Examination of a new arthrodesis technique for equine cervical vertebrae

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A thesis submitted in fulfilment of the requirements for the degree of Master of Veterinary Medicine (M.V.M.)

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October 2010

Abstract

Objectives - To investigate a new technique for fusion of equine cervical vertebrae: 1. Report the findings from a single case. 2. Examine the biomechanical properties of the construct in cadaver specimens and compare the biomechanical properties with the currently used arthrodesis technique.

Study design - Case report, followed by two *in vitro* biomechanical investigations.

Sample population - Single case for the case report then cadaveric adult equine cervical vertebral columns for biomechanical testing.

Methods -A three month old foal with cervical stenotic myelopathy was deemed too small for treatment with a kerf cut cylinder, so arthrodesis was performed using a ventrally placed locking compression plate. The case was followed and reported.

A test modulus was developed to allow biomechanical testing of a single cervical vertebral articulation and the biomechanical properties of different implants were investigated. The investigation was followed by further investigation in different loading directions.

Results -The foal responded well to treatment and had improved 2.5 neurological grades by 30 months post-operatively.

Results of the two biomechanical studies demonstrated that the biomechanical properties of the LCP construct were comparable to superior to the KCC constructs in flexion, extension and lateral flexion.

Conclusions -The LCP technique has potential as an arthrodesis technique for equine cervical vertebrae. Evaluation of the technique in live adult cases is warranted.

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Acknowledgements

The author would like to thank a large number of people and organisations for the help and support provided for this research project:

Professor Christoph Lischer for his idea for the project, his help with the practical testing and write up of the project. His help and support throughout the master's project and surgical residency are greatly appreciated.

Mr Martin Kummer for his help with the case report, specifically in collecting information.

Mrs Jane Heller for her statistical advice and particularly her patience and willingness to help at short notice.

Dr Bob Bailey for his help in project design and expertise in materials testing.

Mr John Walmsley for his expertise in implant placement and help with paper review.

Mr Neil Cox at the University of the West of Scotland for his help and expertise with the mechanical test unit and data collection.

The staff in the post mortem room at the University of Glasgow, for so readily collecting the cadaver specimens, in particular Richard and Michael.

All the staff of the Weipers Centre at the University of Glasgow, who assisted with the research and put up with my cadaver specimen storage and manipulation.

The Iris Gates Fund, who helped fund my residency; which allowed further dissemination of the work presented here at a number of international conferences.

The AO foundation, Synthes® and Wilson Tools®, without whom the materials required for testing would not have been available.

Finally, I would like to thank my wonderful family for all their support over the years.

Author’s declaration

I declare that, except where explicit reference is made to the contribution of others, that this thesis is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

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Chapter One

1. Literature Review and background to the study

1.1 Introduction

Neurological gait deficits resulting from cervical vertebral disease have been reported in horses since 1860 (Mayhew 1860). By 1938 these deficits were recognised frequently enough that a new term "wobbler syndrome" was introduced to describe them (Errington 1938). These gait deficits frequently lead to horse inability to perform athletically and can result in more severe problems such as recumbancy and even death. As a result, much work has been performed investigating these conditions; in 1979 the first surgical treatment for one of these conditions was described (Wagner *et al*. 1979a), since then surgical treatments have been gradually gaining more recognition around the world.

1.2 Anatomy of the equine cervical spine

The equine species in common with all other mammals (except the manatee (*Trichechus*) and two sloth species (*Choleopus* and *Bradypus*)) (Galis 1999), has seven cervical vertebrae; extending from the atlas (C1) to C7 (Figure 1). Similar to the other domestic species the morphology of the cervical vertebrae is complicated, with multiple articular surfaces, bony prominences and foraminae (Getty 1975) (Figure 2). This complicated morphology facilitates a wide range of cervical movement: allowing the neck to flex and rotate in multiple planes, whilst protecting the spinal cord and nerve roots from damage. The degree of flexibility in the equine neck is evident when considering that the normal horse is able to reach the tip of its nose to either tuber coxae caudo-laterally and to the ground behind its extended forelimbs ventrally.

