responsible for the SF cohesive forces that keep the opposing articular surfaces of the joints to each other. Synovial fluid exhibits little or no shear strength, which allows for the opposing surfaces to slide freely across each other; the cohesive bond creates tensile strength that limits joint surface distraction (Koopman and Moreland, 2005). At high loads HA is, however, not an effective lubricant and this is where lubricin seems to play an important role (Brujan, 2010).

Lubricin is found in SF at concentrations of 0.035-0.24 mg/ml (Hui et al., 2012). Lubricin and the related superficial zone proteins, which are mucinous glycoproteins, are responsible for surface lubrication of articular cartilage. They have an important role at high loads where HA is not an effective lubricant (Jay et al., 2007). Unlike lubricin and HA, superficial zone proteins are secreted by chondrocytes in the superficial zone of cartilage (Hui et al., 2012).

Plasma-derived proteins are also a major component of SF. A review of current literature reported that the total protein concentration of normal SF is 19-28mg/ml (Hui et al., 2012). Albumin, the most abundant macromolecule in SF (40-45% of plasma concentration), provides SF with its colloid oncotic pressure, which is an important property that is responsible for the fluid movement across the synovium. The presence of albumin in the joint is due to its low molecular weight, allowing it to transverse the synovial capillary fenestration into SF (Levick and McDonald, 1995). Normal SF also contains glucose and uric acid levels that approximate those of plasma (Brannan and Jerrard, 2006). Normal SF is largely acellular, with less than 200 leukocytes/mm³ (Hui et al., 2012). Normal SF undergoes continuous turnover by the simultaneous processes of plasma ultrafiltrate formation and trans-synovial drainage into the lymph-vessels in the sub-synovium. This translates into the plasma components of SF, water and protein, being replaced approximately every two hours (Brujan, 2010). However, HA and lubricin are selectively retained within the synovial joint because of the molecular sieving by the synovial membrane matrix (Hui et al., 2012). The turnover of HA is considerably slower with complete replacement of HA only taking place in 24 hours (Fraser et al., 1997).

Rheological studies have demonstrated that SF has three non-Newtonian properties: shear-thinning, elasticity and rheopexy (Brujan, 2010). Shear-thinning occurs in a fluid when its viscosity decreases with the increasing shear rate and these fluids are often referred to as pseudo-plastic fluids. In the case of SF, the dynamic loading of a synovial joint reduces the physical entanglement of the HA molecules; which realign parallel with the axis of articulation, resulting in the shear thinning and a reduction in viscosity of the SF. At lower shear rates the tensile strength endowed to SF by HA also stabilises the joints (Cullis-Hill and Ghosh, 1987). In a review of the literature on the rheology of SF in normal and pathological joints, Fam et al. (2007) reported that both the mean HA concentrations and molecular weight are decreased in osteoarthritis and rheumatoid arthritis, probably due to abnormal biosynthesis by Type B synoviocytes and free radical damage to the HA chain. Synovial fluid in rheumatoid arthritis may in fact lose its shear thinning and lubricating ability. Normal SF also has viscoelastic properties; at a low frequency of shear stress, SF is viscous, but as the frequency increases the SF becomes progressively more elastic (Fam et al., 2007; Hui et al., 2012). An example of the practical implication of this phenomenon is, with low frequency input like loading a knee on standing, SF is viscous; however, as the input frequency increases during walking or running, the SF becomes progressively more elastic so as to absorb the mechanical energy and thereby protects the cartilage and the synovial cells during repetitive activity (Brujan, 2010).

Unsworth et al. (1971) investigated the gases within the SF of six joints with rheumatic joint disease; and another joint with a traumatic effusion; and the analysis was done with the use

of a Van Slyke apparatus. They observed that gas constitutes 15% of the SF volume and 80% of the gas is carbon dioxide. It is thought that the gas content will reflect the values seen in arterial blood, but studies analysing the gases in SF have shown that the partial pressures for oxygen and carbon dioxide vary according to the disease of the specific joint (Falchuk et al., 1970; Lund-Olesen, 1970; Treuhaft and McCarty, 1971; Goetzi et al., 1974; Boon and Davidson, 2006).

2.3 CAVITATION IN SYNOVIAL JOINTS

2.3.1 Process of Gas Bubble Formation

Cavitation is the process of bubble or cavity formation in a fluid when it is subjected to a negative pressure (Caupin and Herbert, 2006). Liquids can withstand significant tensile loading or negative pressure (Kuhl et al., 1994). When a liquid is placed under negative pressure it is in a metastable state, and with time, a spontaneous change will occur towards a two-phase system of liquid and vapour. This results in the pressure rising into equilibrium with the vapour pressure (Kuhl et al., 1994). A volatile liquid to vapour-phase conversion occurs when a liquid is rapidly stretched beyond its saturated vapour pressure (Kinjo and Matsumoto, 1998). However, cavitation is not primarily as a result of the reduction of pressure to the liquid's vapour pressure, but rather due to a stress sufficiently large to rupture the liquid that causes cavity formation in a homogeneous liquid; and this stress represents the tensile strength of the liquid at that temperature (Fisher, 1948; Chen and Israelachvili, 1991; Joseph, 1998).

Chen and Israelachvili (1991) researched ultra-thin fluid films analogous to SF films in joints, and reported that cavities form in the liquid above certain tension threshold values. Previous studies have shown that liquids subjected to very high shear rates begin to behave mechanically like solids and can fracture or rupture like a solid (Fisher, 1948). Kuhl et al. (1994) and Chen and Israelachvili (1991) demonstrated that when two surfaces, separated by an ultra-thin film are separated below a critical velocity, it results in a "smooth" and "continuous" separation of the surfaces. As the velocity of the surface separation increases, the opposing surfaces deform, becoming pointed, indicating that the stresses are greatest in the area where the surfaces are pointed. When the opposing surfaces are separated above a specific critical velocity, it results in the fluid fracturing or "cracking open". This process releases the high tensile stress and allows the deformed surface to rapidly "snap back" to its original shape, and a vapour cavity to grow simultaneously between the separating surfaces. The cavity or fracture forms explosively and is basically a vacuum space since solutes and gases have not had time to enter the rapidly-forming cavity (Joseph, 1998). The theory postulates that when subjected to a tensile stress, fluid first has to rupture to form a cavity

into which vapour can fill. It is the tensile strength of the liquid that is related to fluid rupture and cavity formation and not the vapour pressure of the fluid (Kuhl et al., 1994; Joseph, 1998). Hence, cavitation inception occurs when the local pressure falls sufficiently far below the saturated vapour pressure, which is determined by the tensile strength of the liquid at a specific temperature (Joseph, 1998).

2.3.2 Gas Bubble Formation in Synovial Fluid

Synovial fluid is a non-Newtonian fluid that is both elastic and viscous in nature. At high flow rates, the viscous nature of SF will dominate and at slower flow rates the elastic nature will take over (Brujan, 2010). The one possible mechanism of SF gas bubble formation relies on the viscous nature of SF. Synovial joints are sealed units and when the joint surface is distracted, the SF pressure can fall below its vapour pressure; resulting in spontaneous bubble formation (Unsworth et al., 1971). Semlak and Ferguson Jr (1970) demonstrated this with a blocked syringe as an analogy for a joint. Negative pressure was asserted on SF obtained from traumatic and degenerative joint disease effusions by the distraction of the syringe plunger. This caused vaporization in the fluid and a gas bubble could be seen at the tip of the syringe. Unsworth et al. (1971) created an artificial MCP joint and used high speed cine-camera images of the simulated joint space containing SF from rheumatoid effusion to show vapour cavity formation and collapse. This process is known as tribonucleation and occurs when large negative pressures, generated by viscous adhesion between separating surfaces in a fluid, cause bubble formation. It requires two surfaces that are separated by a thin film of viscous liquid very similar to articulating surfaces separated by SF. When the surfaces are rapidly separated, the viscous liquid resists the flow into the widening gap between the surfaces, resulting in the negative pressure (Brujan, 2010). This model of bubble formation has, to date, only been demonstrated in pathological SF.

Fluid fracture is another possible mechanism of bubble formation in SF (Chen and Israelachvili, 1991; Kuhl et al., 1994). The non-Newtonian nature of SF provides it with its elastic behaviour and abrupt articular movement which protects joints. If the joint surfaces are separated through the elastic recoil of SF above a critical velocity, the SF can fracture similar to a solid, resulting in SF cavitation. This type of cavitation does not depend on the vapour pressure of the fluid, but occurs when the tensile stress on the fluid overcomes its tensile strength and subsequently releases substantial amounts of energy. Research on non-Newtonian fluids indicates that tensile strength increases with increasing polymer additives, which improve the viscoelasticity, thereby increasing the cavitation threshold. In the case of SF, HA provides the non-Newtonian properties and is responsible for the tensile strength above the plasma ultra-filtrate (Cullis-Hill and Ghosh, 1987; Wooley et al., 2005). Hyaluronic acid concentrations and molecular weight in SF fluctuate between healthy and pathological joints (Fam et al., 2007; Brujan, 2010). This variation could cause inconsistency in tensile

strength of SF, notionally accounting for the wide range of cavitation tension threshold reported in the literature (3 to 23 kg in the MCP joint) (Watson and Mollan, 1990). The fluid fracture creates a vacuum cavity into which SF vapour and dissolved gasses can freely move to form gas bubbles. This scenario explains cavitation during high velocity manipulation, but does not explain the audible releases associated with cavitation during steady axial distraction on the MCP joint (Unsworth et al., 1971). The sharp crack sound associated with joint manipulation is most likely caused by SF cavitation and is considered synonymous with the inception of cavitation (Chen and Israelachvili, 1991). The precise role of non-Newtonian properties in determining cavitation threshold, however, remains unclear (Brujan and Williams, 2006).

2.4 MUSCULOSKELETAL DIAGNOSTIC IMAGING

Appropriate use of diagnostic imaging techniques is essential for the diagnosis and treatment decisions (Berquist, 2006). Conventional radiography is the most frequently used musculoskeletal imaging modality and is often the initial investigation of any musculoskeletal disorder. Plain film radiographs, which are readily available and relatively inexpensive, are obtained to visualise bony anatomy and the images are easily interpreted. The key limitations include lack of soft tissue discrimination, reduced sensitivity for small bone density changes, the radiographic latent period, and the generation of ionizing radiation (Yochum and Rowe, 2005). Computed tomography (CT) uses a rotating x-ray generator, sensors and a computer to create “slice” images and multiplanar reconstructions of the body (Berquist, 2006). It is used mostly for the visualising of the central nervous and musculoskeletal systems, in which it renders superb detail of bony anatomy. Computed tomography produces ionizing-radiation and the doses can be relatively high. Magnetic resonance imaging (MRI) is a technique that measures mobile hydrogen atom displacement by a magnetic field; and structures with high water content, produces the highest image details. It produces much better soft tissue contrast resolution than CT and is often used for visualisation of soft tissue injuries like ligament or tendon injuries. Magnetic resonance imaging produces no ionizing radiation and is highly recommended due to the fact that it is relatively safe, but, it can be prohibitively expensive (Yochum and Rowe, 2005). Diagnostic US is a readily available, cost-effective and non-invasive imaging modality commonly used to visualise and diagnose numerous musculoskeletal and visceral conditions (Dondelinger, 2006). It may be safely repeated as many times as required during a consultation (Naredo and Bijlsma, 2009). Magnetic resonance imaging, CT and radiographs provide static images of structures and any movement of the subject during image formation, usually compromises its quality. Ultrasound can be rapidly performed; it does not emit ionising radiation and can provide dynamic visualisation of both static and moving structures.

2.4.1 Diagnostic Ultrasound

Diagnostic US rely on the emission and reception of oscillating sound pressure waves with a frequency greater than the upper limit of the human hearing range (Dondelinger, 2006). These oscillating acoustic waves are produced by piezoelectric material, housed in the US transducer, which converts electrical energy into acoustic energy. The acoustic waves directed into the body encounter tissues with different acoustic impedance and an acoustic echo is reflected from the interface of adjacent tissues. The transducer receives these echoes, and the piezoelectric material turns the reflected acoustic energy back into electrical energy. This is then processed by the instrument which results in an image of the tissue on the screen (Naredo and Bijlsma, 2009). Diagnostic US operates in the range of two to 25 megahertz (MHz). The lower frequencies (5 – 10 MHz) are used to image deeper tissues, but the resolution is generally low. High frequency scanning (10 – 18MHz) is generally used for the imaging of superficial structures and allows for better resolution (Dondelinger, 2006; McNally, 2008). High frequency scanning has also been successfully used to visualise hyperechoic foci and microfoci; presumed to be intra-articular gas bubbles and micro-bubbles within an otherwise anechoic SF (Malghem et al., 2011; Jones, 2012).

The resolution of US images has improved considerably in recent years. Ultrasound resolution refers to the ability of a US instrument to distinguish between two structures. US imaging resolutions have two components, viz. spatial resolution and temporal resolution. Temporal resolution is the ability of an instrument to accurately locate the structure or event in time and spatial resolution determines the image clarity. In a well-designed US instrument, spatial resolution is determined by two components, viz. axial resolution and lateral resolution. However the digital image converter and the US instrument display may degrade the displayed spatial resolution beyond the limits imposed it by its axial and lateral resolution (Hedrick et al., 2005). Axial resolution refers to the minimum distance that can be differentiated between two sonographically visible objects, parallel to the ultrasound beam and is mathematically defined as equal to half the spatial pulse length (Ng and Swanevelder, 2011). The lateral resolution is the minimum distance that can be distinguished between sonographically visible objects located at perpendicular to the ultrasound beam (Ng and Swanevelder, 2011). With increasing frequency of US the actual US wavelength decreases, allowing one to better distinguish between objects i.e. better resolution (Narouze, 2010). . Modern US instruments may have multiple spatial resolutions depending on the specific transducer, the specific frequency, depth of focus and the amount with which the image is magnified at the specific point in time. Other technological resolution enhancements such as harmonic imaging and Spatial Compound imaging further enhance image resolution (Hedrick et al., 2005). Ultrasound instrument with high-frequency (12 to 18MHz) linear array transducers are now routinely used in sports medicine and rheumatology, as they provide

better image resolution for superficial soft tissue structures such as muscle, tendon, ligament, and bursa (Chiang et al., 2013) and creates images of a greater spatial resolution than MRI; and functional or dynamic assessment of muscles and tendons can be done in real-time (Woodhouse and McNally, 2011).

Advances in modern US machine programming and processing capability also permit the accurate measurement of structures being imaged with the use of digital callipers (Szabo, 2004). The US instruments use manufacturer specific algorithms and software to determine distances in the image and the digital calliper measurements are routinely used in obstetrics and cardiology to make clinically important measurements (Szabo, 2004). High frequency US and its associated high image resolution allows for accurate placement of the US digital calliper and small measurement increments necessary to make accurate measurement (Szabo, 2004; Narouze, 2010). The minimum detectable measurement with the on-board digital calliper is determined by the wavelength of the US pulse:

$$Wavelength(\lambda) = \frac{velocity\ of\ sound\ wave\ (ms^{-1})}{frequency\ (hz)}$$

The accepted velocity of propagation in soft tissue in medical US imaging is 1540 m/s (Hedrick et al., 2005)

B-mode or grayscale techniques provide anatomic pictures for target lesions, while colour and power Doppler detect soft tissue vascularity (Sharma and Sharma, 2009). B-mode techniques, as used in this study, may be more intuitive to health care professionals because it provides a quick and familiar means of understanding the structure that is being scanned (Kawchuk et al., 2000). Recently, diagnostic US has been accepted to be of value for the detection of peri-articular soft tissue and bony disorders such as rheumatoid arthritis of the MCP joint (McNally, 2008; Sharma and Sharma, 2009; Woodhouse and McNally, 2011).

2.4.1.1 Sonographic Anatomy of the Metacarpophalangeal Joint

Ultrasound examination is increasingly used to image the MCP joints in the early detection of clinically silent synovitis, bony erosion and cartilage changes associated with pathology in the MCP joint (Laredo et al., 2006, McNally, 2008, Ellegaard et al., 2012). A linear array transducer with operating frequency above 10 MHz is mandatory to visualise the MCP joint (McNally, 2008). A literature search did not reveal any information on the sensitivity or reliability for the detection of normal anatomical structures or landmarks in the MCP joint with ultrasound imaging. However, from the literature, it is evident that ultrasound imaging in the sagittal plane of the MCP joint, with a high frequency (>10MHz) linear transducer, is routinely depended on to reveal the superficial structures, peri-articular and articular structures of

MCP joint (Grassi et al., 1993; Raza et al., 2003; Lee and Healy, 2005; Scheel et al., 2005; McNally, 2008; Sharma and Sharma, 2009).

In the normal MCP joint the bony contours of the metacarpal head and proximal phalanx base are smooth. The metacarpal may have a normal indentation on the dorsal aspect of the head, called the dorsal notch. This depression, if present, is smooth, well demarcated with echogenic bone at its base and occurs at the site where the growth plate fuses. The articular cartilage overlying the bone is hypoechoic.

The MCP joint capsule inserts on the metacarpal neck some distance from the articulating surfaces. The dorsal joint capsule is a thin echogenic structure just deep to the extensor tendons (McNally, 2008). The volar plate is positioned centrally on the volar aspect of the MCP joint; and its broad attachment to the base of the proximal phalanx, can be seen on the US. The collateral ligament is best seen on coronal images (Sharma and Sharma, 2009). The proximal recess can be seen on the dorsal and volar longitudinal views and borders the deep surfaces of the overlying tendon. The intra-capsular, but extra-synovial fat is more noticeable in the proximal recess on the dorsal aspect of the joint (McNally, 2008; Sharma and Sharma, 2009). The dorsal proximal recess can extend as much as 20 mm from the joint level and allows for finger flexion (McNally, 2008). Synovial fluid is anechoic and in the resting joint, appears as a dark film in the proximal recess (Sharma and Sharma, 2009).

The extensor and flexor tendons of the fingers are situated deep in the skin of the dorsal and volar surfaces of the MCP joint, respectively. The tendons can be seen as homogenous bright fibrillar echotexture on high resolution US (Sharma and Sharma, 2009). Both the flexor digitorum profundus and superficialis tendons in the tendon sheath are visible in the cruciform pulley and can be identified adjacent to the MCP joint (McNally, 2008). The extensor hood overlying and blending with the extensor tendon appears as a thin echogenic fibrillar structure that overlies the dorsal aspect of the finger (Lee and Healy, 2005).

Several studies have shown good inter- and intra-observer reliability for the detection of abnormality in joint and peri-articular structures in pathological MCP joint with US evaluation (Scheel et al., 2005; Laredo et al., 2006; Scheel et al., 2006; Iagnocco et al., 2012). Iagnocco et al. (2012) found that joint space width measurement, used to quantify cartilage thickness, had moderate to very good intra-observer reliability and Möller et al. (2009) demonstrated an intraclass correlation coefficient for cartilage thickness (i.e. joint space width) of 0.844 and 0.928 for inter-observer and intra-observer reliability respectively. No literature could be found on the sensitivity of detecting a normal synovium or the reliability of differentiating between various points in the synovium, however, ultrasound have been found sensitive for the detection of a synovitis in the MCP joint (Laredo et al., 2006).

Despite the ability of high frequency diagnostic US to visualise the joint capsule and synovium; and the reported importance of these structures in joint cavitation; it is surprising that neither Malghem et al. (2011) nor Jones (2012) mentions any effect that the traction or manipulation had on articular and peri-articular soft tissue and its association with the hyperechoic phenomena, audible release or joint widening. In both these studies the appearance of hyperechoic intra-articular phenomena is proposed to be indicative of intra-articular gas pockets. The hyperechoic sonographic appearance of gas in tissue is characteristic (Koski et al., 2006; Malghem et al., 2011; Jones, 2012). Gas inside tissue appears as a bright or white US image, due to the low sound impedance of the gas causing maximum reflection of the US signal to the transducer, resulting in gas being highly echogenic (Berquist, 2006). In a modern injection site verification technique called GAS-graphy, a glucocorticoid-air-saline mixture used as a contrast medium because of the echogenicity of air and its contrast with the anechoic saline. It is injected into intended sites and the accuracy of the site of injection confirmed with sonographic imaging. This verification technique demonstrated good reliability with inter- observer agreement of greater than 80% (Koski et al., 2006). For the purposes of this study, the visualisation of a hyperechoic focus or microfoci in the MCP joint lumen was considered to be gas bubbles or micro-bubbles. No literature was available on the sensitivity or reliability of detecting echogenic gas bubbles with ultrasound despite its reliability as part of a contrast medium.

2.5 MANUAL THERAPY

Manual therapy refers to procedures in which the hands directly contact the body in order to treat articulations or soft tissue structures (Gatterman and Hansen, 1994). It broadly encompasses procedures such as joint and soft tissue mobilisation, manual traction techniques, and joint manipulation (Bergmann and Peterson, 2011). Joint manipulation is commonly administered by chiropractors and osteopaths and has recently been gaining popularity with physiotherapists, medical practitioners and podiatrists. The increasing use of joint manipulation as a therapeutic modality; and its rise in popularity; warrants a greater need to determine and understand the mechanical, physiological and therapeutic effects (Fryer et al., 2002).

2.5.1 Joint Mobilization

Joint mobilisation is a manual technique that requires moving a joint singularly or repetitively within its physiological range of motion, with the aim to restore joint mobility (Bergmann and Peterson, 2011). It can be applied actively by the patient or passively by a manual therapist. Mobilisation may be applied with slow or fast movements and differs from joint manipulation; in that, no thrust is applied as there is no intention to cause joint cavitation (Hooper, 2005).

2.5.2 Joint Manipulation

Joint manipulation refers to the manual procedure that involves a targeted thrust to move a joint past its physiological limit of movement, without exceeding the anatomical limit (Vernon and Mrozek, 2005). Evans and Lucas (2010) stated that certain features are necessary for joint manipulation to be considered as a therapeutic technique. These are summarised in **Table 2.3**.

Table 2.3 Key features necessary for joint manipulation

Feature	Description
Mechanical response	<ul style="list-style-type: none">• The applied force creates movement in the joint and specifically, articular surface separation with cavitation of the joint• The velocity of joint motion may be variable and the sum of articular displacement is usually zero
Action of the practitioner	<ul style="list-style-type: none">• A force is applied to a joint, with the line of action perpendicular to the articular surface• The force may, but does not need to increase to a peak over time

The term “joint manipulation” is used interchangeably with the chiropractic-specific term “adjustment” (Bergmann and Peterson, 2011). Manipulation has three distinct force-time phases (Evans and Breen, 2006) viz.

- The pre-thrust phase,
- The thrust phase and
- The resolution phase after manipulation.

The thrust phase is characterised by a low amplitude thrust of controlled velocity and direction often referred to as a high-velocity, low-amplitude thrust; and is commonly associated with joint cavitation (Evans and Breen, 2006; Bergmann and Peterson, 2011). Joint manipulation can be applied with a variety of long or short-leverage procedures with specific anatomic contact points (Bergmann and Peterson, 2011) viz.

- Direct (short-lever) adjustments are joint manipulations in which, a high velocity, low-amplitude thrust is applied to a specific joint contact
- Semi-direct adjustments are joint manipulations with a combination of specific joint contact and distant long lever contacts, with a high-velocity, low amplitude thrust
- Indirect (long-lever) adjustments are joint manipulations with nonspecific contact points, distant to the affected joint

2.5.2.1 Kinematic Models for Joint Manipulation

The predominant kinematic model for joint manipulation, originally described by Sandoz in

1976, describes the phases of joint manipulation in relation to its normal range of motion of a synovial joint (**Figure 2.1**). The first phase involves moving a joint passively from its neutral position to the end of its physiological range of motion. This point, called the elastic barrier to movement, or the physiologic barrier, is the point at which the SF cohesive forces are thought to resist further movement. The physiologic barrier prevents the joint from passing its normal physiological limit. With joint manipulation, pressure is maintained on this barrier prior to the manipulative thrust (Sandoz, 1976; Evans and Breen, 2006). The manipulative thrust surpasses this physiologic barrier and results in a sudden “give”, a crack sound (audible release), and a slight increase in the range of motion past the zone of physiological movement. It is commonly accepted that the audible release and additional available movement, known as the paraphysiological zone, is due to SF cavitation; in which the cohesive forces of the SF are disrupted (Unsworth et al., 1971; Mierau et al., 1988; Watson and Mollan, 1990; Cramer et al., 2011). The paraphysiological zone lies between the elastic barrier of resistance and the limit of anatomical integrity of the joint. In comparison to joint manipulation, mobilisation moves the joint from its neutral position to the end of the physiologic range of motion, but does not exceed the physiologic barrier into the paraphysiological zone (Sandoz, 1976).

Panjabi (1992) described a model of joint movement for the functional spinal unit, but this could be applied to any other single synovial joint. The neutral position is the position of a joint within the normal physiologic movement that requires the least amount of energy to maintain. The neutral zone is that segment within normal motion, in which the passive osteoligamentous structures interfere minimally. This leads to relatively small forces affecting large amounts of displacement. The elastic zone is the remaining part of physiological movement from the end of the neutral zone to a point where the passive osteoligamentous structures limit any further range of motion. This end point is analogous to the limit of anatomical integrity of the joint described by Sandoz (1976).

Cavitation may be the only truly distinguishing feature that differentiates manipulation from other forms of manual therapy (Evans and Breen, 2006); and remains the only objective indication that a technically successful manipulation has been applied to a joint (Sandoz, 1976; Mierau et al., 1988; Brodeur, 1995; Reggars, 1999; Evans and Breen, 2006).

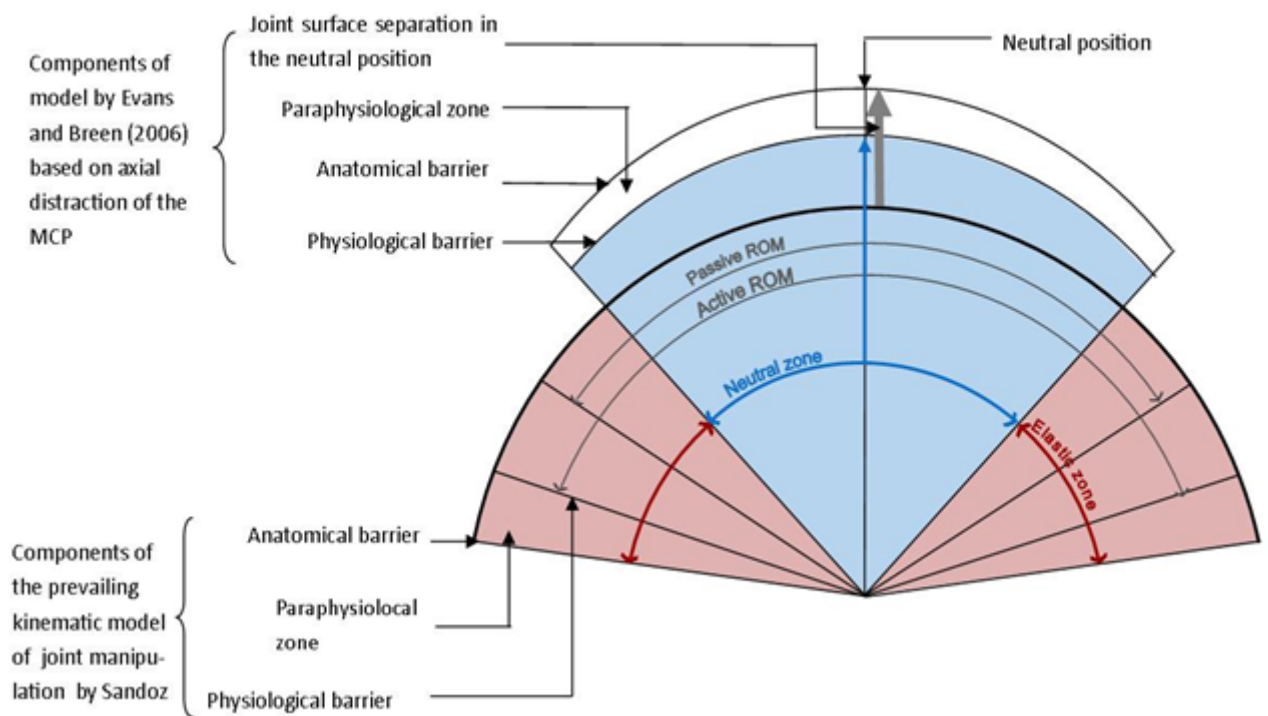


Figure 2.1 A schematic representation of two kinematic models of joint manipulation

(Adapted from Sandoz, 1976; Evans and Breen, 2006)

Most of the studies investigating joint manipulation and cavitation were conducted on the MCP joint using long axis traction (Roston and Haines, 1947; Semlak and Ferguson Jr, 1970; Unsworth et al., 1971; Mierau et al., 1988; Watson and Mollan, 1990; Malghem et al., 2011). These studies contribute significantly towards the knowledge on joint cavitation; even though the long axis traction method of manipulation is not adequately described by the models of manipulation. In the studies involving the MCP joint, pre-load and the actual cavitation during long axis traction occurs with the joint in the midpoint of the neutral zone, which is the neutral position of the MCP joint; and never approaches the physiologic barrier by the previous models. The kinematic model does not describe the articular surface separation, which is a key feature of long axis manipulation of the MCP joint (Sandoz, 1976). In light of the importance of cavitation for manipulative therapists, Evans and Breen (2006) proposed a new model to describe the most efficient way to cause cavitation. They suggested that the pre-thrust position should be in the neutral zone of the target joint, distracting the articular surfaces to a point of resistance. The passive osteoligamentous structures are lax in the neutral zone and the force is, therefore, primarily directed to the cohesive forces of the SF, reducing the loss of kinetic energy. The manipulative thrust is then applied to “gap” the joint further and to overcome the cohesive forces of the SF to cause cavitation. The available extra range of motion perpendicular to the articular surfaces i.e. articular surface separation, is the paraphysiological space and the point of resistance is analogous to the physiologic barrier (Evans and Breen, 2006).

2.5.2.2 Existing Models for Joint Manipulation and Cavitation

Sandoz (1976) presented a model for synovial joint cavitation; in which, the joint soft tissue structures play a key role in SF cavitation. He proposed that when a joint is axially loaded, the soft tissue (synovial folds and to an extent the articular capsule) invaginate because the joint cavity is airtight. The joint behaviour is elastic up to the physiologic barrier. When the joint surfaces are forced past the physiologic barrier, the soft tissue is stretched beyond the limit of invagination, and results in cavitation with its associated audible release sound. Once cavitation has taken place, the intra-articular pressure approximates to atmospheric levels due to the presence of gas in the joint. The joint separation is at a maximum and is limited only by the taut capsular and ligament structures. The author also suggested that if the joint is left alone after cavitation, the gas bubbles will break up and dissolve into the "tissue fluids" and the deformed capsule will assume its normal length (Sandoz, 1976). Brodeur (1995) modified the Sandoz's model by incorporating the work of Chen and Israelachvili (1991) on ultra-thin film liquid cavitation. The joint is modelled with four components: the cartilage, the subchondral bone, the joint capsule (including synovial folds) and the SF (Brodeur, 1995).

This model starts in the resting stage, in which the two opposing cartilage surfaces are in contact and separated only by a thin layer of SF. During the stage of initial separation, small amounts of traction applied to the joint separates the cartilage surfaces; and the resultant intervening space is immediately filled with SF from the periphery of the joint. It is assumed that the joint volume remains constant and, therefore, the joint capsule must invaginate to allow separation of surfaces. This increases the stress on the capsular ligaments causing them to lengthen. The joint surface separation is initially opposed by tension in the articular capsule. This is followed by the stage of further separation. The stress on the capsular ligament increases considerably and it cannot invaginate any further. When the force on the capsule exceeds a certain threshold, the energy in the capsule causes elastic recoil and the capsule snaps back from the SF, resulting in cavitation at the capsular/SF interface. The capsular recoil causes an increase in the joint volume and a reduction in intra-articular pressure. This process of recoil causes release of dissolved gasses at the ligament/fluid interface which coalesce almost instantaneously to form a single bubble within the capsule. These events occur in a very short time interval, at most, 16.6 milliseconds (Watson and Mollan, 1990). During elastic recoil the tension and strain on the capsule drops as it snaps away from the invaginated position. This allows further joint surface separation which is abruptly halted by the anatomical limits of the capsule and the tension on it, as well as the other peri-articular soft tissues. The final stage of joint manipulation is reached when the joint space has been distended significantly and a gas bubble is present in the SF. The external forces are now in balance with the tension on the joint ligaments and the lower intra-articular pressure.

The mechanism for thin fluid film cavitation within a joint is fluid fracture, a process that relies on a critical separation velocity. The separation velocity in Brodeur's model is not generated by the separation of two closely opposed rigid surfaces as suggested by Chen and Israelachvili (1991); but rather by the rapid snap-back of the capsule from the SF. Increasing the rate of loading, results in a proportionally faster snap back and cavitation. If slow separation takes place, the capsule will undergo viscoelastic creep, temporarily reducing the elasticity of the capsule, which requires a greater force for cavitation inception. This supports the view of Roston and Haines (1947) that axial traction of a lax joint may not cause cavitation. It is interesting that in both the Sandoz and Brodeur models, that the joint soft tissue structures play a significant role during cavitation; even though there was no research to demonstrate the soft tissue behaviour during joint cavitation. Furthermore, neither model takes into account the non-Newtonian viscoelastic nature of SF or the viscoelastic nature of hyaline articular cartilage.

There are conflicting views of the mechanism of the cracking sound (audible release) associated with joint manipulation. Roston and Haines (1947) proposed that the sound is generated by the sudden separation of the joint surfaces, but Unsworth et al. (1971) were of the opinion that vapour cavity implosion causes it. Others thought that the sound from the cavitation begins slightly before the drop in tension across the joint (Conway et al., 1993; Meal and Scott, 1986). In Brodeur's model the sound would most likely occur during the snapping back of the joint capsule as a product of the cavitation process.

2.6 EFFECTS OF JOINT MANIPULATION

The physiological effects of joint manipulation are thought to be mechanical and neurophysiologic (Pickar, 2002). Despite a plethora of proposed theories to explain the clinical effects of spinal manipulation, four theories for lesions that respond to manipulation emerge from the published literature (Shekelle, 1994) viz.

- 1 The release of trapped intra-articular material such as synovial folds or meniscoids
- 2 The relaxation of hypertonic muscle by sudden stretching, or the reflexogenic theory
- 3 The disruption of articular or peri-articular adhesions
- 4 Unbuckling of motion segments that have undergone disproportionate displacements.

These theories are primarily based on spinal manipulative therapy and despite the anatomical differences between spinal (zygapophyseal) joints and the MCP joints, it is reasonable to assume that similar effects may occur in the MCP joint. The focus of this study is not to determine the physiological effects or clinical consequences of joint manipulation;

although the study may address certain aspects of it where soft tissue is involved. A critical review argued that only one theory, namely, the release of trapped intra-articular material such as synovial folds, thus far, offers a plausible mechanical explanation for the clinical effects of spinal manipulation on spinal pain (Evans, 2002). It was also argued that, although cavitation seemed unlikely to be an absolute requirement for these intra-articular mechanical events to occur, it is at the very least an indicator of successful joint surface separation, which is a requirement for these events (Evans, 2002).

2.6.1 Mechanical Effects of Joint Manipulation

Joint manipulation introduces a mechanical force into a specific articulation (Conway et al., 1993). The proposed therapeutic effect of this, is its ability to reduce articular abnormalities and normalize joint movement (Shekelle, 1994; Evans, 2002). A summary of some of the proposed mechanical effects of manipulation on synovial joints is presented in **Table 2.4**.

Table 2.4 A summary of the proposed mechanical effects of joint manipulation

Reference	Theory		Proposed effect of joint manipulation
Synovial fold extrapment theory			
Bogduk and Jull (1985)	Synovial fold trapped under the capsule in spinal zygapophyseal joints.	With extension of the spine from a flexed position, the inferior articular process returns to the neutral position. Superior synovial fold fails to re-enter the joint space. It impacts on the edge of the articular cartilage and it buckles; creating a space occupying subcapsular lesion. The resultant capsule distention causes pain and extension is limited.	Joint manipulation results in joint surface separation that may release intra-articular inclusion or allow the re-admission of an extrapped synovial fold.
Synovial fold entrapment theory			
Kos and Wolf (1972)	Cartilage indentation and synovial fold incarceration.	The synovial fold is trapped between the articulating surfaces of the facet joint. The dense fibro-adipose apex of the synovial fold causes an indentation in the articular cartilage surfaces and the apex gets trapped. Movement results in traction on the capsule through the base of the synovial fold; resulting in pain and reflex muscle spasm.	Joint manipulation causes joint gapping that releases trapped synovial folds, interrupting the pain–spasm cycle and preventing premature joint degeneration. Joint manipulation would appear to be the treatment of choice for trapped synovial folds (Evans, 2002). Joint cavitation is a reliable indicator that gapping of the joint has occurred (Evans, 2002).
Korr (1975)	Pain and hypomobility.	Pain as a result of impaction of the synovial fold or traction of the joint capsule induces reactive muscle spasm and joint locking.	
Bogduk and Jull (1985)	Tension on joint capsule.	Rupture of incarcerated synovial fold with movement causes haemarthrosis and loose body formation in the joint.	
Jones et al. (1989)	Secondary biochemical changes and early degeneration.	Synovial fold entrapment causes biochemical and ligamentous changes that result in premature joint degeneration.	
Disruption of articular or peri-articular adhesions			
Lewit (1999)	Joint blockage as an articular phenomenon.	Cervical motion restrictions remain present and become more pronounced as myorelaxants and anaesthesia mitigated muscle involvement. Motion restrictions are most likely an articular phenomenon as a result of mechanical blockage.	It is thought that joint manipulation can break the connective tissue cross-linkages and adhesion in articular and peri-articular tissue (Evans, 2002; Pickar, 2002). Joint manipulation is an effective intervention for treating these derangements because sufficient joint surface separation or shear as a result of manipulation is thought to (1) stretch the affected tissue; (2) sever the adhesive fibres; and (3) re-establish mobility without triggering an inflammatory reaction and recurrence of the fibrosis (Gatterman, 2005; Bergmann and Peterson, 2011)
Jones et al. (1989); Trudel and Uhthoff (2000)	Immobility and development of articular adhesions.	Hypomobility can result in extracapsular and intracapsular adhesion formation. Extracapsular adhesion is a result of progressive contracture of the capsule and peri-capsular structures, and intracapsular adhesions are fibroadipose tissues that form across the joint space and can obliterate it.	
Jones et al. (1989); Evans (2002)	Injury and articular adhesions.	Injuries such as a capsular tear, a subchondral fracture or intra-articular haemorrhage could act as a precipitating factor for intra-articular fibrosis and eventual complete ankylosis.	
Semlak and Ferguson Jr (1970)	SF cohesive forces.	A proposed intra articular adhesion that can act as an obstacle to joint movement, especially when asymptomatic restriction is present, may be the action of atmospheric pressure combined with cohesive property of SF.	

SF = Synovial fluid

Neurophysiological Effects of Joint Manipulation

The mechanical changes caused by joint manipulation are thought to result in secondary physiological sequelae due to sensory inflow to the central nervous system. In addition to this, it has been suggested that spinal manipulation has a primary neurophysiologic effect by stimulating mechanoreceptors, proprioceptors and nociceptors of the joint capsule and musculotendinous structures (Korr, 1975; Wyke, 1979; Brodeur, 1995; Pickar, 2002). This could, theoretically, be applicable to the MCP joint as well.

Many theories pertaining to the neurophysiological effect of joint manipulation have recently gained attention. Korr (1975) originally suggested that high gains in facilitated gamma motor neurons impair joint mobility, and that the bombardment of muscle spindle impulses through the actions of joint manipulation, may result in increased joint mobility. Recent experimental data show that impulse loads comparable to high velocity, low amplitude thrust manipulation, can evoke significant afferent discharges from muscle spindles, Golgi tendon organs and high threshold mechanoreceptors (Pickar and Wheeler, 2001; Pickar et al., 2007; Pickar and Bolton, 2012). Recently Clark et al. (2011) observed that the short-latency stretch reflex, a critical component of the pain-spasm-pain model for low back pain, is altered by spinal manipulation only if associated with joint cavitation. The authors speculate that the cavitation response to manipulation may down-regulate muscle spindle sensitivity or Type 1a afferent stretch reflex pathways and that greater joint gapping caused by cavitation, could result in the reflex activity observed (Clark et al., 2011). The reader is advised to consult the relevant literature for further details of the neurophysiologic effects of joint manipulation; since it was not the focus of this study but was presented here in a précis format for completeness of the discussion.

2.7 INVESTIGATIONS INTO JOINT CAVITATION IN THE METACARPOPHALANGEAL JOINT

Many authors have used the MCP joint to investigate joint manipulation and specifically joint cavitation (Roston and Haines, 1947; Semlak and Ferguson Jr, 1970; Unsworth et al., 1971; Meal and Scott, 1986; Mierau et al., 1988). The choice of the MCP joint has been popular for this type of research for the following reasons:

- Ease with which the MCP joint can be cavitated (Mierau et al., 1988)
- Ease and supposed safety with which the MCP joint can be repeatedly radiographed
- Easy accessibility of the MCP joint (Semlak and Ferguson Jr, 1970)

The MCP joint is a normal synovial joint consisting of the same basic components as other

synovial joints, including the spinal zygapophyseal joints (Moore et al., 2009). Meal and Scott (1986) compared the sound recorded during a cervical spine manipulation to that of the MCP joint. They reported that the cervical audible releases had the same characteristic pattern to those of the MCP joint, and are most likely caused by the same mechanisms. The sound is biphasic and a reduction in tension occurred after the first wave peak and before the second wave peak (Meal and Scott, 1986). This shows that despite the difference in the location of these joints, the mechanism of sound production during manipulation appears to be very similar. A summary of the studies investigating cavitation in the MCP joint is presented in **Table 2.5**.

The studies on the MCP joint shown in **Table 2.5** and the supposed clinical effects of joint cavitation are indications of the significance of understanding joint cavitation to manual therapists. From the pioneering work done by Roston and Haines in 1947 to this study, the same basic method of distractive manipulation of the MCP joint has been used with various methods of imaging and recording. Their findings form the basis of our understanding of joint cavitation. Traction of the MCP joint is a reliable method to cause joint cavitation and the cavitation process is associated with three near simultaneous phenomena; a sudden jump in joint surfaces, an audible crack and the appearance of an intra-articular gas bubble (Roston and Haines, 1947; Semlak and Ferguson Jr, 1970; Unsworth et al., 1971). The gas bubbles can be seen as sharply outlined radiolucent spaces on radiographs and as hyperechoic foci or microfoci with high frequency US (Roston and Haines, 1947; Unsworth et al., 1971; Mierau et al., 1988; Malghem et al., 2011). Unsworth et al. (1971) were the first to propose that the gas bubble formation is as a result of cavitation in the SF. The most likely causes of the audible release appear to be the collapse of unstable cavitation gas bubbles or the snap-back of the joint capsule as it recoils from the SF during cavitation (Unsworth et al., 1971; Brodeur, 1995). The audible release during manipulation is of keen interest to manual therapists, as this is the only instantaneous evidence that a technically successful joint manipulation was performed (Evans and Breen, 2006). Meal and Scott (1986) were able to demonstrate that the mechanism of audible release i.e. sound production, was the same in the MCP and cervical zygapophyseal joints and Mierau et al. (1988) reported a significant association between the audible release and SF cavitation in the MCP joint. Once cavitation has occurred, the MCP joint enters the refractory period, which lasts between 17 to 30 minutes. Malghem et al. (2011) demonstrated that micro-bubbles reside in the joint in this period and Unsworth et al. (1971) demonstrated that gas bubbles in SF take approximately 30 minutes to be absorbed into the SF.