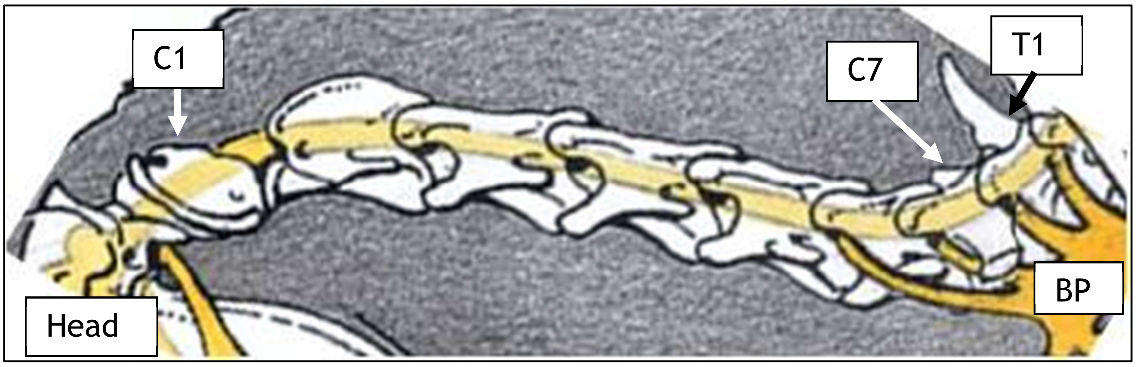


Figure 1: Diagram of equine cervical vertebrae. Spinal cord and nerve tissue shaded yellow. C1=1st cervical vertebra; C7=7th cervical vertebra; T1=1st thoracic vertebra; BP=brachial plexus.

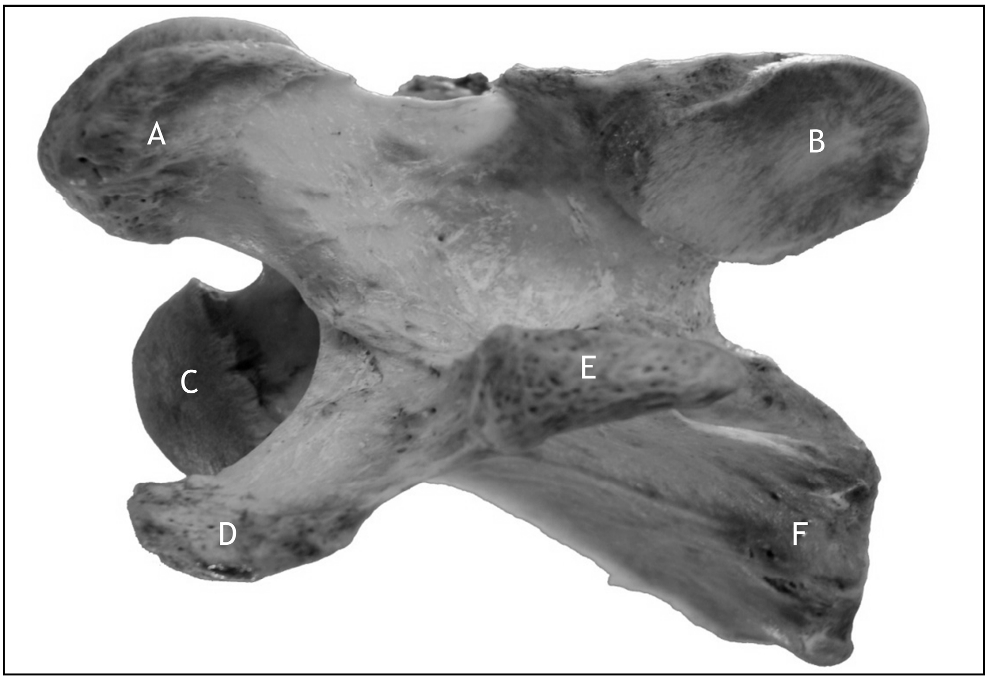


Figure 2: Photo of a fifth cervical vertebra from the left side. A=outer surface of left cranial articular process joint; B=articular surface of left caudal articular process joint; C=cranial articular surface of vertebral body; D=cranial tubercle of left transverse process; E=end of left transverse process; F=outer aspect of caudal articular surface of vertebral body.

Development of the vertebral column occurs via a complex pathway with a series of carefully regulated steps during gastrulation and neurulation. The embryologic origin of the spine is in a cell that is induced to migrate out of the somite toward the notochord and the neural tube. Sclerotomal cells collect in segments at the embryonic midline and surround the neural tube and the notochord. In a series of steps called “metameric shift” the sclerotomes then recombine with each other to form segments (which become the precartilaginous vertebral bodies). Spinal nerves exit the neural tube and pass between the newly formed vertebral bodies. Because of complexities in the formation of the atlas and axis, eight cervical somites result in only seven vertebrae; with eight cervical nerves (Rush 2006).

1.3 Pathology of the equine cervical spine

Pathology of the cervical vertebrae can result in restriction to the normal range of movement, damage to the spinal nerves and/or compression of the spinal cord and subsequent neurological deficits, which can all be of major clinical significance. These pathologies can be either developmental or acquired: Developmental pathologies can be divided into three categories (Icenogle and Kaplan 1981):

1. Malformation – the result of failed embryonic differentiation of a specific structure causing it to be absent or improperly formed.
2. Disruption – the destruction of an anatomic part during the foetal stage of gestation that formed normally during the embryonic period.
3. Deformation – the alteration in the shape or structure of an individual vertebra or segment that had initially differentiated normally during the foetal and/or postnatal periods.

Reported developmental pathologies include: Cervical stenotic myelopathy (CSM), atlanto-axial subluxation / luxation, atlanto-occipital malformation / luxation, block vertebrae, butterfly vertebrae and hemivertebrae.
Acquired pathologies can be the result of single traumatic incidents, such as falling during racing; or the result of repetitive trauma, or overloading due to abnormal neck positioning; such as over flexing of the neck during disciplines such as dressage. Reported acquired pathologies include: fractures, luxations / subluxations and osteoarthritis.

The details of some of the more common conditions observed in horses are discussed below.

1.3.1 Common developmental pathologies

1.3.1.1 Cervical Stenotic Myelopathy

Background:

Cervical Stenotic Myelopathy (CSM) is the leading cause of non-infectious spinal cord ataxia in the horse (Nixon *et al.* 1982; Powers *et al.* 1986; Papageorges *et al.* 1987; Rush Moore *et al.* 1992) and is estimated to affect approximately 2% of Thoroughbred horses (Rooney 1969). As such, it has major implications for horse welfare and economics. In this developmental condition, cervical vertebral deformation leads to stenosis of the vertebral canal which results in intermittent or continuous compression of the spinal cord (Rooney 1969; Reed *et al.* 1985; Powers *et al.* 1986). Intermittent compression is seen with cervical vertebral instability (CVI), which occurs most commonly at C3-C4 and C4-C5 during neck ventroflexion (Reed *et al.*1981; Rantanen and Gavin 1981; Wagner *et al.* 1987; Papageorges *et al.* 1987) and is classed as dynamic compression or Type 1. Continuous compression irrespective of neck position occurs with cervical static stenosis (CSS), which occurs most commonly in the caudal cervical region C5 to C7 (Powers *et al.* 1986; Papageorges *et al.* 1987) and is classed as Type 2 compression.

The condition has been shown to occur most commonly in fast growing, young male horses with Thoroughbreds and Quarter Horses being overrepresented (Rooney 1963; Mayhew *et al.* 1978; Reed *et al.* 1981; Powers *et al.* 1986; Wagner *et al.* 1987; Mayhew 1989). In a study of ataxic horses (mostly Thoroughbreds) which underwent myelography; 1-2 year old horses affected at the C3-C4 intervertebral articulation was the most common finding (Papageorges *et al.* 1987).