There are limitations to the studies shown in **Table 2.5**. In the early radiographic studies, the images were taken at various predetermined levels of traction, which provided only static images of what is essentially a dynamic process. Therefore, the assumption that joint

separation, gas bubble formation and audible release occurred simultaneously required verification. Watson and Mollan (1990) attempted to address this by using cineradiography. None of these studies attempted to demonstrate the influence of distractive manipulation and joint cavitation on the joint capsule, synovial membrane and peri-articular structures. This influence is important as these structures play a critical role in joint stability and integrity (Semlak and Ferguson Jr, 1970); and will theoretically have an important influence on the cavitation process (Sandoz, 1976; Brodeur, 1995). This influence is particularly important due to the postulated neurophysiologic effect, said to be mediated by capsular and peri-articular nervous receptors (Pickar, 2002) and the disruption of capsular and peri-articular adhesions (Shekelle, 1994). Sandoz (1976) and later Brodeur (1995) proposed a theoretical model which included and described joint capsule and peri-articular soft tissue behaviour during manipulation. Brodeur's hypothetical model has been widely accepted as an accurate description of the joint behaviour when manipulated; despite a paucity of robust evidence supporting this theory (Bergmann and Peterson, 2011).

Table 2.5 A summary of studies investigating cavitation in the metacarpophalangeal joint

Reference	Sample size	Methodology	Assessment tools	Results		Conclusions
				Joint separation	Imaging	
Roston and Haines (1947)	N/A	A string connected the middle phalanx of the 3 rd digit and a spring scale to an upright member of the radiography unit. The patient-self applied a manual axial distractive force to the 3 rd MCP joint by drawing the hand away from the upright member. Serial radiographs were taken at certain tension levels	Serial radiographs Spring scale: tensiometer	Mean resting separation was 1.8 mm 0 to 7 kg traction led to separation of between 0.5 to 2.0 mm. At tensions above 7 kg, an audible release came from the joint and the separation jumped between 1 to 3 mm A maximum traction of 18.5 kg was applied and the largest separation for a typical example was 5.6 mm Joint audible release was followed by a refractory period of 17 to 22 min	Prior to the audible release, radiographs revealed a homogenous intra-articular appearance With tension on the joint, a sharply outlined clear “space” bound by the cartilage surfaces was seen on the radiograph of the joint that experienced the audible release	The authors created a load displacement graph that characterises the manner in which the MCP joint behaves during an audible release
Semlak and Ferguson Jr (1970)	25 MCP joints	A pulley and weights simultaneously distracted the 3 rd and 5 th MCP joints in an axial direction. Loads were increased and radiographs taken at 5 to 15 sec intervals A 25 gauge needle was inserted into the 3 rd MCP joint to create communication with the exterior atmospheric pressure and loading and radiographs were repeated The study included an experiment in which a syringe, analogous to a joint, places fluids inter alia SF under negative pressure	Radiographs Tension: weights	A mean of 0.8 mm surface separation was observed at loads between 0 to 3.6 kg Between 3.6 kg (8lb) to 4.1 kg (9lb) a sudden separation was seen There was minimal separation beyond 4.1 kg (9lb) In the cannulated joint the separation was continuous and proportionate to the force applied	Appearance of a gas shadow accompanied the sudden separation In the cannulated joint, traction was immediately accompanied by the appearance of intra-articular gas	The intra-articular space on radiographs is indeed gaseous and that atmospheric pressure plays a fundamental role in joint stability
Unsworth et al. (1971)	12 3 rd MCP joints of which 5 cavitated and 7 did not	Axial load was applied to the 3 rd MCP joint by pneumatic machine The load applied was measured and serial radiograph exposures were taken simultaneously	Tension: pneumatic device Serial radiographs Tension transducer: measures	The initial mean resting joint space was 1.35 mm with a range of 0.98 to 1.98 mm In 5 individuals, displacement was gradual at first to between 10 to 16 kg; and then an audible release occurred with a sudden jump in the joint surfaces The other 7 experienced no audible	A crescent- shaped area of “high contrast” was present in all the joints that experienced an audible release No gas spaces were seen in joints that did not cavitate	This is the first study to link the phenomena of fluid cavitation with the audible release, jump of articular surface separation and intra-articular radiolucent spaces with joint manipulation.

			tension Ultraviolet recorder: records applied loads	release or jump in joint surface separation. The mean final resting joint space was 1.56 mm with a range 1.26 to 2.07 mm Repeated measurements were done in 1 joint to find the time required for the joint space to return to initial levels. Resting joint space was 0.98mm and at the instant of audible release it was 2.5 mm. It took 15 min for the joint to return to pre- procedure levels		
Meal and Scott (1986)	8 participants Up to 4 MCP joints in both hands of a single participant were used successively and the procedure was repeated after a 30 min interval to allow for the refractory period to elapse	The participant was placed in a sound-roof room with a sound recording device directed at the target MCP joint The participant gave a silent signal for tension to the joint to start and then to stop once audible release had occurred. The tension and sound waves were simultaneously recorded Sound wave recordings were also made from manipulations of the cervical spine	Tension transducer: measured tension Sound level meters: detected sound waves Ultraviolet recorders: recorded the tension transducer and sound meter signals	The sound wave for the audible release was consistent, with 2 peaks separated by a dip The duration of the audible release sound varied between 0.025 to 0.075 sec and the intensity varied by ~20% The tension levels for the audible release varied from a low of 3 kg to a high of 23 kg. Habitual knuckle crackers required less tension to crack and produced a lower amplitude sound wave The audible releases were accompanied by a drop in the recorded tension during the sound wave The sound waves produced during the cervical spine manipulations appeared identical as the ones produced in the MCP joints	No imaging was used	The study showed that the audible release associated with progressive axial traction of the MCP joint produces a double sound wave “exactly the same” as sound waves produced during cervical spinal manipulation
Mierau et al (1988)	62 MCP joints were used to demonstrate gas bubble	62 MCP joints were used in the first part. A PA radiograph was taken of the 3 rd MCP joint in neutral position. A 2 nd radiograph was taken with 2.7 kg (6lb) traction applied	Radiographs Digital calliper and microsurgical	Of the 62 joints, 42 (68%) had an audible release The mean resting joint space in the cracking joints was 1.61 mm pre-	39 joints of 62 (63%) had a radiographically- visible gas cavity present and experienced audible release 20 of 62 joint (32%) did not experience	This study, using a larger sample size, concurred with some of the earlier studies

	<p>presence and articular surface separation</p> <p>66 MCP joints were used to compare the effect of mobilisation versus long axis manipulation on MCP joint passive flexion</p>	<p>to the joint</p> <p>An attempt was then made to cavitate the joint using axial traction. The presence or absence of the audible release was recorded</p> <p>A 3rd radiograph was taken in the resting position and a 4th with the joint distracted with 2.7 kg</p> <p>The second part was a randomised controlled clinical trial in which 66 MCP joints were either mobilised or manipulated with a long axis force. Passive finger flexion at the MCP joint was tested prior to and after the procedures</p>	<p>eye-loops: measured surface separation</p> <p>Goniometer: measure MCP joint flexion</p>	<p>traction and 1.66 mm post-traction and for non-cavitating joints it was 1.62mm pre-traction and 1.66 mm post-traction. There was no significant difference between cavitating and non-cavitating, and pre- and post-treatment figures. The resting joint separation range of all the joints was 1.61 to 1.66 mm</p> <p>Pre-intervention traction (2.7 kg) revealed that the mean increase of surface separation of the cavitating joints was significantly lower at 0.82 mm than in non-cavitating joints at 1.35 mm ($p < 0.01$)</p> <p>In the post intervention traction measurements, there was no significant difference between manipulable and non-cavitating joints</p> <p>Significantly greater increases were seen in post-treatment passive flexion in the manipulation group versus the mobilization group</p>	<p>audible release, but 5 of these had a gas bubble present.</p>	<p>which reported that joint manipulation was associated with radiographically visible gas cavities, and audible release. It also found that the distraction measures prior to cavitation were significantly lower in cavitating versus non-cavitating joints at a constant force. It was suggested that this occurred because the elastic barrier of resistance was encountered in the cavitating joint at that point. The authors hypothesised that the inability of some joints to cavitate may be because they lacked an elastic barrier.</p>
<p>Watson and Mollan (1990)</p>	<p>1 MCP joint</p>	<p>The participant was seated with the palm of his left hand on an empty cassette film</p> <p>The cineradiography camera was started and the participant had to pull his own left 3rd finger until the MCP joint cavitated</p> <p>30 frames before the audible release and 10 frames after, were printed at the same magnification</p> <p>The distances between the subchondral margins were measured on an early image to establish a baseline and the subsequent measures were all divided by this to normalise the values</p>	<p>Siemens Senograph with a 35mm cine-camera was used at a frame rate of 120 per seek to produce images of the joint</p> <p>Vernier calliper was used for the joint surface separation</p>	<p>A slow increase in separation was seen up to ~0.15s before the audible release. From this point to the audible release, separation was constant</p> <p>Separation increased rapidly to almost maximum within two frames, i.e. 16.6 ms after the audible release; after which, a plateau was reached</p>	<p>A shadow appeared in the joint between two frames. This indicated that a bubble was formed and stable in less than 8.3 ms</p>	<p>The rapid gas bubble creation concurs with studies of vapour and not gaseous bubble formation</p> <p>The plateau of separation prior to cavitation indicates that soft tissue laxity had been removed and that increasing tension across the joint is probably borne by SF</p>

Malghem et al. (2011)	1 subject in which the left 3 rd MCP joint was distracted and investigated by US, radiographs, MRI and CT imaging	The first subject applied traction to a 3 rd MCP joint himself and a radiograph was taken during the traction	measures Conventional radiographs	Traction caused a significant increase in surface separation in all subjects. Two independent observers noted the measurements	In subject 1, widening of the joint space and a radiolucent gas like cavity was seen on the radiograph. The US images showed that widening was immediately followed by the appearance of an intra-articular hyperechoic band and post-traction hyperechoic microfoci persisted along the metacarpal head. Re-traction caused increased numbers of the microfoci; which persisted for at least 30 min in the joint	The authors concluded that traction of a joint caused reduction in intra articular pressure; which can generate a hyperechoic band in the joint cavity. It was also concluded that intra-articular hyperechoic microfoci that correspond with gas micro-bubbles, can persist in the SF after traction has ceased; and is not necessarily pathological
	22 volunteers with healthy, non-arthritis left 3 rd MCP joints which were used for the traction and an US scan procedure	In separate sessions traction was applied to the same joint and held for 15s and this was repeated 3 times over. The joint was scanned with US before, during and immediately after traction to assess for hyperechoic foci. The joint was scanned again after 15 min, 30min, and again after 60 min In another session, the traction manoeuvres were repeated and radiographic, CT and MR imaging were performed a few min after to visualize any residual intra-articular gas. The traction manoeuvre was done on the left 3 rd MCP joint of the 22 volunteers Traction was maintained on the joint for 15 sec with the other hand. US was done on these joints before, during and after joint manipulation Close attention was paid to detect and record audible release with the traction The US recordings were evaluated for the presence of hyperechoic foci and widening of the joint space	A dual slice CT scanner MRI was performed on a 1.5 Tesla scanner and included standard T1 and T2 weighted sequences All sonographic scans were done in the longitudinal plane of the MCP joint using a 17.5MHz transducer	The mean increase of joint separation in the group with hyperechoic observation was 2.5 mm from 1.5 mm pre-traction to 4 mm during traction for observer 1; and 2.3 mm from 1.7 mm pre-traction to 4 mm during traction for observer 2. This was significantly larger than in those subjects in whom no hyperechoic phenomena were seen. The separation increase at traction in this group for observer 1 was 1.2 mm, moving from 1.6 mm to 2.8 mm; and for observer 2 it was 0.8 mm, moving from 1.9 mm to 2.7 mm Joint could not be "re-cracked" for 20 to 30 min; which is similar to previous findings of the post-cavitatory refractory period	3D submillimetric gradient echo magnetic resonance sequence showed some very small, low signal intensity foci; an indirect sign of the presence of the presumed gas micro-bubbles in the dorsal aspect of the joint In 10 of the 22 other subjects, a hyperechoic intra-articular band was seen during traction and hyperechoic microfoci persisted after traction. In 8 of these 10 cases, an audible release was discerned as the hyperechoic band occurred. In the 12 remaining subjects neither an audible release nor hyperechoic observations were recorded	

N/A = not available, MCP = metacarpophalangeal, MRI = magnetic resonance imaging, etc. = et cetera, ms = milliseconds, sec = seconds, mm = millimetre, kg = kilogram, CT = computed tomography, US = ultrasound, SF = synovial fluid, lb. = pound, min = minutes, 3D = three dimensional; MHz = megahertz; PA = posteroanterior

2.8 INVESTIGATIONS INTO JOINT CAVITATION USING VARIOUS DIAGNOSTIC IMAGING MODALITIES

Various studies have attempted to demonstrate the features of MCP joint cavitation in other synovial joints, especially in spinal zygapophyseal joints (**Table 2.6**). To date, no study has been able to demonstrate gas bubble formation in the zygapophyseal joints after manipulation. The investigation of joint cavitation in zygapophyseal joint spaces appears to be problematic due to their small size, changing orientation and the difficulty in isolating movement in the individual joints (Cascioli et al., 2003; Cramer et al., 2011). Currently the only imaging modalities able to demonstrate intra-articular gas bubbles and micro bubbles in synovial joints that cavitate are diagnostic US, plain-film radiographs and 3D submillimetric gradient echo MRI (Mierau et al., 1988; Malghem et al., 2011; Jones, 2012).

Table 2.6 A summary of studies investigating joint cavitation using various diagnostic imaging modalities

Reference	Joint investigated	Diagnostic imaging	Findings
Cascioli et al. (2003)	C2/C3, C3/C4 and C4/C5 zygapophyseal joints	Plain-film radiographs CT	After cervical manipulation there was no evidence of gas in the joint space or an obvious increase in cervical zygapophyseal joint space widths
Cramer et al. (2011)	L4/L5 and L5/S1 zygapophyseal joints	MRI	Spinal manipulation resulted in greater joint gapping than no manipulation, and cavitated joints gapped more than non-cavitated joint. No gas was visualised in the joints
Jones (2012)	Trapezometacarpal joint	Diagnostic US	In all the joints that cavitated conspicuous echogenic gas cavities were discernible in the joint space

MRI = magnetic resonance imaging, CT = computed tomography, US = ultrasound

2.9 CONCLUSION

Although there are numerous studies that have investigated the process of joint cavitation in the MCP joint (**Table 2.5**), no consensus has been reached on the actual mechanism of cavitation and how this results in its clinical effects and the audible release so valued by manual therapy practitioners. The uncertainty that exists may be resolved by investigating the roles of the joint capsule, synovial membrane and peri-articular structures in joint manipulation and cavitation. No research has attempted to demonstrate the influence of distractive manipulation and joint cavitation on these structures, despite the supposed role they may have on the cavitation process and the clinical benefits of their involvement.

This study, therefore, attempted to provide a better understanding of the anatomical effects of joint manipulation to improve the rationale for using joint manipulation by manual therapists in certain clinical conditions; and to enhance the acceptance of this therapeutic intervention by the scientific and health care community.

CHAPTER THREE

MATERIALS AND METHODS

3.1 STUDY DESIGN AND PERMISSION TO CONDUCT THE STUDY

This research study is designed in the form of a pre-post experimental investigation. Primary data were obtained from the US recordings and printouts of the traction manipulation of the third MCP joint of the left hand and the selected anthropometric assessments of the participants. During the conceptualizing of the research procedure and prior to the approval of this study, a pilot study was done to ensure that the pertinent anatomy and presumed hyperechoic gas bubbles would in fact be discernible and measurable with the equipment available. Approval to conduct this study was obtained from the Durban University of Technology's Faculty of Health Sciences Research Committee and the Institutional Research Ethics Committee (REC 82/12) (**Appendix A**).

3.2 PARTICIPANT RECRUITMENT

3.2.1 POPULATION

Male and female individuals between the ages of 18 to 28 were recruited from the campuses of the Durban University of Technology in the Ethekeini Metropolitan area and via word of mouth.

3.2.2 SAMPLING METHOD, SAMPLE SIZE AND RECRUITMENT

The sample size was calculated using data reported by Unsworth et al. (1971) and in consultation with an experienced biostatistician (Esterhuizen, 2013). Assuming an alpha level of 0.05 and 80% power, it was determined that there should be at least 12 participants per group (24 in total) in order to detect a difference after traction between mean resting joint surface separation of the participants in whom cavitation did occur; and of those in whom cavitation did not occur. However, due to the lack of existing evidence for synovial membrane movement during joint manipulation, the minimum sample size was set at 20 per group (40 in total).

The third MCP joint of the left hand of right-handed individuals was assessed during the study. The left hand was selected due to a low incidence of left handedness among young adults and to ensure a homogenous sample (Spiegler and Yeni-Komshian, 1983). Prior to the research procedure, it was unknown whether or not cavitation will take place in a participant. Hence, to ensure that the statistical requirements were met, recruitment was continued until both the cavitation and non-cavitation groups had at least 20 participants in each group. At the end, the final sample size was 42 participants. The participants were grouped after the research procedure as follows:

Group 1: 22 participants in whom joint cavitation did take place

Group 2: 20 participants in whom joint cavitation did not occur

The research was conducted at the Chiropractic Day Clinic (CDC) and at the Radiography Clinic of DUT. Permission was obtained from the Head of the Radiography Department (**Appendix B**) and the Clinic Director of the CDC for the use of the facilities and instruments.

The participants were recruited by directly having approached individuals on the campuses of the DUT in the Ethekwini Metropolitan area. The participants did not have to be students of DUT to participate in the research. Those who expressed their willingness to participate were given a verbal explanation of the study and the letter of information (**Appendix C**) to inform them of the research. They were then asked a few preliminary questions as reflected in **Table 3.1**.

Table 3.1 Preliminary questions for prospective participants

Questions	Expected response	
1. Would you be willing to answer a few questions I have, about you possibly taking part in my research study?	Yes ✓	No
2. Are you between 18 and 28 years old?	Yes ✓	No
3. Are you right handed?	Yes	No ✓
4. Have you ever had any injuries to the middle finger of your left hand?	Yes	No ✓
5. Are you pain-free in your fingers, hands and wrists?	Yes ✓	No
6. Do you suffer from arthritis in your hands or fingers?	Yes	No ✓
7. Do you crack your knuckles or fingers once or more every day?	Yes	No ✓
8. Do you have very loose, slack or lax joints?	Yes	No ✓

If the prospective participant answered “Yes” to Question 1, 2, 3 and 5 and “No” to Question 4, 6, 7 and 8, an appointment was then scheduled at the CDC within 5 working days. If the response to Question 8 was “unsure”, it was treated as a “Yes”. They were reminded not to

“crack” their knuckles on the day of the scheduled appointment. At the CDC, the prospective participant received a letter of information and informed consent (**Appendix C**); which gave a detailed explanation of what the research study entailed, what was expected of participants and also informing the participants that they were free to withdraw from the study at any given time. The researcher then answered any question the participant may have had regarding their participation and involvement in this study. If the prospective participant agreed to participate in the study, he/she was required to sign the letter of information and the consent form (**Appendix C**). A case history (**Appendix D**), physical examination (**Appendix E**) and an orthopaedic examination of the wrist and hand (**Appendix F**) was conducted for each participant, to determine if the participant was eligible for enrolment in the study according to the inclusion and exclusion criteria. The clinical assessments at the CDC were approximately two hours long for each of the participants. If time allowed, the researcher and the enrolled participant then proceeded to the Radiography Clinic; otherwise an appointment was scheduled for a radiographic consultation within five working days of the initial consult. The participants were allocated a participant code on the data collection sheet (**Appendix G**) to protect their identity. They were instructed not to “crack” their knuckles on the day of the Radiography Clinic consultation. If they did “crack” their knuckles on the day of their consultation, a duration of half an hour was allowed for the refractory period to lapse (Unsworth et al., 1971).

3.3 INCLUSION AND EXCLUSION CRITERIA

3.3.1 Inclusion Criteria

- The participants were between the ages of 18 – 28 years to ensure a homogeneous sample.
- The participants were asymptomatic with respect to any wrist, hand or finger complaints.
- Participants were right-hand dominant to ensure sample homogeneity.

3.3.2 Exclusion Criteria

- Individuals with any contra-indications to manipulation (Bergmann and Peterson, 2011).
- Individuals with previous trauma to the left hand and wrist.
- Individuals with ligament laxity of the left third MCP joint (Brodeur, 1995).
- Females who were pregnant or suspected that they may have been pregnant. This measure was in place to prevent individuals who were prone to ligament laxity, from participating in the study.

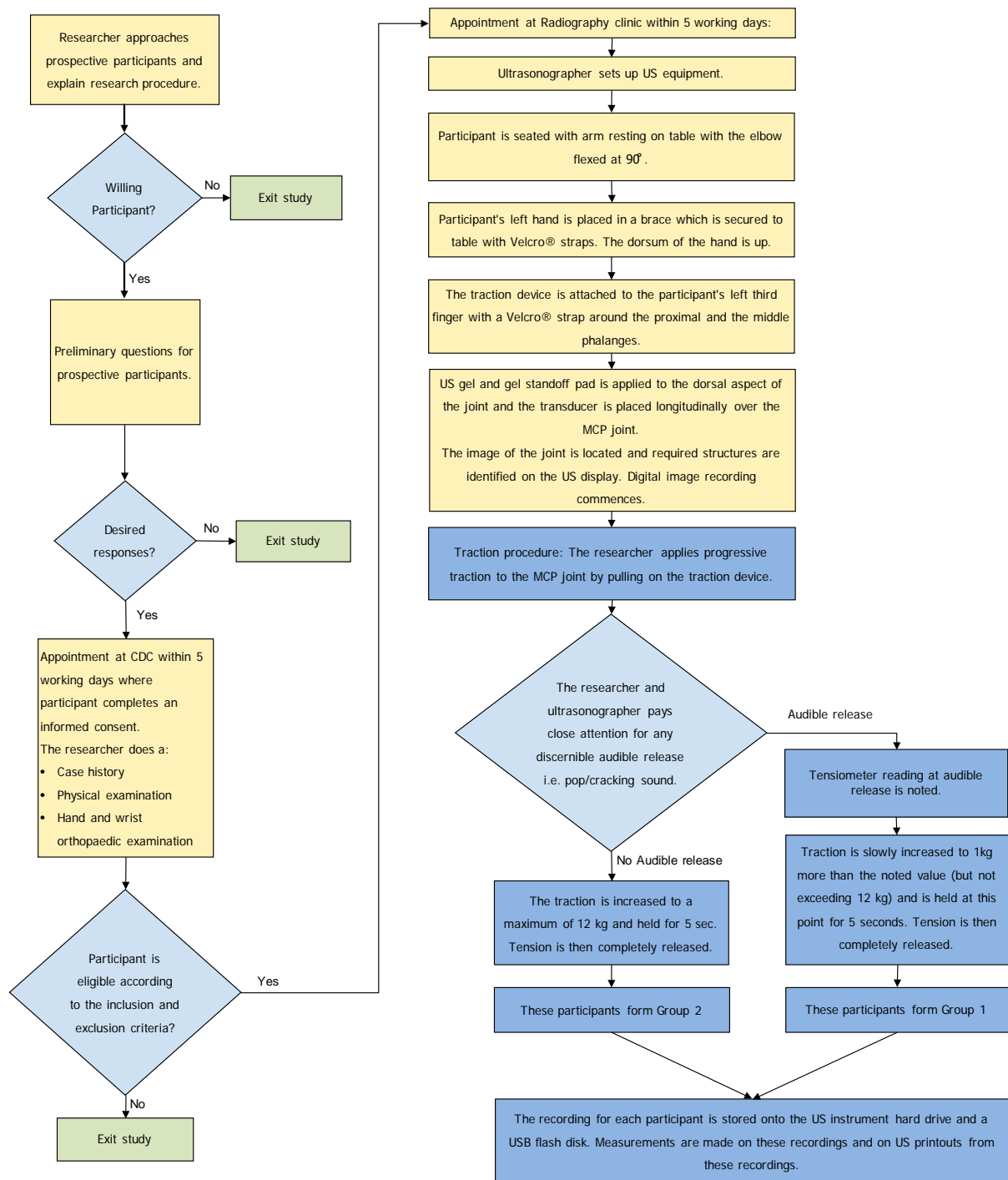


Figure 3.1

A flow chart of the general sequence of events of the study

3.4 RESEARCH PROCEDURE

Prior to the arrival of the participant at the Radiography Clinic, the air conditioning unit in the US room was set to 22° Celsius. The sonographer was a lecturer in the Department of Radiography at DUT. The sonographer switched on the US machine (Siemens ACUSON X300™ Premier edition, Siemens Medical Solutions USA), selected “B-mode” and then selected the Siemens VF 13-5 linear transducer; after which she typed in the participant code in the US instrument. The researcher then calibrated the digital tension meter with a 10 kg test weight. A plank with two 50 mm Velcro® straps was attached to the examination table with two G clamps (**Figure 3.2 (a)**).



On arrival at the Radiography Clinic, the participant was accompanied to the US room where he/she was introduced to the sonographer. The door of the US room remained closed during the research procedure to ensure the privacy of the participant; and to ensure there were no major changes in the ambient environmental temperature. The participant was seated on a height adjustable chair, which did not have wheels; and was on a flat surface in front of the table with the US instrument to the left of him/her. The researcher was seated directly opposite the participant and the sonographer to the participant's left, next to the US instrument.



The researcher adjusted the height of the chair to allow the forearm to rest on the table with the elbow flexed at 90°. The participant's left hand and wrist was placed in a wrist brace appropriate to the size of the participant's hand and wrist (**Figure 3.2 (b)**) (Unsworth et al., 1971). The participant's forearm was then positioned on the plank fixed to the table with the dorsal aspect of the hand up, with the muscles of the forearm in a relaxed state. The Velcro® straps attached to the plank were then firmly placed over the wrist brace, ensuring that the wrist was immobilised while ensuring that the participant was still comfortable.

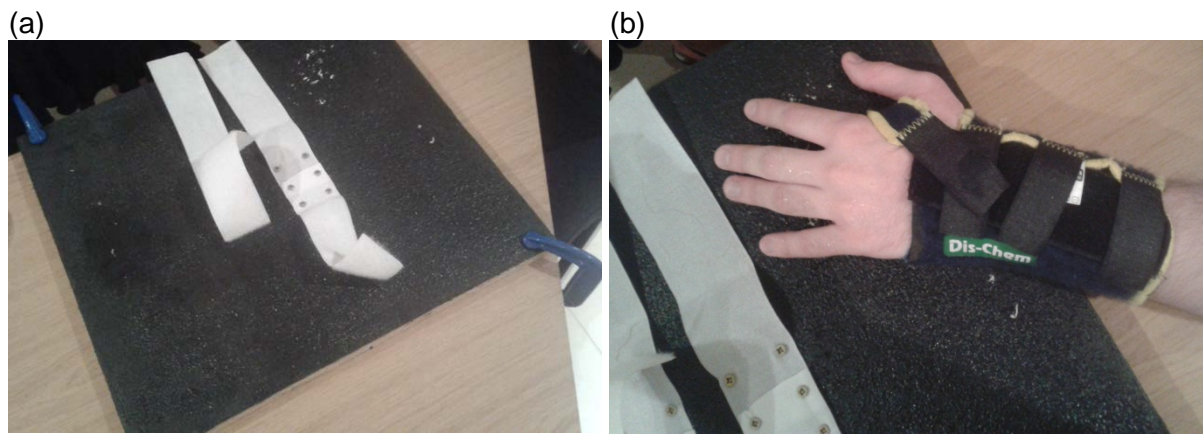


Figure 3.2 Equipment used to stabilise the arm and wrist. (a) A plank with Velcro® straps was fastened to a table with two G clamps. (b) The participants' left hand was placed in a brace.



The traction device was firmly attached to the participant's left third finger with a Velcro® strap around the proximal and the middle phalanges. The finger was positioned so that the metacarpal and proximal phalanx was axially aligned. The nail capillary bed refill was checked to ensure that digital circulation was not compromised.



The researcher enquired whether the participant felt comfortable or not. If the participant stated that he/she was comfortable, the procedure continued; if not, then he/she was given the option of withdrawing from the study.



The sonographer then applied a small amount of US coupling medium (Ultra/Phonic Free, Conductivity Gel, Pharmaceutical Innovations Inc., USA) over the dorsal surface of the distal metacarpal, the dorsal MCP joint and the proximal dorsal surface of the proximal phalanx (**Figure 3.3 (a)**). A 1.5cm X 9cm standoff pad (Ultra/Phonic Focus Conforming Gel Pad, Pharmaceutical Innovations, Inc., USA) was placed over the dorsal surface of the MCP joint. The transducer was placed longitudinally onto the standoff pad on the dorsal surface and in the median plane of MCP joint (**Figure 3.3 (b)**). The research was conducted on the left third MCP joint because previous research investigating joint cavitation was also done on third MCP joints (Roston and Haines, 1947; Unsworth et al., 1971; Semlak and Ferguson Jr, 1970; Malghem et al., 2011). The MCP joint is a convenient joint to investigate and image (Sandoz, 1976) and manipulation was applied in a long axis direction, as this is an effective method to produce a cavitation in the MCP joint (Roston and Haines, 1947; Unsworth et al., 1971; Watson and Mollan, 1990; Malghem et al., 2011). This method of manipulation allowed the ultrasound transducer to remain stationary over the MCP joint during the procedure, allowing for accurate imaging and measurements (Malghem et al., 2011).

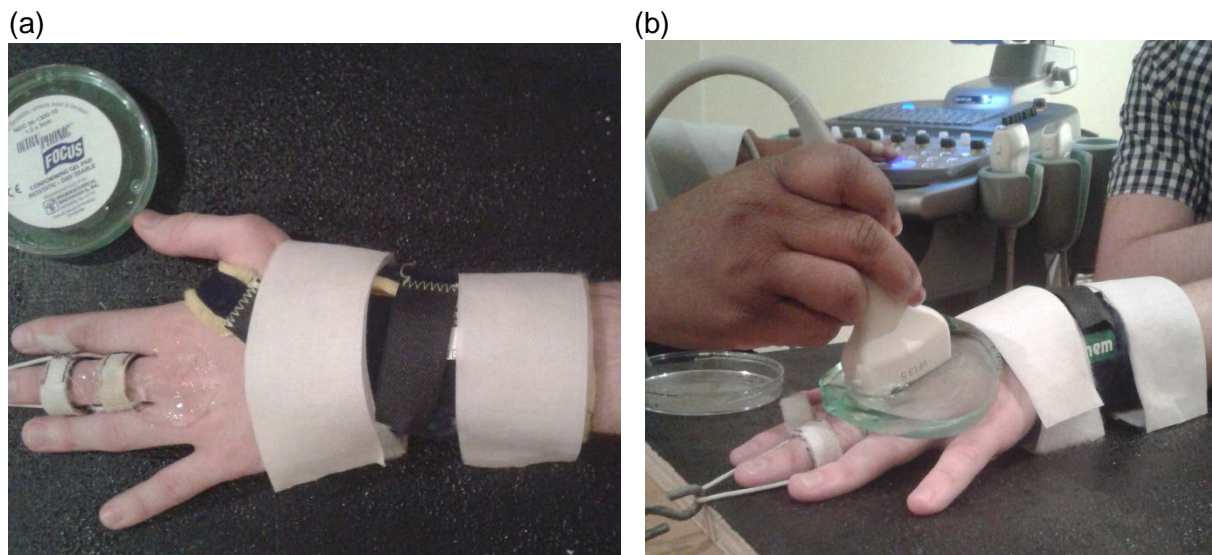


Figure 3.3 The left hand was poisoned with the dorsal surface up. The 3rd MCP joint was placed in a neutral position with the metacarpal and the proximal phalanx axially aligned. (a) The traction device was attached with a Velcro® strap above and below the PIP joint and US gel was applied to the dorsal MCP joint. (b) The gel standoff pad was then placed over the 3rd MCP joint and the US transducer positioned longitudinally over the median plane of the joint.



The sonographer located the image of the MCP joint and started the digital image recording. The structures that were visualised included the proximal and distal joint surface, the dorsal synovial membrane, the SF and the extensor digitorum tendons. Once the appropriate image was located, the sonographer maintained the image by keeping the US transducer stationary throughout the rest of the procedure.



The researcher then took hold of the traction device by gripping the handle of the digital tension meter, and moved it until the string of the traction device was tight in a long axis direction. Traction was applied to the left 3rd MCP joint by pulling the tensiometer of the traction device in the axial direction. A progressive increase in traction was applied to the finger (**Figure 3.4**). If during traction the researcher and sonographer discerned an audible release indicating that cavitation had taken place, the tension displayed on the digital tension meter was recorded. Cavitation was observed if a hyperechoic focus and a sudden joint space separation appeared on the US screen; and if there was an audible release i.e. a pop or crack sound was heard.



Figure 3.4 Scanning techniques and axial traction procedure.



The traction was increased slowly up to one kilogram more than the noted value, and was held at this point for five seconds (Unsworth et al., 1971; Bergmann and Peterson, 2011). If during traction neither the researcher nor the sonographer could discern an audible release, the traction was increased to a maximum of 12 kg. During the procedure the traction never exceeded 12 kg regardless of whether cavitation occurred or not. The traction on the MCP joint was limited to 12 kg to prevent breaching the anatomical integrity of the MCP joint and ensuring that no injury occurred to the participant. It has been previously reported that cavitation normally took place between eight to 16 kg of traction (Roston and Haines, 1947; Unsworth et al., 1971; Mierau et al., 1986) even though cavitation can occur up to as much as 23 kg of traction (Meal and Scott, 1986). Some studies investigating the cavitation of the MCP joint using long axis manipulation never recorded the amount of traction applied (Watson and Mollan, 1990; Reggars, 1999; Malghem et al., 2011). In all the literature reviewed in which this technique was used, none reported any injury or discomfort to any of the participants. Sandoz (1976) combined the load displacement graphs of Roston and Haines (1947) and Unsworth et al. (1971) and reported that the anatomical integrity of the MCP joint becomes challenged beyond 18 kg of traction. A maximum of 12 kg traction, therefore, provided a safety margin of six kg and was considered sufficient to result in cavitation in the MCP joint.



The researcher then slowly decreased the tension on the finger until the tension measured zero kg and the string of the traction device was lax. The traction device and wrist brace was

removed from the participant's hand, which was thereafter cleaned, using disposable tissue paper. This concluded the participant's involvement in the study.

3.5 TOOLS AND INSTRUMENTS

Table and Straps

Two broad Velcro® straps were attached to a wooden plank. The plank was secured to a sturdy table with two G clamps prior to the research procedure. The Velcro® straps were placed around the wrist brace to secure the wrist and forearm to the wooden plank and table.

Wrist brace

A wrist and hand brace was used to immobilise the distal radio-ulnar, radio-carpal, inter-carpal and carpometacarpal joints, but leaving the MCP joints exposed and mobile. Selections of braces in small, medium, large and extra-large sizes were used for the left hand (depending on the size of the participant's hand).

Traction device

This consisted of a digital tension meter attached to a loop of 36 kg breaking-strain Dacron string by means of a steel s-hook. The ends of the string were attached to two Velcro® straps which were fastened around the proximal and middle phalanges, respectively, of the left third digits. The device was positioned so that when the Velcro® straps were fastened, the ends of the string was positioned on the medial and lateral aspect of the finger (**Figure 3.3 and Figure 3.4**). The tension meter is an objective measurement tool used in similar studies to record the tension applied over the MCP joint (Roston and Haines, 1947; Unsworth et al., 1971; Mierau et al., 1986; Meal and Scott, 1986). The digital tension meter was a Salter Electrosamson (Salter Electrosamson 25kg x 20g, Brecknell, USA) with a maximum capacity of 25 kg and readability of 0.02 kg increments. Before each use, the instrument was calibrated using a 10 kg calibrating weight.

Diagnostic Ultrasound Instrument

The US is an objective imaging and measurement modality that is commonly used in musculoskeletal imaging (Woodhouse and McNally, 2011). High frequency US (> 10 MHz) provides images of satisfactory resolution to distinguish between intra-articular structures in the MCP joint (McNally, 2008) and high frequency US has been used to demonstrate presumed echogenic gas bubbles associated with joint cavitation in small synovial joints of the hand (Koski et al., 2006, Malghem et al., 2011, Jones, 2012) and Malghem et al. (2011) evaluated joint space measures with several different US devices. In this study all the imaging was done on a single US machine (Siemens ACUSON X300™ Premier edition,

Siemens Medical Solutions USA) by the same sonographer. All the imaging was done in B mode, using the Siemens VF 13-5 linear transducer (Siemens Medical Solutions USA), which allowed the required resolution to identify all the relevant structures (McNally, 2008; Malghem et al., 2011). The procedures were recorded onto the US machine's hard drive and after each procedure the data were transferred from the US instrument hard drive to a USB flash drive (KINGMAX Semiconductor Inc., Taiwan).

The measurements were done on these recordings using the digital calliper of this US unit. On delivery of the US unit, the manufacturer ensured that all the correct updates were in place so that the instrument and the transducers are calibrated. The handover documents (available at the Department of Radiography at DUT) verify that this was done. This US instrument and transducer combination allowed the unit's digital calliper to render measurements with increments of 0.1mm. The Siemens Acuson X300™ premium edition has a measurement accuracy of less than 3% variability in depth or distance measurements using two-dimensional (Siemens Medical Solutions, 2008).

3.6 IMAGE QUALITY AND RESOLUTION

The minimal allowable image depth for the Siemens VF13-5 transducer (Siemens Medical Solutions USA) used was 30mm resulting in a vertical image resolution of each image of 0.05 mm/pixel. The beam width of the transducer is 38.4mm resulting in a horizontal image resolution of 0.048mm/pixel. Quality assurance testing was done on the US instrument and transducer in question using a Gammex 403 GS LE precision multipurpose phantom on a protocol as prescribed by Hedrick et al (2005). It was determined that the maximum measurable axial resolution at 30mm depth was 0.5mm in keeping with the standard for this type of transducer (Hedrick et al., 2005). The lateral resolution recorded at both 30mm and 60mm was 1mm which falls within normal limits of the transducer type (Hedrick et al., 2005). The limitation of image resolution using this transducer and depth of scanning would be due to the spatial resolution and not due to the instrument's image processing and display capability (Hedrick et al., 2005).

The quality assurance testing also involved verifying the accuracy of the digital calliper. The vertical distance measurement revealed excellent accuracy with 0% error. The horizontal distance measurement accuracy was satisfactory and fell within the 3% error as determined by the manufacturer (Siemens Medical Solutions USA, 2008). The ultrasound phantom is maintained and checked for accuracy annually by a Gammex agent (**Appendix I**).

On commencement of the research there was some concern regarding the quality of some of the images from first four participants. A specialist musculoskeletal radiologist was consulted regarding the image quality, resolution and measurements, and the research procedure was demonstrated to him. He concurred that the structures we wanted to see and the relevant measurement was possible with the equipment available to us. To improve image quality further, he also suggested that we use an 18 MHz hockey stick transducer or a gel standoff pad as a coupling medium with the Siemens VF 13-5 transducer (Siemens Medical Solutions USA) (Mercouris, 2013). The 18 MHz transducer was prohibitively expensive and hence the decision was made to use the standoff pad. According to Klauser and Peetrons (2010) coupling mediums like gel standoff pads improve ultrasound image resolution and reduces fluid, tissue and vessel compression and is hence helpful in the assessment of superficial structures. A 1.5cm X 9cm conforming gel pad (Ultra/Phonic Focus Conforming Gel Pad, Pharmaceutical Innovations, Inc., USA) was used as a standoff pad on all the subsequent scans. The image quality improved considerably with the use of the standoff pad (**Figure 3.5**), and the images and measurements of the first four participants were discarded from the study.

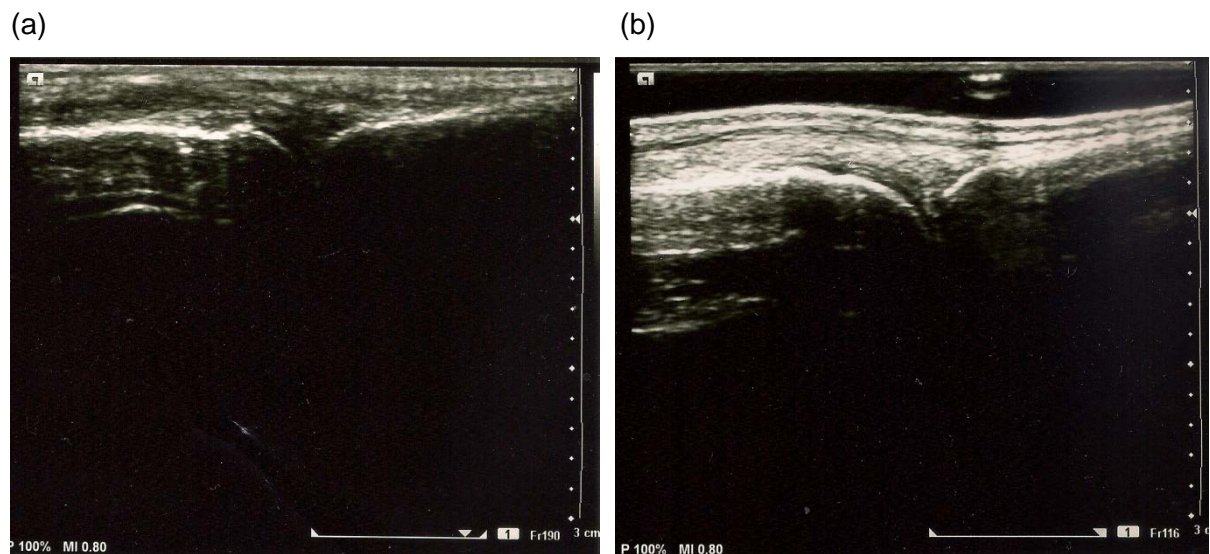


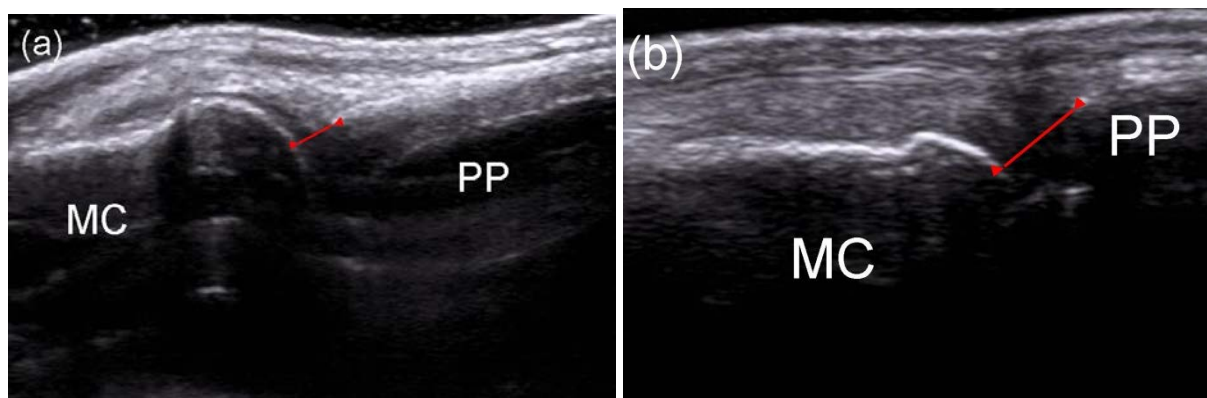
Figure 3.5 Ultrasound images of the same 3rd MCP joint: In (a) only US gel used as a coupling medium and the image quality is lacking. In (b) a gel standoff pad used as a coupling medium which results in improved image quality of the same joint.

3.7 OUTCOME MEASURES

All data gathered from the US recordings and printouts, and study-specific data such as age, height, weight, race and sex were recorded on the data collection sheet (**Appendix E**) for each participant. For the purposes of this study, the point just prior to cavitation was defined as the last recorded US image frame of the US recording, in which no hyperechoic microfoci or focus could be discerned prior to the appearance of the hyperechoic microfoci or focus. In

participants where there were no discernible hyperechoic microfoci or focus, it was recorded that no cavitation had taken place.