Aetiology:

The cause of CSM has not been elucidated, but appears to be the result of multiple factors. Genetic and environmental influences have been proposed. There is currently no evidence to suggest that CSM is directly heritable by simple Mendelian dominant or recessive patterns (Wagner *et al.* 1957). Falco *et al.* (1976) found no evidence of inheritability of in coordination in a retrospective study of 134 horses. Wagner *et al.* (1985) bred 33 foals from 12 mares and 2 stallions with CVM and found no increased incidence of CVM in the foals. Nutrition, rapid growth, trauma and abnormal biomechanical forces likely contribute to the development of CSM in genetically predisposed individuals. It is likely that genetic predisposition is dependent on multiple alleles and variable penetrance (Reed *et al.* 1985; Gabel *et al.* 1987; Glade 1987; Knight *et al.*1990a; Knight *et al.* 1990b).

Signs:

Clinical signs of CSM include: symmetrical ataxia, paresis and spasticity, which are usually worse in the pelvic than the thoracic limbs (Rooney 1963; Reed *et al.* 1981; Mayhew 1989). Histopathological changes associated with the condition include: wallerian degeneration, malacia and fibrosis at sites of cord compression and demyelination in the white matter tracts in adjacent segments of the spinal cord (Mayhew *et al.* 1978a; Mayhew 1989).

Diagnosis:

Diagnosis of the condition is based on clinical signs, neurological examination and plain radiography (Reed *et al.* 1981). Definitive diagnosis of spinal cord compression is made from myelograms taken under general anaesthesia (Rush 2006). Magnetic resonance imaging and / or CT can be used to aid diagnosis; however the size of these machines currently limits the ability to visualise the entire adult horse’s neck.

Treatment:

Medical

Conservative treatment involves nutritional adjustments (restricting energy and protein), systemic anti-inflammatory drugs (corticosteroids, dimethyl sulfoxide and nonsteroidal anti-inflammatory drugs) and direct medication of the cervical vertebral articulations with corticosteroids where appropriate. Dietary adjustments have been successful in some horses (Mayhew 1993), but systemic anti-inflammatory drugs alone have not resulted in spontaneous recovery (Moore 1993). Medication of the cervical articular process joints is only appropriate for arthropathies.

Surgical

In some cases it is possible to relieve compression of the spinal cord by stabilising the affected cervical vertebrae (Wagner *et al*. 1979a; Wagner *et al*. 1979b; Grant *et al*. 1985a; Grant *et al*. 1985b; Rush Moore *et al*. 1993). A technique using surgical implants to encourage bony fusion and stability between cervical vertebrae as a treatment of cervical spinal cord compression in horses was first reported in 1979 (Wagner *et al*.). The technique has progressed from implantation of a homologous bone dowel to the implantation of a stainless steel cylinder with bone graft (Cloward Bagby basket) to the more recent open-ended threaded, stainless steel cylinder (Kerf Cut Cylinder (KCC)). The technique is now widely used for treatment of cervical stenotic myelopathy in North America and the U.K. It has been estimated that up to 2000 horses have had cervical vertebral arthrodesis surgery (Walmsley 2005).

Clinical assessment following surgical stabilisation of the cervical vertebrae report varying success; return to ridden work has been shown to range from 43% to 79% (Grant *et al*. 1985b; Nixon and Stashak 1985; Rush Moore *et al*. 1993; Trostle *et al*. 2003; Schuette 2005; Walmsley 2005). The complication rate associated with these procedures is high, with major complications being ventral migration of implant and vertebral fractures. One review reported a 9% fatality rate (Rush Moore *et al*. 1993). Questions regarding the safety of performing surgery on neurologically unsound animals have been alluded to (Walmsley 2005) as post-surgery not all of these animals regain normal neurological function.

1.3.1.2 Atlanto-axial luxation

A development abnormality in the odontoid process (dens) of the axis (malformation, absence or separation from the axis) leads to excessive mobility at the atlanto-axial articulation and repetitive or constant spinal cord compression. This results in weakness, spasticity and ataxia in all four limbs (Funk and Erikson 1968; Guffy *et al*. 1969) the degree and progression of which depends on the amount of laxity at the articulation.