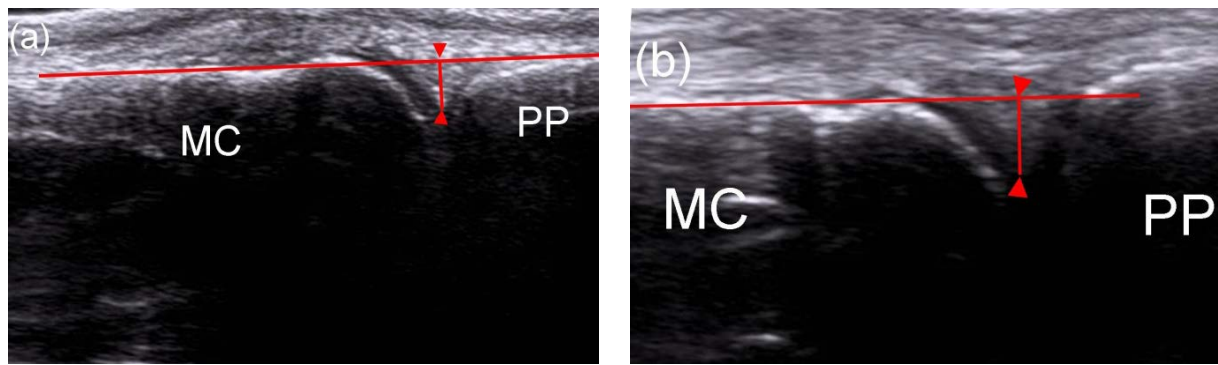
Joint surface separation: This was the minimum distance (mm) between the articulating surface of the metacarpal head and the dorsal edge of the proximal articular surface of the proximal phalanx (**Figure 3.6**). It was measured in the resting joint prior to traction (**Figure 3.6 (a)**), during traction at a point just before cavitation, during traction after cavitation (**Figure 3.6 (b)**), and again the resting joint with the traction removed. In participants where there was no evidence of cavitation, the measures were taken in the resting joint prior to traction, at maximum traction (i.e. 12 kg) and again at the resting joint with the traction removed.



MC = metacarpal; PP = proximal phalanx

Figure 3.6 Joint surface separation of the third metacarpophalangeal joint (a) at resting and (b) after cavitation during traction

Synovial membrane position: A tangential line was drawn along the dorsal surface of the shaft of the metacarpal passing over the dorsal notch if present, and through the dorsal aspect of the head of the metacarpal. A perpendicular line was then drawn from this tangential line to the palmar-most aspect of the dorsal synovial membrane. The length of this line (mm) represented the synovial membrane position. A measurement dorsal to the tangential line was assigned a negative value, but if it was palmar to this line, a positive value was assigned (**Figure 3.3**). This was measured in the resting joint prior to traction (**Figure 3.3 (a)**), during traction at a point just before cavitation, during traction after cavitation (**Figure 3.3 (b)**); and again the resting joint with traction removed. In participants where there was no evidence of cavitation, the measures were taken in the pre-traction resting joint, at maximum traction (i.e. 12 kg) and again at the resting joint with traction removed.



MC = metacarpal; PP = proximal phalanx

Figure 3.7 Synovial membrane position of the third metacarpophalangeal joint (a) in resting position and (b) at maximum traction

Gas bubbles: Gas bubbles will appear as hyperechoic foci or microfoci in the joint space (Malghem et al., 2011). Hyperechoic is defined as a bright or white US image; which is as a result of the low sound impedance of a structure causing maximum reflection of the US signal to the transducer (Yochum and Rowe, 1996; Malghem et al., 2011). The presence or absence of gas bubbles was recorded in the pre-traction resting joint, during traction at a point just before cavitation, during traction after cavitation and again at the resting joint with traction removed.

Gas bubble location: In participants in whom hyperechoic microfoci or focus were detected during the procedure (i.e. cavitation occurred); US images were printed at the stages where the joint was at rest prior to traction, during traction just prior to cavitation, during traction after cavitation and at the resting joint after the procedure. In each of these printouts, the MCP joint was divided into three equal parts by drawing two lines in a long axis direction parallel to the dorsal surface of the metacarpal shaft (**Figure 3.4**). The white arrows in **Figure 3.4** point to the gas bubbles present in the middle and dorsal thirds of the joints space during maximum traction after cavitation has taken place. If one of the lines crossed over a bubble, that bubble was recorded as present in both the adjacent thirds. The location of the gas bubbles was recorded in each of the print outs.

Traction force: The tension across the joint during the traction of the MCP joint was monitored using a digital tension meter in kg. The digital tension meter reading was recorded at a point in time in which cavitation took place. Cavitation was said to have taken place if a hyperechoic focus and a sudden joint space separation appeared on the US screen and an audible pop or crack was heard by the researcher and the sonographer.

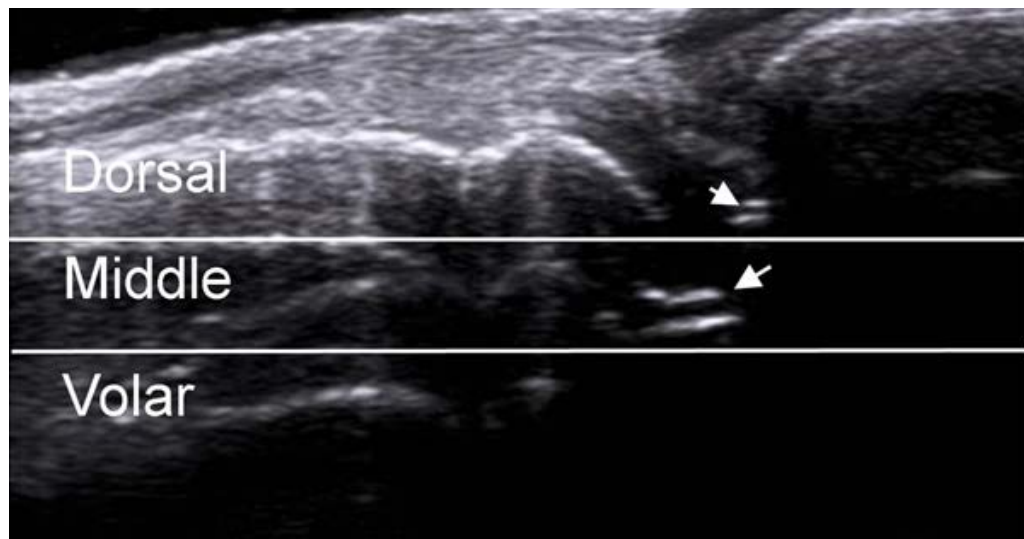


Figure 3.8 Gas bubble location in the third metacarpophalangeal joint

3.8 STATISTICAL ANALYSIS

The IBM SPSS version 20 was used to analyse the data and a p value <0.05 was considered as statistically significant. The means of the two groups were compared using independent sample t-tests, and the association between an audible release and gas bubble formation was compared using Pearson's chi square tests (Esterhuizen, 2013).

3.9 ETHICAL CONSIDERATIONS

Written informed consent was obtained from all the participants in this study. The participant's identity was not revealed in the data analysis and the clinical and radiographic information of the participants were available only to the researcher and the supervisor. The door to the ultrasound room in the Radiography Clinic was closed during the research process to ensure privacy. Long axis manipulation and cavitation of the third MCP joint is a safe procedure and there were no risks to the participants. In a recent study of 215 adults, it was reported that habitual knuckle cracking was not a risk factor for osteoarthritis of the hand (Deweber et al., 2011). All participants were thoroughly screened during the case history and physical examination to determine any contra-indication to joint manipulation. Traction of the third MCP joints was limited to a maximum of 12 kg, which is below the level at which the anatomical integrity of the joint will be challenged; thus preventing injury to the joint (Sandoz, 1976). If any participant felt any discomfort due to immobilisation of the hand and forearm or due to the traction of the third MCP joint, the procedure would have been terminated immediately. Diagnostic US is a cost-effective and commonly-used modality for imaging of the musculoskeletal system and is particularly effective in imaging the smaller joints of the hands and fingers (McNally, 2008; Woodhouse and McNally, 2011). It is a safe imaging modality with very little risk associated with it (Duck, 2008). There was no radiation exposure to the participants; unlike previous studies, which used plain film radiographs (**Table 2.5**).

CHAPTER FOUR

RESULTS

4.1 AGE AND SELECTED ANTHROPOMETRIC CHARACTERISTICS OF THE PARTICIPANTS

The total number of participants was 42, with 22 in Group 1 and 20 in Group 2. The mean, standard deviation and range of the age, height, weight and body mass index (BMI) of the 42 participants is presented in **Table 4.1**, by group and in total. Group 1 consists of participants in whom an audible release took place and Group 2 in whom no audible release occurred.

There was no significant difference between the two groups with respect to age, height, weight and BMI ($p > 0.05$; t-test). The mean \pm standard deviation of the body mass index (BMI) of the respective groups and of all participants is depicted graphically in **Figure 4.1**. The sex distribution within each group and overall is shown in **Table 4.2**. There was no significant difference between the groups, with respect to sex of the participants.

Table 4.1 The mean, standard deviation and range for age, height, weight and BMI of participants

Group		Age (yrs)	Height (m)	Weight (kg)	BMI (kg/m ²)
Group 1	Mean \pm SD	21.8 \pm 2.6	1.7 \pm 0.1	62.9 \pm 11.5	22.1 \pm 3.2
	Range	19.0 – 27.0	1.5 - 1.8	38.0 - 80.0	15.8 - 28.3
Group 2	Mean \pm SD	21.8 \pm 3.3	1.7 \pm 0.1	65.1 \pm 18.1	22.2 \pm 4.5
	Range	18.0 – 29.0	1.5 - 1.9	35.0 - 100.0	14.2 - 32.7
p value		0.984	0.819	0.638	0.765
All participants	Mean \pm SD	21.8 \pm 2.9	1.7 \pm 0.1	64.0 \pm 14.8	22.3 \pm 3.8
	Range	18.0 - 29.0	1.5 - 1.9	35.0 - 100.0	14.2 - 32.7

BMI = body mass index; SD = standard deviation; yrs = years; m = metres; kg = kilograms; kg/m² = kilogram per metre squared

Table 4.2 Sex count and percentages for Group 1, Group 2 and all participants

Group		Male	Female
Group 1	<i>n</i>	12	10
	count %	54.5%	45.5%
Group 2	<i>n</i>	13	7
	count %	65.0%	35.0%
p value		0.491	
All participants	<i>n</i>	25	17
	count %	59.5%	40.5%

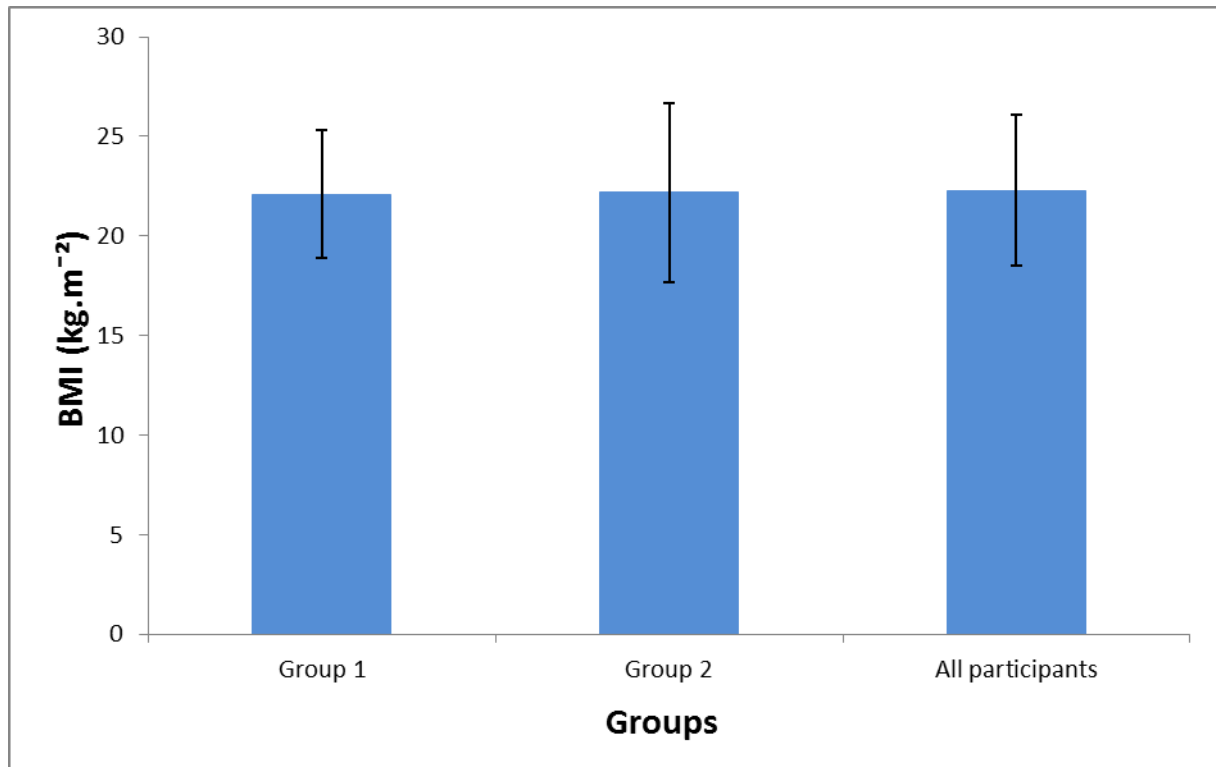


Figure 4.1 The mean \pm SD of the BMI (kg/m²) of the participants

4.2 THE EFFECT OF LONG AXIS MANIPULATION ON JOINT SURFACE SEPARATION IN THE METACARPOPHALANGEAL JOINT

The mean, standard deviation and range for joint surface separation of both groups and overall are shown in **Table 4.3**. There was no significant difference in joint surface separation between Group 1 and Group 2 at the baseline, maximum traction and in the post-procedure resting joint ($p > 0.05$; t-test). The mean \pm standard deviation for joint surface separation for Group 1 and Group 2 is depicted graphically in **Figures 4.2** and **4.3** respectively. Based on this statistical finding, the alternate hypothesis was rejected.

Table 4.3 Mean \pm SD, range and t-tests to compare the mean joint surface separation between Group 1 and Group 2 and overall; and the ranges at the specific stages of long axis manipulation

		Baseline	Pre-cavitation	Max traction	Resting
Group1	Mean \pm SD	2.0 \pm 0.4	2.8 \pm 1.0	5.5 \pm 0.8	2.0 \pm 0.4
	Range	1.5 - 3.1	1.6 - 5.7	4.1 - 6.7	1.5 - 3.0
Group 2	Mean \pm SD	2.0 \pm 0.4		5.9 \pm 1.0	2.0 \pm 0.3
	Range	1.5 - 3.2		4.1 - 7.5	1.6 - 3.1
<i>p</i> value		0.991		0.147	0.619
Total	Mean \pm SD	2.0 \pm 0.4	2.8 \pm 1.0	5.6 \pm 0.9	2.0 \pm 0.4
	Range	1.5 - 3.2	1.6 - 5.7	4.1 - 7.5	1.5 - 3.1

All joint surface separations were measured in millimetres

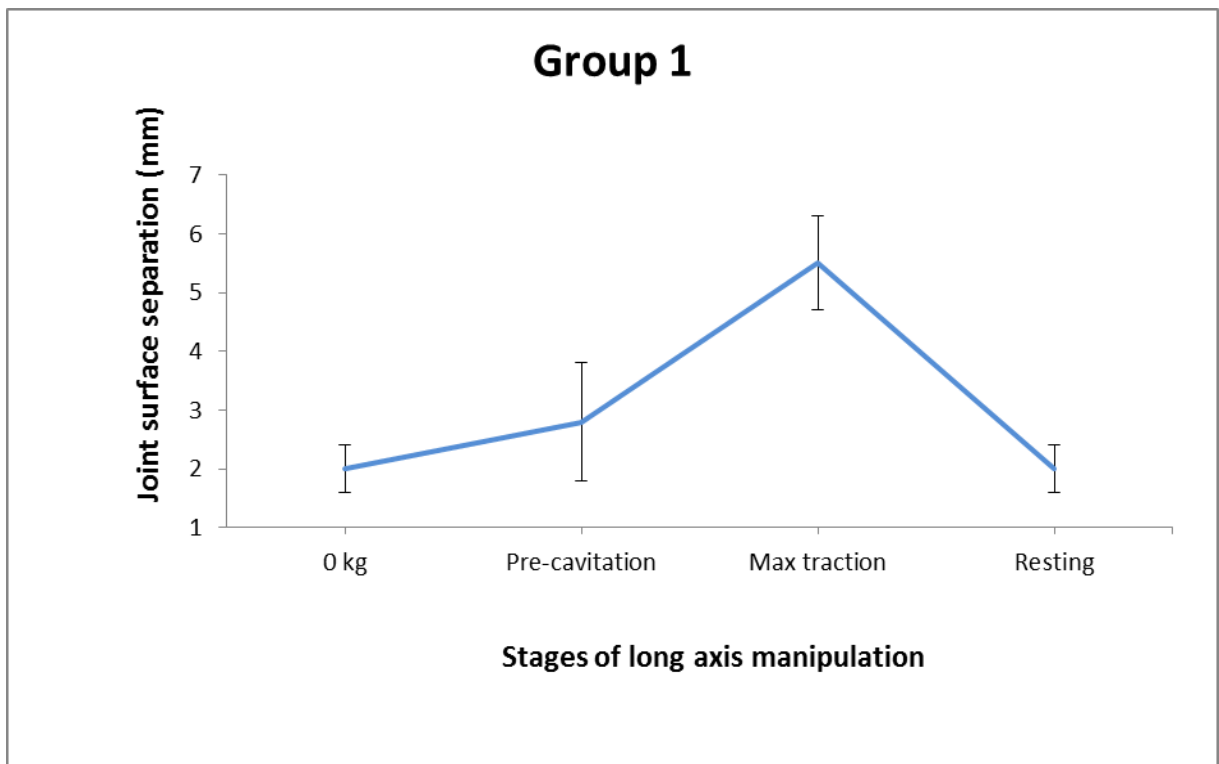


Figure 4.2 The mean \pm SD of the joint surface separation in participants who experienced an audible release

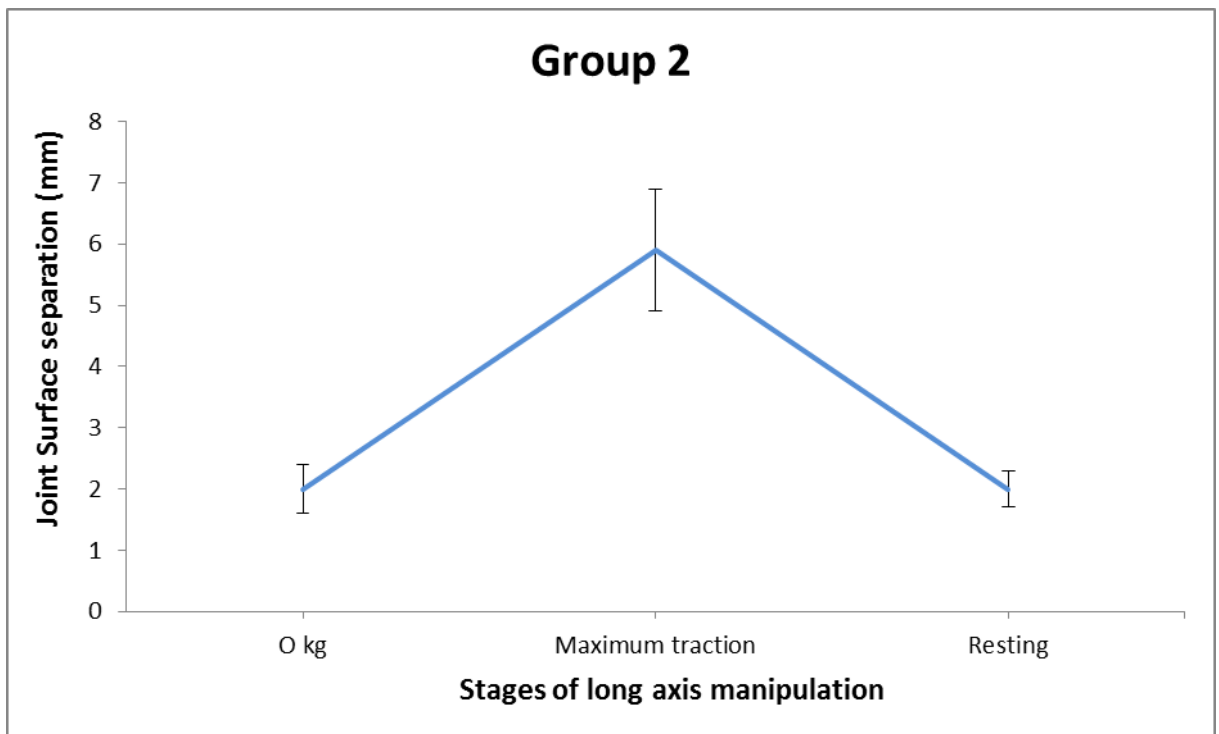


Figure 4.3 The mean \pm SD of the joint surface separation in participants who did not experience an audible release

4.3 THE EFFECT OF LONG AXIS MANIPULATION ON SYNOVIAL MEMBRANE POSITION IN THE METACARPOPHALANGEAL JOINT

The mean, standard deviation and range for the synovial membrane positions in both groups and overall are shown in **Table 4.4**. There was no significant difference between the groups at any of the stages ($p > 0.05$; t-test). The mean \pm standard deviation for joint surface separation for Group 1 and Group 2 is portrayed graphically in **Figures 4.4** and **4.5** respectively. Based on this statistical finding, the alternate hypothesis was rejected.

Table 4.4 Mean \pm SD, range and t-tests to compare the mean synovial membrane position between Group 1 and Group 2 and the ranges at the specific stages of long axis manipulation

Group1	Mean \pm SD	2.0 \pm 0.7	2.1 \pm 0.6	1.8 \pm 1.0	1.9 \pm 0.4
	Range	0.9 – 3.4	1.3 – 3.5	0 – 3.4	1.1 – 2.6
Group 2	Mean \pm SD	2.0 \pm 0.5		1.5 \pm 0.9	2.0 \pm 0.6
	Range	1.4 – 3.6		0 – 3.2	1.0 – 3.1
	<i>p</i> value	0.960		0.339	0.537
Total	Mean \pm SD	2.0 \pm 0.6	2.1 \pm 0.6	1.7 \pm 0.9	2.0 \pm 0.5
	Range	0.9 – 3.6	1.3 – 3.5	0 – 3.4	1.0 – 3.1

All the synovial membrane positions were measured in millimetres

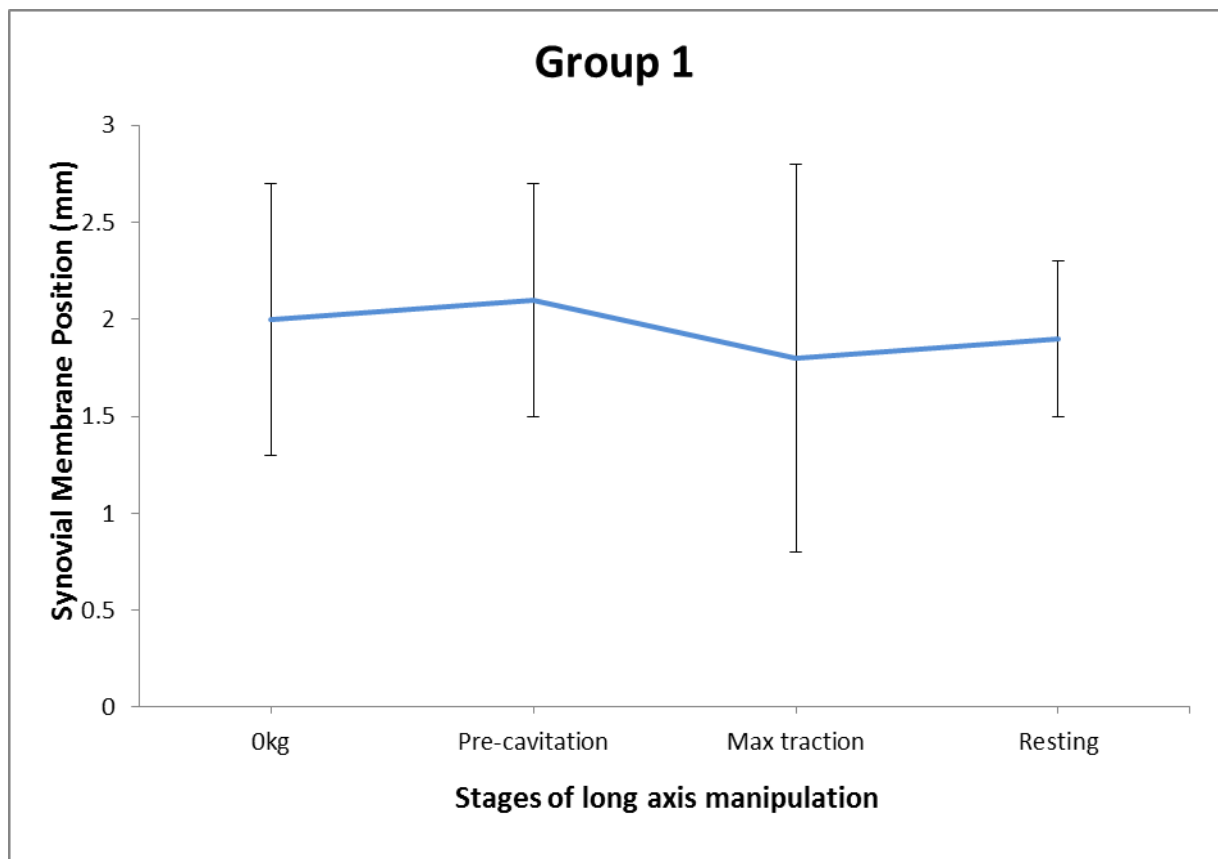


Figure 4.4 The mean \pm SD of the synovial membrane position in participants who experienced an audible release

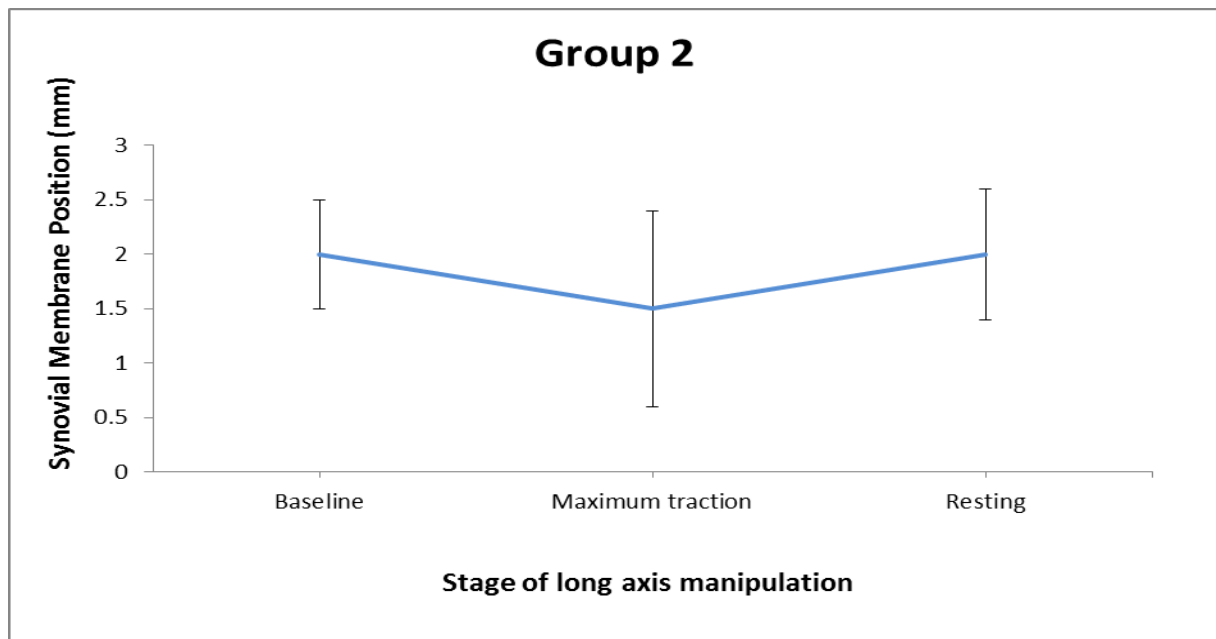


Figure 4.5 The mean \pm SD of the synovial membrane position in participants who did not experience an audible release

4.4 GAS BUBBLE FORMATION AND ITS ASSOCIATION WITH AN AUDIBLE RELEASE IN THE METACARPOPHALANGEAL JOINT

The two individuals had hyperechoic foci, presumably gas bubbles, present in the MCP joint space before the long axis manipulation procedure. The data for these were excluded from the data analysis for gas bubble formation, and its association with an audible release. In 95.5% of the participants in whom an audible release had occurred, an intra-articular gas bubble was discerned in the US recording. In those participants, in whom the traction did not result in an audible crack or pop, no gas bubble was discerned on the US images (**Table 4.5**). Pearson's chi square test yielded a value of 36.172 (No cells have an expected count of less than 5. The minimum expected count is 8.55) and gas bubble appearance was significantly associated with an audible release ($p < 0.001$). Based on this statistically significant finding the alternate hypothesis was accepted.

Table 4.5 Cross tabulation of the audible release and gas bubble appearance

			Gas bubble absent	Gas bubble present	Total
Audible release	No	<i>n</i>	18	0	18
		% within group	100.0%	0.0%	100.0%
	Yes	<i>n</i>	1	21	22
		% within group	4.5%	95.5%	100.0%
Total		<i>n</i>	19	21	40
		%	47.5%	52.5%	100.0%

4.5 GAS BUBBLE LOCATION AND MOVEMENT DURING LONG AXIS MANIPULATION

In Group 1 ($n = 22$), the gas bubbles seen as intra-articular hyperechoic signals were first observed after pre-cavitation and most (95.5%) were seen at maximum traction in this group. After releasing traction, the joint returned to the resting position and in 42.9% ($n = 9$) of the participants, the gas bubbles could not be visualised. In the remaining participants, the gas bubbles had moved to various places in the joint space. In 42.9% ($n = 9$) the gas bubbles moved up and were present in the dorsal third of the joint, in 9.5% ($n = 2$) bubbles were observed in the middle and dorsal third; and in one case gas bubbles were seen in the dorsal, middle and ventral thirds of the joint space. The stage and location of the gas bubble appearance and subsequent movement is presented graphically in **Figure 4.6**. The incidence of gas bubbles in the volar, middle and dorsal aspects of the joint is given as a percentage of the whole group ($n = 22$).

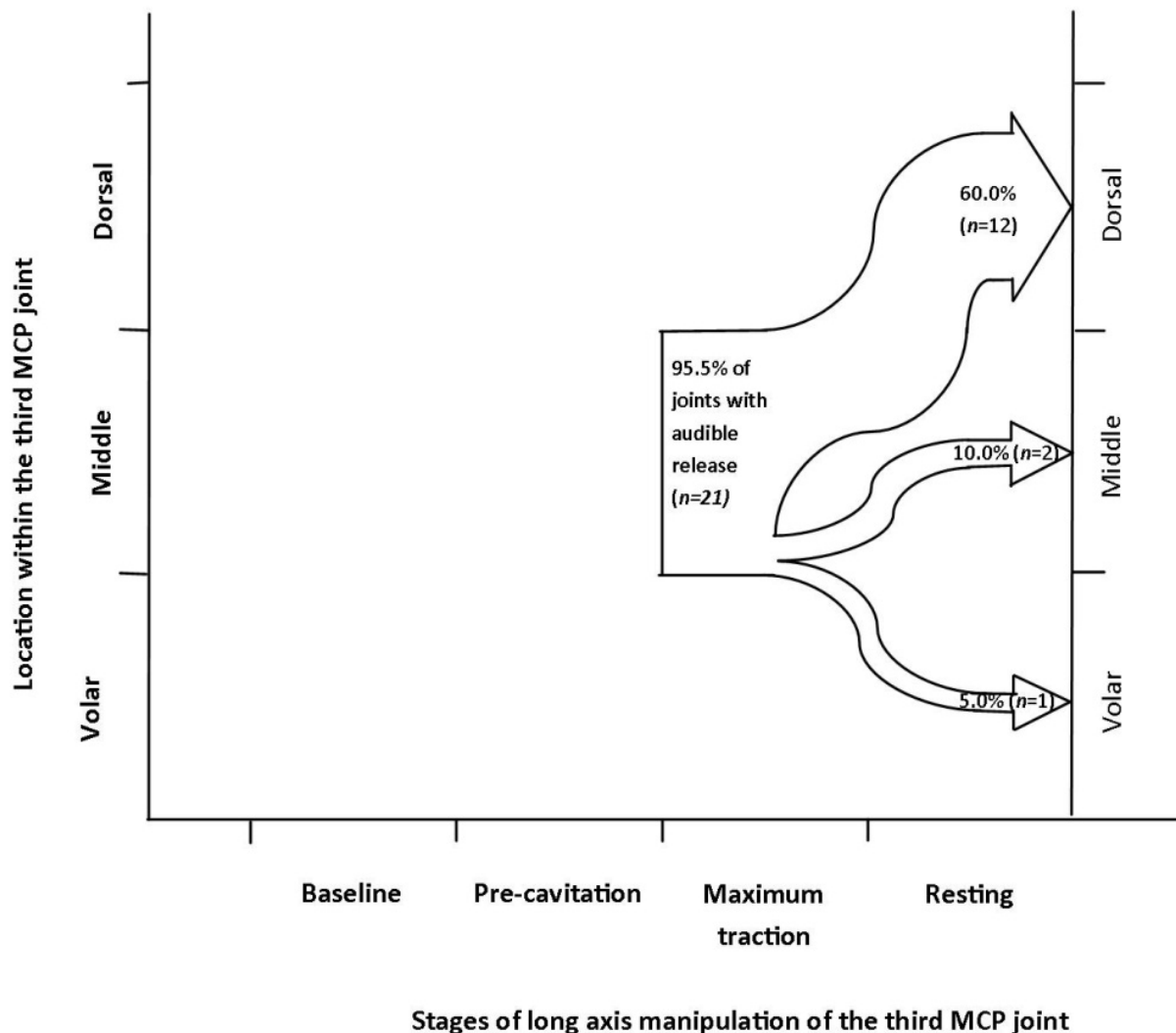


Figure 4.6 Graphic representation of the location of gas bubbles at various stages of long axis manipulation in the metacarpophalangeal joint in those who experienced an audible release

4.6 THE ASSOCIATION BETWEEN THE TRACTION FORCE AND THE GAS BUBBLE APPEARANCE DURING LONG AXIS MANIPULATION OF THE METACARPOPHALANGEAL JOINT

The mean manipulative force recorded in participants, in whom gas bubble formation was observed during long axis traction, was 5.7 kg. In the participants in whom no gas bubbles were seen, the mean distractive force was 12.0 kg. There was a significant difference between the mean long axis traction force applied in those with and in those without a gas bubble appearance (**Table 4.6**; $p < 0.001$; t -test). The frequency distribution of the force of long axis traction, at which audible release occurred, is presented graphically in **Figure 4.7**. Based on this statistically significant finding the alternate hypothesis was accepted.

Table 4.6 t-tests comparing the mean traction force (kg) between participants in who gas bubble formation was observed and in those it was not

Gas bubble/s	<i>n</i>	Mean (kg)	Std. Deviation	Std. Error Mean	Range	<i>p</i> value
Present	21	5.7	2.3	0.4987	2.3 - 11.8	<0.001
Absent	18	12.0	0.0	0.0000	12.0- 12.0	

kg = kilograms

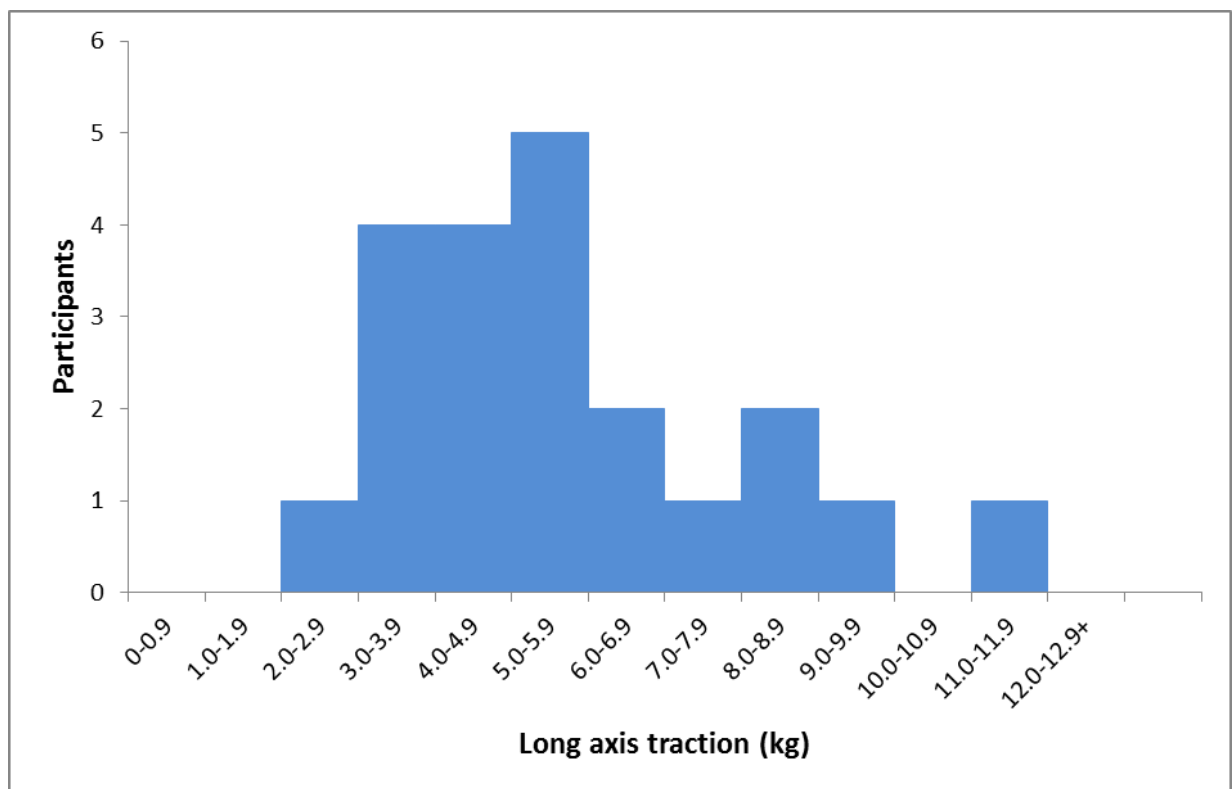


Figure 4.7 The frequency distribution of the force of traction (kg) at which an audible release occurred

4.7 REPORTING OF ANY PAIN OR DISCOMFORT DURING THE LONG AXIS MANIPULATION OF THE METACARPOPHALANGEAL JOINT

None of the participants reported discomfort or pain during the research procedure and no injury or post-procedure pain or discomfort was reported to the researcher by any of the participants.

CHAPTER FIVE

DISCUSSION

5.1 AGE AND SELECTED ANTHROPOMETRIC CHARACTERISTICS OF THE PARTICIPANTS

All participants were healthy young adults between 18 and 28 years of age; which was in keeping with the inclusion criteria of this study and ensured sample homogeneity. It also minimised the inclusion of participants with degenerative joint disease which might have influenced the results. The mean age of the participants (**Table 4.1**) was lower than that reported in previous studies that investigated cavitation in the MCP joint (Unsworth et al., 1971; Mierau et al., 1988; Malghem et al., 2011). There was no significant difference between the groups with regard to the selected anthropometric characteristics (**Table 4.1**). This shows that the data was not skewed in favour of either group; and also ensured sample homogeneity. The mean BMI for each group and overall, was within the normal range for adults (**Figure 4.1**), (World Health Organization Global Data Base on Body Mass Index, 2011); and the mean of the height and weight of participants (**Table 4.1**) was lower than that reported by Jones (2012). More males participated in the study ($n = 25$) than females ($n = 17$), but sex did not have a significant impact on the incidence of cavitation. It was observed that females seemed more apprehensive about participating in the study when they were initially approached by the researcher.

5.2 THE EFFECT OF LONG AXIS MANIPULATION ON JOINT SURFACE SEPARATION IN THE THIRD METACARPOPHALANGEAL JOINT

The mean baseline resting joint space was 2.0 mm in both the non-cavitating and cavitating joints, and there was no statistical difference between the groups (**Table 4.3**). This measurement is greater than the mean resting joint space reported in radiographic studies which varied from 1.35 mm as reported by Unsworth et al. (1971), 1.6 mm by Mierau et al. (1988) to 1.8 mm reported by Roston and Haines (1947). The measurement differences between this study and previous radiographic studies may be due to the different imaging modalities and the measuring methods that were used (**Table 2.5**). Unsworth et al. (1971) reported that the resting joint surface separation (JSS) in non-cavitating joints was 25% greater than in non-cavitating joints. This was presented as evidence of a possibly thicker SF film or lax ligaments in non-cavitating joints. However, Mierau et al. (1988) using a larger sample observed no significant difference for resting JSS between “cracking” ($n = 39$) and

“non-cracking” ($n = 15$) participants; a finding that is supported by Malghem et al. (2011). The finding of this study supports the earlier observations of Mierau et al. (1988) and Malghem et al. (2011) (**Table 2.5**).

Ultrasound recordings of the MCP joint during traction and cavitation allowed for the identification of the pre-cavitation point; one frame prior to the appearance of the echogenic gas bubble in the joint. The increase in joint separation in joints that cavitated was 0.8 mm (from a mean of 2.0 mm at baseline to a pre-cavitation figure of 2.8 mm). This was in keeping with the initial joint separation reported by Semlak and Ferguson Jr (1970). The articular surfaces separated slowly from baseline to a point, after which the speed abruptly accelerated. This acceleration is indicative of the jump in JSS reported in previous studies (Roston and Haines, 1947; Unsworth et al., 1971; Semlak and Ferguson Jr, 1970). The pre-cavitation JSS was variable, ranging from 1.6 mm to 5.7 mm (**Table 4.3**). Semlak and Ferguson Jr (1970) observed that the joint lumen is sealed against its external environment and the intra-articular volume remains constant during movement. Brodeur (1995) proposed that because the joint volume remains constant during long axis traction, any JSS increase will also result in joint capsule and synovium invagination.

The range observed in the pre-cavitation JSS could be accounted for by physiologic variations in the MCP joint, specifically the SF and/or the joint capsule and synovium; with the assumption that the joint manipulation velocity was constant and there was no muscle resistance from the participants. A difference in the SF cavitation tension threshold can exist between individuals. In SF, the HA levels and molecular weights vary, even in seemingly normal joints which could lead to variability in SF cavitation thresholds levels (Fam et al., 2007; Brujan, 2010). In joints with higher SF cavitation thresholds, increased tension levels will result in greater JSS prior to cavitation. Natural variation in the joint capsule and synovium extensibility also occurs in normal joints because of slight differences in the Type I to Type III collagen ratio in these tissues (Simmonds and Keer, 2007). Increased extensibility will result in greater JSS at a constant joint volume before SF reaches its cavitation thresholds; and it is thought that capsular and ligament laxity may prevent cavitation from taking place (Roston and Haines, 1947; Unsworth et al., 1971). Chen and Israelachvili (1991) reported that cavitation occurs when the surface separation velocity surpasses a critical level; and that separation velocity greater than this critical level, results in thin fluid film cavitation at comparatively less surface separation. In all the joints that cavitated, the critical separation velocity had to have been attained. In this study, tension was applied in a slow steady fashion, but some slight variation in the velocity of its applications may have occurred, which could also account for the variability in the pre-cavitation JSS.

The mean JSS at the maximum recorded traction in cavitated and non cavitated joints were 5.5 mm and 5.9 mm respectively and the difference was not statistically significant (**Table**

4.3). Malghem et al. (2011) reported that the mean maximum JSS was 4 mm in joints that cavitated versus a maximum of 2.8 mm in those that did not cavitate (**Table 2.5**). In their study, traction was applied by the participants themselves, using their contra-lateral hand and the traction force was not measured (Malghem et al., 2011). The differences between the two groups in this study and of those reported by previous studies for maximum measured JSS may, therefore, be explained by the dissimilarities in the amount of traction applied. Mierau et al. (1988) were unable to show a significant difference in the post-manipulative JSS between cavitated and non-cavitated joints, even with only 2.7 kg of traction being applied. The lack of a significant difference in surface separation between cavitated and non-cavitated joints indicates that even though cavitation may be an indication of successful joint gapping (Evans and Breen, 2006), the absence of a joint cavitation does not indicate that inferior joint gapping has occurred.