Medical therapy to reduce inflammation (corticosteroids and hyperosmotic agents) and minimal stress / handling to reduce the trauma to the region are indicated but not curative. Surgical stabilisation from a ventral approach is feasible and two successful techniques have been reported for traumatic luxations: one using two six hole broad dynamic compression plates (McCoy *et al.* 1984) and the other using two 6.5mm cancellous screws (Nixon 1996). Subtotal dorsal laminectomy has also been described as a salvage procedure in foals (Slone *et al.* 1979; Nixon and Stashak 1988). Overall the prognosis for this condition is poor.

1.3.1.3 Atlanto-occipital Malformation

This condition is reported most frequently in Arabian foals (Mayhew *et al.* 1978b; Wilson *et al.* 1985; Watson and Mayhew 1986), in which it is inherited in an autosomal recessive manner with no sex predilection (Mayhew *et al.* 1978b; Watson and Mayhew 1986). In other breeds it occurs as a congenital defect which occurs at random and is non-genetic. This developmental defect occurs during embryogenesis before the end of the sixth week of gestation (Mayhew *et al.* 1978b; Wilson *et al.* 1985; Watson and Mayhew 1986) and results in the atlas being fused to the occipital bone and often malformation of the odontoid process of the axis. This results in weakness and ataxia and commonly an extended head posture. Clinical signs progressively worsen as the spinal cord is persistently or repetitively compressed and then as fibrous tissue forms within the joint space.

Conservative treatment is recommended if no neurological gait deficits are observed. Surgical correction of the atlantoaxial subluxation is advocated by some (Rush 2006), but treatment of Arabian breeds is generally discouraged to avoid their presence in the gene pool.

1.3.1.4 Block, Butterfly and Hemivertebrae

These developmental abnormalities result in altered shapes of the cervical vertebrae, which can have varying effects on their articulations and the vertebral canal (Rush 2006). Treatment is not always necessary and is rarely attempted and prognosis depends on the degree of malformation and spinal cord involvement.

1.3.2 Common acquired pathologies

Trauma to the spinal column in horses occurs most frequently in the cervical and thoracolumbar vertebra and the reported incidence varies (Jeffcott 1980; Nixon 1996; Pinchbeck and Murphy 2001) whilst traumatic incidents can result in fractures and luxations of almost any configuration and in any position, certain types are more commonly reported than others.

1.3.2.1 Fractures of the axial dens with atlantoaxial subluxation

These occur most frequently through the physis of the dens in foals younger than 6 months (Owen and Smith-Maxie 1978; Slone *et al*. 1979; McCoy *et al*. 1984; Nixon 1996), likely because the physis at this site closes by 8-12 months. They are most commonly reported when foals fall with their necks in hyper flexion (e.g. somersault). The fracture commonly results in compression at the atlantoaxial joint resulting in neurological deficits, the degree of which depends to some extent on the severity of the initial injury.

Signs range from mild to severe neurological deficits and death. If the injury is mild, anti-inflammatory drugs and rest may allow fibrous union of the fracture without further development of neurological deficits. A recent case series reported on older horses and a pony which suffered fracture of the dens, without subluxation and responded well (4 out of 5 survived) to medical management with or without the application of a splinting device to the neck (Vos *et al*. 2008). Surgical repair is warranted if the neurological signs are severe or deteriorating. Surgical decompression, realignment and then stabilisation is the goal of treatment and three reports using different surgical techniques for successful stabilisation of the dens have been published (Owen and Smith-Maxie 1978; McCoy *et al*. 1984; Nixon 1996).

Atlantoaxial subluxation also occurs without fracture of the dens. Successful surgical treatment of this condition has been performed using subtotal dorsal laminectomy to reduce the pressure on the spinal cord. Four cases treated with this technique reported two complete recoveries, one satisfactory improvement and one case lost to follow up (Nixon and Stashak 1988; Nixon 1996).

1.3.2.2 Fractures of the vertebral bodies

These are less frequently reported than fractures involving the dens and reports of surgical repair are rare (Nixon 1996; Pinchbeck and Murphy 2001) although some success has been achieved with a lag screw technique (Barnes *et al.* 2005). Despite being the most common type of spinal fractures; fractures of C3 to C7 are rare in the adult horse. Fractures of the vertebral body are more commonly reported than fractures of the articular facets (Pinchbeck and Murphy 2001). Clinical signs depend on the degree of impingement / damage to the spinal cord and range from none to death, with mild to severe neurological deficits to all four limbs in between. Treatment options depend on the degree of neurological involvement and can include: supportive medical care, box rest and neck splints. There are only a limited number of published reports of successful repair techniques using implants (Nixon 1996).