The post-traction JSS measures were taken on the US recording immediately after long axis manipulation, once all the traction on the joint had been eliminated. There was no significant difference between the post-traction resting JSS in cavitated versus non-cavitated joints (**Table 4.3**). The mean JSS values started at and returned to 2.0 mm from the pre-traction to the post-traction measures in the cavitated joints; and in the non-cavitated joints the mean resting values actually decreased very slightly from 2.0 mm to 1.9 mm. This is in contrast to the findings by Unsworth et al. (1971) in which, the resting JSS only returns to pre-intervention levels after 15 minutes. In their study, traction was reapplied to the joint after cavitation occurred to create joint displacement curves for the cracking and post-cracking joint. The repeated traction may have caused viscoelastic creep of the passive restraining structures of the joint, causing the slow return of the JSS after cavitation. The procedure of this study was a once-off joint traction that took a maximum of 20 seconds to complete from start to post-traction rest. Therefore, the distraction may have been inadequate for the viscoelastic creep to occur. The ranges of the JSS were very similar for Group 1 and 2 at each stage of manipulation (**Table 4.3**). This finding and the lack of significant differences of the mean JSS between the groups at these stages indicate that JSS has no apparent effect on the incidence of joint cavitation.

5.3 THE EFFECT OF LONG AXIS MANIPULATION ON SYNOVIAL MEMBRANE POSITION IN THE THIRD METACARPOPHALANGEAL JOINT

To the researcher's knowledge, this is the first study that attempted to demonstrate soft tissue movement associated with distractive manipulation in the MCP joint. The mean synovial membrane position (SMP) was similar in both baseline and post-traction resting joints, and there was no statistical difference between the cavitating and non-cavitating groups (**Figure 3.2**) (**Table 4.3**). In the resting MCP joint, the dorsal synovium could be seen

as an echogenic layer over the hypoechoic cartilage surface of the metacarpal head and the dorsal surface of the proximal phalangeal base, forming an apex where the joint surfaces approximated.

The mean pre-cavitation SMP measure was 2.1 mm and, therefore, a mean synovial membrane deflection of 0.1 mm towards the joint space had taken place from the base line SMP measure (**Table 4.3**). This is the first study that observed the synovium invagination that was proposed by Sandoz (1976) and Brodeur (1995). The pre-cavitation SMP, like the pre-cavitation JSS, was variable and ranged from 1.3 mm to 3.5 mm. The SMP variability could be influenced by the same factors of pre-cavitation JSS variability. In joints with a high SF cavitation threshold, more capsule and synovium invagination will accompany greater JSS prior to cavitation, when compared to joints with lower SF cavitation thresholds (Brodeur, 1995). In individuals with greater joint capsule and synovium extensibility, more soft-tissue invagination and a greater JSS has to occur before the capsular and synovium elastic limits are reached and SF tension levels can increase sufficiently to cause cavitation. It is also possible that above-threshold joint separation velocities caused cavitation to occur at reduced JSS, resulting in less synovial membrane invagination.

At maximum traction, the SMP in both the cavitation and non-cavitation groups was more superficial (dorsal) than the baseline measure and no significant statistical difference was found between the groups (**Table 4.4**). The dorsal joint capsule of the MCP joint is closely associated with the extensor tendon through the attachments of the extensor hood; and it is possible that at high levels of distraction, the taut tendon and extensor hood limits the amount of capsular deflection. This prevents excess synovial membrane invagination into the joint space. Other parts of the joint capsule and synovium will have to invaginate more to keep the joint volume constant. This will most likely be at the medial and lateral aspect of the joint because the volar plate and volar tendons will have a similar effect on the synovium and joint capsule as the dorsal structures.

This pre-cavitation point is synonymous with the physiologic barrier in prevailing models for joint manipulation (Sandoz, 1976) and is thought to be due to the SF cohesive forces (Semlak and Ferguson Jr, 1970). The physiologic barrier ought to prevent a joint that has not cavitated, from entering the paraphysiological zone and testing the anatomical integrity of the joint (Sandoz, 1976). However, the results of this study show that neither the JSS nor the SMP differed significantly between cavitated and non-cavitated joints at maximum traction (i.e. the anatomical limit). This finding, and the fact that no “pre-cavitation” physiologic barrier was found in the non-cavitating joints, points to the possible absence of this physiologic barrier in some individuals or the inability to breach this barrier in the joints that did not cavitate. Joint cavitation is thought to have three near-simultaneous phenomena: audible release, intra-articular gas bubble formation and a sudden separation of the articular

surfaces (Unsworth et al., 1971; Mierau et al., 1988; Watson and Mollan, 1990). The US recordings of this study showed a sudden JSS acceleration that always preceded the appearance of the hyperechoic gas presence and the surface separation reached its maximum within two frames of the US recording. Of the two visualised features of cavitation, the abrupt acceleration (jump) of JSS may herald the start of cavitation and not the visualisation of the gas bubble. Therefore, the mean real pre-cavitation measure may in fact have then been marginally lower than the measured mean of 2.8 mm. Fluid fracture described by Chen and Israelachvili (1991) is the probable mechanism for cavitation in the thin SF film separating joint surfaces. When the fluid tension threshold (SF cohesive force) is breached, fluid fracture occurs, resulting in a vacuum cavity into which vapour and dissolved gasses can escape to form the gas bubbles. The formation of a sonographically-invisible vacuum cavity may cause an increase in the intra-articular volume before the gas bubble appearance, which may also explain the JSS acceleration and the variability of the JSS and SMP at the pre-cavitation point in the US recording.

5.4 THE EFFECT OF LONG AXIS MANIPULATION OF THE THIRD METACARPOPHALANGEAL JOINT ON JOINT CAVITATION

5.4.1 Gas Bubble Formation and its Association with an Audible Release in the Metacarpophalangeal Joint

In 21 of the 22 participants, in whom the traction manipulation resulted in audible release, a hyperechoic focus and/or microfoci was observed in the joint space on the US recording (**Table 4.5**). These hyperechoic foci and microfoci most likely indicate gas bubbles and micro-bubbles respectively present in the MCP joint, due to SF cavitation (Malghem et al., 2011). In the 18 subjects that did not experience an audible release, none had gas bubbles present in the joint during the traction. The presence of the gas bubble observed with US imaging was significantly associated with an audible release ($p < 0.001$) which confirmed the findings of Mierau et al. (1988). The significant association between the audible release and the sonographically-visible gas bubble confirms the view that an audible release is necessary for a successful joint cavitation.

The mechanism of audible release i.e. sound generation, remains uncertain. It is commonly accepted that the collapse of the cavitation-associated gas bubble is responsible for the audible release (Unsworth et al., 1971; Bergmann and Peterson, 2011). Both Meal and Scott (1986) and Conway et al. (1993) reported that the audible release started marginally before a drop in tension across the joint. It is reasonable to assume that this drop in tension heralded the “jump” of the joint surfaces reported by Unsworth et al. (1971). In the current study, the sudden acceleration of joint gapping always preceded the appearance of intra-articular gas

bubble. It is, therefore, unlikely that gas bubble implosion is the cause of audible release. A possible mechanism of audible release may be the capsular snap-back suggested by Brodeur (1995). The US recordings were able to demonstrate capsular and synovial membrane movement during long axis manipulation of the MCP, and so it is theoretically possible that capsular snap back during cavitation could result in the audible release. However, it is also possible that another likely mechanism for the audible release associated with cavitation is the actual process of fluid fracture. The fact that audible release starts before a drop in tension across the joint (Meal and Scott, 1986); and that the jump in JSS happens before gas bubble formation, indicates that it is possible that audible release can coincide with fluid fracture. But the actual mechanism of how fluid fracture may cause an audible release remains unclear.

5.4.2 Gas Bubble Location and Movement During Long Axis Manipulation

In all the MCP joints, in which both an audible release and gas bubble appearance were observed, these echogenic intra-articular phenomena was first observed shortly after the commencement of the rapid acceleration in the JSS. The echogenic gas pockets were present in the middle third of the joint space from their inception up to the point where the joint surfaces were maximally separated in the US recordings. From the point of maximum JSS to the resting post-traction joint, the gas bubbles decreased in size, in some cases breaking into multiple micro-bubbles and moved to various places in the joint space. In nine of the participants the gas bubble could not be visualised in the post-traction resting joint. The MCP joints were scanned on the dorsal longitudinal aspect using a high frequency linear transducer. High frequency transducers have limited tissue penetration and some bubbles located in the MCP joints may not have been visualised (Berquist, 2006). It is also possible that post-cavitory micro bubbles lodged in the joint recesses could not be visualised using the longitudinal view. Of the 12 other participants, 9 had gas bubbles that floated up into the dorsal third of the joint space, two had gas bubbles that were present in both the dorsal and middle thirds of the joint space (**Figure 4.6**); and in one case, gas bubbles were present in the dorsal, middle and volar thirds of the joint space. To the researcher's knowledge this is the first study that describes gas bubble behaviour in the MCP joint during and after joint manipulation.

These gas bubbles are thought to originate when the cavitation process causes SF to fracture, forming a vacuum cavity into which water vapour and dissolved gases escape (Chen and Israelachvili, 1991). The density of both respiratory gases and vapour is lower than water, which is a major liquid component of SF, and so the gas micro-bubbles visualised in the dorsal joint space may have floated there (Giancoli, 2013). When the joint surface returns to its resting position after distraction, the bubbles will also be squeezed from

between the surfaces to the periphery of the joint. As stated previously, high frequency US does not penetrate very deep into the joint and as such, volarly-located gas bubbles may be present, but not visualised. The gas bubbles seen in the middle and volar thirds of the joint appeared to be trapped between the stationary joint surfaces and movement of the joint may have well resulted in further migration.

5.5 THE ASSOCIATION BETWEEN THE LONG AXIS MANIPULATION FORCE AND GAS BUBBLE APPEARANCE IN THE THIRD METACARPOPHALANGEAL JOINT

The mean traction force at which cavitation occurred was 5.7 kg and in all the individuals in whom no features of cavitation were observed during traction, the tension was increased to 12 kg. There was a significant difference between mean traction force applied to those with and without a gas bubble appearance ($p < 0.001$; t-test) (**Table 4.6**). The mean of 5.7 kg at which cavitation was seen did not fall in the range of the 8 to 10kg as reported by Roston and Haines (1947), the 10 to 16 kg reported by Unsworth et al. (1971), or the 3.6 to 4.1 kg reported by Semlak and Ferguson Jr (1970) who used a larger sample size than both Roston and Haines (1947) and Unsworth et al. (1971). The individual long axis manipulation tension measures were variable ranging between 2.3 kg to 11.8 kg. This compares well with previous studies (**Table 2.5**) and may well have been even more variable if traction was not limited to 12 kg. This variability may be accounted for by the reasons given for the JSS and SMP variability viz. the variability of SF cavitation threshold, capsular extensibility and separation velocity of the joint surfaces. In the 18 joints which did not cavitate, the mean tension was significantly higher than that reported for cavitating joints (**Table 4.6**). Roston and Haines (1947) and Unsworth et al. (1971) suggested that joint laxity and the inability of a subject to relax his/her muscles may have prevented cavitation. It is also reasonable to assume that a high SF cavitation threshold or greater capsular extensibility (without becoming lax) may prevent sufficient SF tension to cause cavitation before the maximum of 12 kg was reached. It is also likely that the velocity at which these joints were distracted was insufficient to breach the threshold required for thin SF film cavitation. Since a relatively steady distractive force was applied, it would be interesting to observe the effect differing velocities have on joint cavitation. This requires further investigation.

Meal and Scott (1986) observed traction forces at cavitation ranging between 3 and 23 kg and reported that less force was required to cavitate the MCP joint in subjects that were habitual knuckle crackers. The results of this study is in contrast to their findings as none of the participants were habitual knuckle crackers; and the greatest incidence of cavitation occurred between 5.0 to 5.9 kg of traction (**Figure 4.7**), which is in the mid spectrum of the

range (**Table 4.6**). There are a few possible explanations for this. In their study, Meal and Scott (1986) (**Table 2.5**) repeatedly manipulated the MCP joints of a small group of subjects with, sometimes, only the refractory period between the manipulations. This could have led to viscoelastic creep of the joint capsule and ligaments, resulting in subsequent manipulations requiring decreasing amounts of traction force to cause the cavitation. They also did not report the maximum traction tension threshold. The possibility exists that if higher tension forces were used in the current study, a greater incidence of joint cavitation and a greater mean traction force could have resulted. It would be interesting to observe the incidence of joint cavitation and the levels of manipulative force required to cause the cavitation of the MCP joints in habitual knuckle crackers versus non-habitual crackers.

5.6 CLINICAL IMPLICATIONS OF THE FINDINGS

This study found that the audible release associated with manipulation of the MCP joint indicates that a successful joint cavitation has occurred. As previously mentioned, joint cavitation appears to be the only objective indication that a technically successful manipulation has been applied to a joint (Sandoz, 1976; Mierau et al., 1988; Brodeur, 1995; Reggars, 1999; Evans and Breen, 2006). The clinical effects of joint manipulation are thought to be mediated by the mechanical separation of the joint surfaces, and the stretching and movement of the articular soft tissue (Evans, 2002). This investigation demonstrated that long axis manipulation of the MCP joint was able to cause the mechanical separation of the joint surfaces; regardless of whether an audible release took place or not. Manual therapists should, therefore, be aware that even though cavitation may be an indication of successful joint gapping, the absence of a joint cavitation does not indicate that inferior joint gapping has occurred. This study also provided dynamic visualisation of the synovium movement during long axis manipulation of the MCP joint. This is the first experimental evidence that articular soft tissue can be affected by joint manipulation. It is, therefore, hypothetically possible for joint manipulation to influence articular soft tissue lesions (adhesions) as described previously (Jones et al., 1989; Lewit, 1999; Trudel and Uhthoff, 2000; Evans, 2002) and to stimulate capsular and synovial sensory receptors (Korr, 1975; Wyke, 1979; Brodeur, 1995; Pickar, 2002). Another possible therapeutic effect of joint manipulation may be a momentary improvement in nutrient supply to the articular surfaces. The separation of the joint surfaces and movement of the synovium during manipulation causes a net flow of SF from the periphery of the joint to the opening gap between the joint surfaces. This will bathe the avascular articular cartilage with nutrient-rich SF. Joint cavitation, as a result of joint manipulation, will also cause considerable turbulence of SF because of fluid fracture and bubble inception (Chen and Israelachvili, 1991). The turbulence of the SF and gas bubble migration observed in this study could potentially activate joint receptors, resulting in

neurophysiological effects reported by Clark et al. (2011). The persistence of micro-bubbles between the synovium and the osseous or cartilage surfaces of the joint may cause stimulation of the soft tissue sensory receptors. These micro-bubbles persist in the joint for the duration of the refractory period (Unsworth et al., 1971), and may result in neurophysiological stimulation that persists after the direct manipulative stimulation has ended.

This study was performed in the MCP joints of young, healthy individuals and the results observed may be different to those of individuals with pathological joints. Joint pathology is often associated with anatomical changes of the synovium, osseous and ligamentous structures (Boon and Davidson, 2006). Capsular and synovial thickening, and inflammatory joint synovitis may reduce soft tissue extensibility preventing cavitation from taking place. Arthritic and traumatic joint injury often causes a joint effusion and changes in SF consistency; and rheological properties have been reported (Falchuk et al., 1970; Goetzi et al., 1974). The abnormal SF volume and consistency may change its behaviour during manipulation and large SF volumes may prevent it from reaching the tension threshold required for cavitation to occur. Further investigation is, therefore, required to establish the effect of joint manipulation and joint cavitation on pathological joints and how these effects relate to the documented clinical outcomes.

None of the participants of this study reported any discomfort, pain or injury during or after the research procedure. The safety of long axis manipulation of the third MCP joint and the accessibility of this joint to imaging, makes it the ideal joint to further investigate the phenomena associated with joint manipulation and cavitation. Furthermore, the use of the diagnostic US demonstrated the changes in the MCP joint in real-time which is a considerable advantage over plain-film radiographs and the expensive CT and MRI diagnostic imaging. The use of diagnostic US made imaging easy to conduct and the images were of sufficiently high resolution to allow for the necessary assessments

5.7 LIMITATIONS OF THIS STUDY

A concern of this study is that transducer placement and the consistency of the resultant images was not quantified, which could affect the credibility of the results and conclusions of this study. Kawchuk et al. (2000) demonstrated the accuracy and reliability of ultrasonic quantification of osseous and soft tissue displacement in the indentation loading of bovine para-spinal muscle loading. In this technique called ultrasound indentation, the transducer placement was fixed or mechanically assisted to ensure consistency of placement and the osseous movement was induced by the mechanically assisted transducer in a uniaxial direction. The measurements of displacement in the uniaxial direction were found to be accurate and reliable on the resultant images (Kawchuk et al., 2000; Kawchuk et al., 2001;

Kawchuk et al., 2006). However, in this study the osseous and soft tissue movement is not generated by the transducer and the displacement force acts on tissues at $\pm 90^\circ$ to beam direction. The manufacture and validation of a system to establish the consistency of transducer location and anatomical landmark identification for this study would have been prohibitively expensive. Another problem with fixed transducer placement in this study would be that the axial traction was applied by a hand held device and, therefore, slight deviation from the axial plane of the joint was possible which would result in loss of image and/or the landmarks. Even if traction was in a precise axial direction, there is no guarantee that the desired landmarks would remain in the imaging plane if the transducer was to remain in a fixed position. It is much more likely that due to differences in soft tissue compliance of peri-articular structures that some lateral, anterior-posterior and/ or rotational deviation does occur which would defeat the object of standardised transducer placement. It is the view of this researcher that fixing of the transducer in line with the above mentioned studies will compromise image consistency. Other methods of standardising transducer placement will have to be explored prior to attempts to validate these findings.

Another concern is that no evidence is available to demonstrate that consistent images of the same anatomical landmarks could be generated. In this study, the researcher relied on visual identification and tracking of the specified anatomical landmarks in the US images without any objective way to quantify and verify this. Kawchuk et al. (2000) demonstrated that visual assessment as a simple technique of US identification and tracking of anatomical landmarks does not yield a larger error than more sophisticated techniques. Like the transducer placement, prior validation testing was not feasible and there are no means known the researcher to retrospectively generate data about consistency of images and anatomy. In saying this, the selected transducer placement and scanning techniques were in line with previous studies (Naredo et al., 2006; Möller et al., 2009; Malghem et al., 2011; Ellegaard et al., 2012; Iagnocco et al., 2012) and these US techniques are relied upon in pragmatic settings to reveal the relevant structures for this study (Grassi et al., 1993; Raza et al., 2003; Lee and Healy, 2005; Scheel et al., 2005; McNally, 2008; Sharma and Sharma, 2009). No literature could, however, be found on the sensitivity or reliability of identifying anatomical landmarks with high frequency ultrasound in a non-pathological MCP joints. Sensitivity and reliability testing of the ultrasound identification of the normal structures in the MCP joints needs to be done in order to verify the findings of this study.

In this study, all the observations and measurements were made by a single observer and no second unbiased observations or measurements were done. As previously mentioned, no literature on the sensitivity or reliability of detecting normal MCP joint structures was available. Therefore, a limitation of this study may be that no inter- or intra-observer reliability could be determined from the data which could have affected the results of this study and

hence the conclusions that has been reached. However, considering that 1) US scanning is routinely used in a pragmatic setting to detect the relevant anatomy in this study (Grassi et al., 1993; Raza et al., 2003; Lee and Healy, 2005; Scheel et al., 2005; McNally, 2008; Sharma and Sharma, 2009), 2) the techniques used were according to previous work investigating the cavitation phenomenon in the MCP joint (Malghem et al., 2011) and 3) that similar methods of scanning the MCP joint yielded moderate to good reliability in detecting and measuring structures in the MCP (Szkudlarek et al., 2003; Naredo et al., 2006; Szkudlarek et al., 2006; Möller et al., 2009; Iagnocco et al., 2012), it is the opinion of the author that the results are likely to be accurate, but this requires future reliability testing and validation of the results before firm conclusions are reached.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSION

The mean JSS measurements at the baseline, maximum traction or post-traction stages of long axis manipulation were not significantly different between those in whom cavitation occurred and in those that it did not. The ranges of the JSS for the cavitation and non-cavitation groups were very similar at each stage of manipulation. The JSS measures, therefore, appear to have no direct effect on the incidence of joint cavitation. This study was able, for the first time, to demonstrate synovial membrane movement associated with long axis manipulation; and found there were no significant differences between the groups with respect to the mean SMP at the baseline, maximum traction or post-traction stages of the manipulation. There was substantial pre-cavitation JSS and SMP variability, which indicated that, even in a seemingly homogenous sample, there is some unaccounted-for physiological trait that influences the cavitation process.

In 21 of the 22 participants in whom the manipulation resulted in an audible release, gas bubble formation was observed. The Alternate Hypothesis (H_a) which stated that there would be a significant association between audible release and the presence of intra-articular gas bubbles was, therefore, accepted. This indicates that at least in the MCP, audible release is a reliable indicator of a successful joint cavitation. It was also shown that sonographically-visible gas bubble inception occurs in the middle of the joint space and that gas micro-bubbles persisted in some of the joints after SF cavitation. The majority of the observable micro-bubbles migrated to the dorsal aspect of the joint lumen after the joint manipulation. The mean traction force at which cavitation occurred was 5.7 kg and was significantly different to the mean of 12 kg in participants in whom no cavitation could be elicited.

The implications of this study are significant when one considers that the absence of cavitation may be accounted for by inherent physiological variability of the joint and not necessarily due to substandard joint manipulation. The results have shown that joint cavitation is a strong indication of successful joint manipulation.

6.2 RECOMMENDATIONS

The major recommendations arising from the results of this study are:

- A method to standardise and measure transducer placement needs to be devised and validated to ensure that in future studies of the MCP joint, the consistency of the images can be quantified.
- Sensitivity and reliability testing of the ultrasound identification of the normal structures in the MCP joints should be investigated
- The study should be repeated with multiple observers, independent of the research procedure and with more than one observation for each of the measurements of joint surface separation and synovial membrane position in future studies using ultrasound quantification to describe manipulation of the MCP joint.
- The role of the velocity of joint manipulation on joint cavitation should be investigated.
- The effects of habitual knuckle cracking versus non habitual knuckle cracking on the incidence of joint cavitation and levels of manipulative force required to cause the cavitation should be investigated.
- The results of this study should be published in a peer-reviewed, accredited journal and presented to health care professionals such as primary contact physicians, orthopaedic surgeons and chiropractors in order to promote a better understanding of the anatomical effects of joint manipulation, improve the acceptance of this therapeutic intervention by the scientific and health care community; and to improve the rationale for using joint manipulation by manual therapists in certain clinical conditions.

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INSTITUTIONAL RESEARCH ETHICS COMMITTEE (IREC)

1 February 2013

IREC Reference Number: **REC 82/12**

Mr W P Fogwell
19 Savage Street
Carrington Heights
Durban
4001

Dear Mr Fogwell

The effect of long axis manipulation of the third metacarpophalangeal joint on articular surface separation, peri-articular soft tissue movement and joint cavitation

I am pleased to inform you that Full Approval has been granted to your proposal REC 82/12.

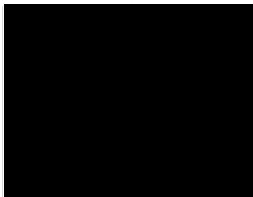
The Proposal has been allocated the following Ethical Clearance number IREC 005/13. Please use this number in all communication with this office.

Approval has been granted for a period of one year, before the expiry of which you are required to apply for safety monitoring and annual recertification. Please use the Safety Monitoring and Annual Recertification Report form which can be found in the Standard Operating Procedures [SOP's] of the IREC. This form must be submitted to the IREC at least 3 months before the ethics approval for the study expires.

Any adverse events [serious or minor] which occur in connection with this study and/or which may alter its ethical consideration must be reported to the IREC according to the IREC SOP's. In addition, you will be responsible to ensure gatekeeper permission.

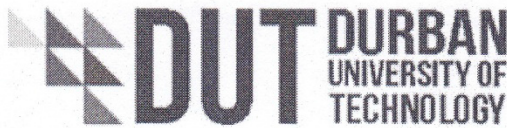
Please note that any deviations from the approved proposal require the approval of the IREC as outlined in the IREC SOP's.

Yours Sincerely



Dr D F Naude
Chairperson: IREC

APPENDIX B



Department of Radiography

Memo

To: Whom it may concern.
From: Mrs S Naidoo
HOD/Senior Lecturer: Radiography
Date: October 31, 2012
RE: Permission for ultrasound scans for Chiropractic Research.

To Whom It May Concern,

Student Name: William Fogwell
Student Number: 20710713
Research Title: The effect of long axis traction of the third metacarpophalangeal joint on articular surface separation, peri-articular soft tissue movement and joint cavitation.
Supervisor: Dr Junaid Shaik
Contact Number: 079 465 6879
Email: williamfogwell@yahoo.com

I hereby authorize permission for part of the above Chiropractic student's research to be conducted in the Department of Radiography at the Durban University of Technology. The ultrasound scans will be performed by Ms Z Dlodla (lecturer and qualified sonographer).

Yours truly

A black rectangular box redacting the signature of Mrs S Naidoo.

Mrs S Naidoo (Head of Department: Radiography)

Faculty of Health Sciences Ritson Road Campus

Durban University of Technology
P.O.Box 1334
Durban 4001
Tel: 27 31 3732875/2450
Fax: 27 31 3732574
Email: naleden@dut.ac.za

APPENDIX C



INSTITUTIONAL RESEARCH ETHICS COMMITTEE (IREC) LETTER OF INFORMATION

Dear Participant

Thank you for taking an interest in this research project. Your willingness to participate in this study is greatly appreciated. Kindly find below a brief explanation of the purpose and methods of this study.

Title of the Research Study:

The effect of long axis manipulation of the third metocarpophalangeal joint on articular surface separation, peri-articular soft tissue movement and joint cavitation.

Principal Investigator/s/researcher: William Peter Fogwell
Co-Investigator/s/supervisor/s: Dr. J. Shaik (M. Tech. Chiro.; M. Med. Sci. (SM))

Brief Introduction and Purpose of the Study:

Chiropractic is a healthcare profession that specialises in spinal and musculoskeletal health and often use methods like joint manipulation to treat muscle, joint or nerve pain. Joint manipulation often results in a popping or cracking sound. This process is called joint cavitation. Studies have shown that through this cavitation process, certain nerve endings are stimulated around the joint and the surrounding soft tissue (i.e. muscles, tendons and ligaments) which in turn can have a therapeutic effect and reduce muscle tension and reduce pain.

Finger or spinal joints have two bones connected to one another at the joint. Each bony surface is covered with cartilage and has a fluid called synovial fluid in between. This fluid is contained by a group of ligaments, known as a joint capsule. Research has shown that joint cavitation results in three events: a cracking sound, a sudden separation of the bones in the joint and a gas bubble appearing in the joint. These studies did not demonstrate the effect of cavitation on the joint capsule despite the obvious importance of the joint capsule in producing the beneficial effects of joint manipulation.

The purpose of this study is to investigate the effect that joint cavitation has on the joint capsule and other soft tissue surrounding this joint and how this is related to the cracking sound, the gas bubble formation in the joint and the separation of the articulating surfaces of the joint.

Outline of the Procedures: The participant will be required to attend two consultations.

a) First consultation:

The first consultation at the Chiropractic Day Clinic (CDC) will be done to check if you are eligible for the research according to inclusion and exclusion criteria. The researcher will do a case history, physical examination and an examination of the hand and wrist which will take a maximum of 2 hours.

Inclusion Criteria: To be part of this study you must...

- Be between the ages of 18-28 years.
- You may have no injuries to the middle finger of your left hand.
- Your fingers, hands and wrist must be pain free.
- You do not crack your knuckles or fingers once or more per day.

Exclusion criteria: You will not be eligible to take part in this study if ...

- You are contraindicated to manipulation (you have a fracture, your ligaments are too lax, you have a medical condition such as cancer or bone infection or osteoporosis).
- You are left handed.
- You have previous trauma to the left hand or wrist.
- You have ligament laxity of the middle finger of your left hand (i.e. you are able to bend your fingers and thumb much more than most normal people).
- For females: If you are pregnant or suspect you may be pregnant. This is prevent us including anyone with excessive movements in the joints).

b) Second consultation:

A second appointment will be scheduled for an eligible participant at the Radiography Clinic within 5 working days of the first appointment.

At the second consultation the actual research procedure will be done in the ultrasound room at the Radiography Clinic. Please do not crack your knuckles before this consultation. You will be seated and your right hand will be placed into a wrist brace which will be attached to a table. A strong twine that is connected to a digital tension scale, will be attached to your middle finger with Velcro straps. The ultrasonographer will apply ultrasound gel to top of the finger and will start scanning the joint. The procedure will be recorded on to the ultrasound machine. During the scan the researcher will apply tension to the right middle finger by gently pulling the scale. At this point two possibilities exist. If there is a sudden crack sound in a joint of the finger the tension on the finger will be increased slightly (1kg). If there is no sound the traction will be increased to 12 kg traction. After either of these possibilities the tension will be decreased completely. At the end of the procedure the hand will be cleaned and removed from the brace and the Velcro straps will be removed from the finger. If you experience any unpleasant sensation in your finger or hand, please inform the researcher immediately and the procedure will be stopped; and you are free to withdraw from the study. The second consultation will take a maximum of 30 minutes.

c) Responsibilities of the participant:

- To arrive on time for the scheduled appointments.
- To not crack your knuckles on the day of the consultations.

d) Venue

- First consult: Chiropractic Day Clinic
Durban University of Technology, Mansfield Campus
11 Ritson Rd
Berea
Durban
- Second consult Radiography Clinic
Durban University of Technology, Mansfield Campus
11 Ritson Rd
Berea
Durban

Risks or Discomforts to the Participant: The participant may experience discomfort in the hand and wrist during the research procedure because of the wrist brace, the Velcro straps around the right middle finger or the actual tension of the right middle finger.

Benefits:

To the Researcher: The researcher will graduate with a Masters degree in Chiropractic. The results of the study will be published as an article in a peer reviewed journal with the researcher and supervisor as the authors.

To the Participant: The participant will receive a voucher for one free conservative treatment for a musculoskeletal complaint at the CDC valid for 3 years from the date of the consult at the Radiography clinic.

Reason/s why the Participant May Be Withdrawn from the Study:

- If the participant fails to show up for an appointment.
- If the participant experiences any unpleasant sensations during the traction procedure.

Remuneration: There will be no financial remuneration for participating. The participant will receive a voucher for one free Chiropractic treatment for a musculoskeletal complaint at the CDC valid for 3 years from the date of the consult at the Radiography Clinic.

Costs of the Study: No cost for the participant.

Confidentiality: The names of all participants will be coded on the data sheets. The clinical and radiographic information of the participants will be available only to the researcher and the supervisor. The door to the ultrasound room in the Radiography clinic will be closed during the research process to ensure privacy.

Research-related Injury: If there is injury to the joint or hand because of the research procedure, the participant will be given free treatment for the injury at the CDC. If the participant feels any discomfort because of the bracing of the hand and forearm or due to the traction of the right middle finger, the procedure will immediately be stopped and the participant will be assessed for an injury that might be causing the discomfort. If an injury has occurred, the participant will be given free treatment at the CDC for the injury.

Persons to Contact in the Event of Any Problems or Queries:

Please contact the researcher (0794656879), my supervisor (031 373 2588) or the Institutional Research Ethics administrator on 031 373 2900. Complaints can be reported to the DVC: TIP, Prof F. Otieno on 031 373 2382 or dvctip@dut.ac.za.

General:

Please note that participation in this study is voluntary and that a participant can withdraw from the study at anytime. 40 participants are required for this research study. A copy of this letter will be supplied to the participant and in order to for you to become a participant you need to sign the informed consent part of this letter.



**INSTITUTIONAL RESEARCH ETHICS COMMITTEE (IREC)
CONSENT**

Statement of Agreement to Participate in the Research Study:

- I hereby confirm that I have been informed by the researcher, _____ (name of researcher), about the nature, conduct, benefits and risks of this study - Research Ethics Clearance Number: _____,
- I have also received, read and understood the above written information (Participant Letter of Information) regarding the study.
- I am aware that the results of the study, including personal details regarding my sex, age, date of birth, initials and diagnosis will be anonymously processed into a study report.
- In view of the requirements of research, I agree that the data collected during this study can be processed in a computerised system by the researcher.
- I may, at any stage, without prejudice, withdraw my consent and participation in the study.
- I have had sufficient opportunity to ask questions and (of my own free will) declare myself prepared to participate in the study.
- I understand that significant new findings developed during the course of this research which may relate to my participation will be made available to me.

_____ Full Name of Participant	_____ Date	_____ Time	_____ Signature / Right Thumbprint
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I, _____ (name of researcher) herewith confirm that the above participant has been fully informed about the nature, conduct and risks of the above study.

_____ Full Name of Researcher	_____ Date	_____ Signature
----------------------------------	---------------	--------------------

_____ Full Name of Witness (If applicable)	_____ Date	_____ Signature
---	---------------	--------------------

_____ Full Name of Legal Guardian (If applicable) Date	_____ Signature
---	--------------------

APPENDIX D
DURBAN UNIVERSITY OF TECHNOLOGY
CHIROPRACTIC DAY CLINIC
CASE HISTORY

Patient: _____ Date: _____

File # _____ Age: _____

Sex : _____ Occupation: _____

Intern : _____ Signature _____

FOR CLINICIANS USE ONLY:

Initial visit

Clinician: _____ Signature : _____

Case History:

Examination:

Previous:
Current:

X-Ray Studies:

Previous:
Current:

Clinical Path. lab:

Previous:
Current:

CASE

STATUS:

PTT:	Signature:	Date:
------	------------	-------

CONDITIONAL:

Reason for Conditional:

Signature:

Date:

Conditions met in Visit No:

Signed into PTT:

Date:

Case Summary signed off:

Date:

Intern's Case History:

1. Source of History:

2. Chief Complaint : (patient's own words):

3.		Present Illness:	
		Complaint 1	Complaint 2
< Location			
< Onset : Initial:			
Recent:			
< Cause:			
< Duration			
< Frequency			
< Pain (Character)			
< Progression			
< Aggravating Factors			
< Relieving Factors			
< Associated S & S			
< Previous Occurrences			
< Past Treatment			
< Outcome:			

4. Other Complaints:

5. Past Medical History:

- < General Health Status
- < Childhood Illnesses
- < Adult Illnesses
- < Psychiatric Illnesses
- < Accidents/Injuries
- < Surgery
- < Hospitalizations

6. Current health status and life-style:

- < Allergies
- < Immunizations
- < Screening Tests incl. x-rays
- < Environmental Hazards (Home, School, Work)
- < Exercise and Leisure
- < Sleep Patterns
- < Diet
- < Current Medication
- < Analgesics/week:
- < Tobacco
- < Alcohol
- < Social Drugs

7. Immediate Family Medical History:

- < Age
- < Health
- < Cause of Death
- < DM
- < Heart Disease
- < TB
- < Stroke
- < Kidney Disease
- < CA
- < Arthritis
- < Anaemia
- < Headaches
- < Thyroid Disease
- < Epilepsy
- < Mental Illness
- < Alcoholism
- < Drug Addiction
- < Other

8. Psychosocial history:

- < Home Situation and daily life
- < Important experiences
- < Religious Beliefs

9. Review of Systems:

- < General
- < Skin
- < Head
- < Eyes
- < Ears
- < Nose/Sinuses
- < Mouth/Throat
- < Neck
- < Breasts
- < Respiratory
- < Cardiac
- < Gastro-intestinal
- < Urinary
- < Genital
- < Vascular
- < Musculoskeletal
- < Neurologic
- < Haematologic
- < Endocrine
- < Psychiatric

PHYSICAL EXAMINATION: SENIOR
Patient Name : _____ **File no :** _____ **Date :** _____

Student : _____ **Signature :** _____

VITALS:

Pulse rate:			Respiratory rate:	
Blood pressure:	R	L	Medication if hypertensive:	
Temperature:			Height:	
Weight:	Any recent change? Y / N		If Yes: How much gain/loss	Over what period

GENERAL EXAMINATION:

General Impression	
Skin	
Jaundice	
Pallor	
Clubbing	
Cyanosis (Central/Peripheral)	
Oedema	
Lymph nodes	Head and neck
	Axillary
	Epitrochlear
	Inguinal
Pulses	
Urinalysis	

SYSTEM SPECIFIC EXAMINATION:

CARDIOVASCULAR EXAMINATION

RESPIRATORY EXAMINATION

ABDOMINAL EXAMINATION

NEUROLOGICAL EXAMINATION

COMMENTS

Clinician:
Signature :

APPENDIX F

Hand and wrist regional examination

Patient: _____
 Intern: _____
 Clinician: _____

File no: _____ Date: _____
 Signature: _____
 Signature: _____

Observation:

	Right	Left
1. bony and soft tissue contours		
2. hand posture		
3. vasomotor changes		
4. scars, skin creases, and muscle wasting		
5. fingernails		
6. dominant hand		

Palpation:

Posterior surface		Right	Left
1.	Anatomical snuff box		
2.	Carpal bones		
3.	Metacarpal bones		
4.	Phalanges		
5.	Pulses and capillary refill		
6.	Radial styloid		
7.	Radial (Lister's) tubercle		
8.	Ulnar styloid		
9.	6 extensor tendon tunnels	Right	Left
	i. Abd poll long Ext poll brev		
	ii. ECRB ECRL		
	iii. Ext poll long		
	iv. Ext digit Ext index		
	v. Ext digiti mini		
	vi. ECU		

Anterior surface		Right	Left
1.	Tendons (Lat to med)		
	a. Flexor carpi radialis		
	b. Flexor poll longus		
	c. Flexor digit super		
	d. Flexor digit profund		
	e. Palmaris long		
	f. Flexor carpi ulnaris		
2.	Palmar fascia and intrinsic muscles		

Active movements

Passive movements

	Right	Left		Right	Left
1.	Pronation (85-90°)		Tissue stretch		
2.	Supination (85-90°)		Tissue stretch		
3.	Ulnar deviation (15°)		Bone		
4.	Radial deviation (30-45°)		Bone		
5.	Wrist flexion (80-90°)		Tissue stretch		
6.	Wrist extension (70-90°)		Tissue stretch		
7.	Finger movements				
8.	Thumb movements				

Resisted isometric movements

		Right	Left
1.	Flexion		
2.	Extension		
3.	Radial dev		
4.	Ulnar dev		
5.	Finger	Opposition	
		Adduction	
		Abduction	

Functional movements

Gross Grip Strength

Precision Grip Strength

		Right	Left		Right	Left
1.	fist grip			pinch		
2.	cylinder grip			chuck		
3.	hook grip			key		
4.	sphere grip					

Special tests

		Right	Left
1.	Finkelstein's test		
2.	Tinel's		
3.	Phalan's test		
4.	Reverse phalan's test		
5.	Allen's test		
6.	Froment's sign		
7.	Watson's test		
8.	Scaphoid compression test		
9.	Lunatotriquetral ballotment test		
10.	Bunnel littler test		
11.	Tight retinacular test		
12.	Ligament stability		

Joint play movements

Hand and fingers

			Right	Left
1.	MCP and PIP + DIP	Long axis extension		
		AP, PA glide		
		Rotation		
		Side glide		
2.	Distal inter-metacarpals	AP, PA glide		
		Rotation		

Wrist

			Right	Left
1.	Long axis extension			
2.	AP glide			
3.	Carpal extension			
4.	Carpal flexion			
5.	Ulnar deviation			
6.	Radial deviation			
7.	UI-men-triq AP+ PA glide			
8.	Inf rad-ulnar rotation	AP, PA glide		
		Rotation		

APPENDIX G
Data collection sheet.

Participant number:	Date:
Gender:	Age:
	Occupation:
Height:	Weight:
	Group:

	Base line before traction			During traction						Resting joint after traction		
				Pre cavitation			Post Cavitation					
Joint surface separation (mm)												
Synovial membrane position (mm)												
Gas bubble/s present	Yes		No	Yes		No	Yes		No	Yes		No
Location of gas bubble/s	Dorsal	Middle	Ventral	Dorsal	Middle	Ventral	Dorsal	Middle	Ventral	Dorsal	Middle	Ventral
Audible release	Yes		No	Yes		No	Yes		No	Yes		No
Traction force (kg)												

APPENDIX H

DURBAN UNIVERSITY OF TECHNOLOGY

Patient Name:		File #:	Page:
Date:		Visit:	Intern:
Attending Clinician:		Signature:	
<div style="display: flex; justify-content: space-between;"> <div style="width: 35%;"> S: Numerical Pain Rating Scale (Patient) Least 0 1 2 3 4 5 6 7 8 9 10 Worst </div> <div style="width: 15%; text-align: center;"> Intern Rating <input style="width: 40px; height: 20px;" type="text"/> </div> <div style="width: 30%; text-align: right;"> A: </div> </div> <div style="display: flex; justify-content: space-between;"> <div style="width: 35%;"> O: </div> <div style="width: 15%; text-align: center;"> P: </div> <div style="width: 30%; text-align: right;"> E: </div> </div> <div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> Special attention to: </div> <div style="width: 50%;"> Next appointment: </div> </div>			
Date:		Visit:	Intern:
Attending Clinician:		Signature:	
<div style="display: flex; justify-content: space-between;"> <div style="width: 35%;"> S: Numerical Pain Rating Scale (Patient) Least 0 1 2 3 4 5 6 7 8 9 10 Worst </div> <div style="width: 15%; text-align: center;"> Intern Rating <input style="width: 40px; height: 20px;" type="text"/> </div> <div style="width: 30%; text-align: right;"> A: </div> </div> <div style="display: flex; justify-content: space-between;"> <div style="width: 35%;"> O: </div> <div style="width: 15%; text-align: center;"> P: </div> <div style="width: 30%; text-align: right;"> E: </div> </div> <div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> Special attention to: </div> <div style="width: 50%;"> Next appointment: </div> </div>			


APPENDIX I



Gammex

Ultrasound Phantom Maintenance Data Sheet
Date: 11/30/2012

Phantom Model: 403GS LE-0.5 dB/cm/MHz
Phantom Status: new
Phantom Mass: 2739.8g
Phantom Serial Number: 802259-3943-5

Tested by: bv 

Test Conditions:
Test Temperature: 73.4 degrees F
Test Humidity: 24.8 % RH

The Reference phantom is: 400276 Ref 0.5
The reference attenuation is: 0.506 dB/cm/MHz
The test phantom differs from the reference phantom by -0.09 dB/cm
The computed attenuation coefficient of the phantom is 0.49 dB/cm/MHz

The intensity of the image signal at 2 cm is 79.80
The intensity has dropped 50% at a depth of 10.00 cm

Pin to Pin Distance Measurement:

Vertical Pin Spacing:

Nominal Distance = 2.00 cm	Error:
Pin 1 to 2: 2.00 cm;	0.1%
Pin 2 to 3: 2.00 cm;	0.0%
Pin 3 to 4: 2.00 cm;	0.0%
Pin 4 to 5: 2.00 cm;	0.0%
Pin 5 to 6: 2.00 cm;	0.0%
Pin 6 to 7: 2.00 cm;	0.1%
Pin 7 to 8: 2.00 cm;	0.0%

Horizontal Pin Spacing:

Nominal Distance = 3.00 cm,	Error:
Pin 1 to 2: 3.06 cm;	1.8%
Pin 2 to 3: 3.06 cm;	1.8%
Pin 3 to 4: 3.11 cm;	3.7%

Gray Scale Target Relative Echogenicity

Target 2 (-6 dB):	-6.17 dB
Target 3 (+6 dB):	6.26 dB
Target 4 (+12 dB):	13.61 dB

GAMMEX

7600 Discovery Drive
P.O. Box 620327
Middleton, WI 53562-0327 U.S.A.

1-608-828-7000
1-800-GAMMEX 1
FAX 1-608-828-7500

E-mail: sales@gammex.com • <http://www.GAMMEX.com>