1.3.2.3 Arthropathy of the articular process joints

There are a number of reports of caudal cervical articular process joint (C5-C7) pathology leading to spinal cord compression and subsequent ataxia and paresis (Powers *et al.* 1986; Dyson and Whitwell 1987; Dyson 2003; Hahn 2006; Hahn *et al.* 2007; Levine *et al.* 2007; Van Biervliet 2007). Arthropathy of these joints is also reported to lead to neck pain and stiffness (Dyson 2003) and forelimb lameness (Foreman *et al.* 1990; Mackay and Mayhew 1991; Moore *et al.* 1992; Ricardi and Dyson 1993; Nixon 2002). The condition is recognised more commonly in older animals (Powers *et al.* 1986; Wagner *et al.* 1987; Mayhew 2002; Nout and Reed 2003; Hahn 2006; van Biervliet *et al.* 2006). Diagnosis of the condition is made by a combination of one or more of radiography, ultrasonography, myelography and nuclear scintigraphy, although diagnosis based on plain radiographs has recently been questioned (Down and Henson 2009). Treatment in the form of systemic anti-inflammatories and rest may be palliative. Direct intra-articular medication with corticosteroids has been advocated (Grisel *et al.* 1996; Snyder and Spier 2001), although no objective assessment has been performed.

1.4 Pathology of the canine cervical spine

The canine species is also affected by specific common cervical vertebral pathologies, which, as in the horse, have also been labelled “Wobbler syndrome”. There is a breed predilection for Doberman pinschers and Great Danes, and in Dobermans the over representation has been attributed to both congenital and acquired relative vertebral canal stenosis (Al-Mefty *et al.* 1993; Da Costa *et al.* 2006). In contrast to horses, which (because of differing anatomy) do not suffer significant intervertebral disc disease, dogs with cervical disc associated spinal cord compression far outnumber those admitted with other types of “Wobbler” syndrome (Seim and Withrow 1982; VanGundy 1988; Vangundy 1989; McKee and Sharp 2003; Read *et al.* 1983). This combined with the differences in anatomy and size means that treatment options for dogs differ from the horse.

Static compression of the canine cervical spinal cord can be treated by ventral decompression and / or laminectomy. However, for cases with dynamic cervical cord compression additional stabilisation is often required to reduce instability following decompression and to prevent the disc space from collapsing. Ventral decompression alone has been shown to exacerbate instability (particularly in extension) in some cases (Chambers *et al.* 1982; Chambers *et al.* 1986; Koehler *et al.* 2005; Macy *et al.* 1999). In order to try and combat the instability, a large number of different techniques have been used, including: Interbody screws, washers, bone grafts (cancellous, cortical, and cortico-cancellous) in various shapes orientations and types, metallic spacers, metallic plates (stainless steel and titanium), plastic plates with unicortical and bicortical screws, smooth pins, threaded pins and bone screws with polymethylmethacrylate bridges, interbody or intervertebral cement plugs with and without anchor holes or retention screws, “Harrington rods” and metallic plates with locking screws. These have all been used to maintain distraction and/or graft retention to allow for bony fusion of the affected vertebrae (McKee and Sharp 2003; McKee *et al.* 1990; Koehler *et al.* 2005; Ellison *et al.* 1988; Bruecker *et al.* 1989a; Bruecker *et al.* 1989b; Goring *et al.* 1991; Dixon *et al.* 1996; Queen *et al.* 1998; Rushbridge *et al.* 1998; McKee *et al.* 1999; Jeffery and McKee 2001).

The variety of surgical treatments contrasts with the limited number of surgical techniques reported in equine cases and further highlights the differences between the species. The variety of treatment options also suggests that a perfect surgical solution has yet to be devised and this is upheld by the number of reported complications associated with the techniques, of which early implant failures with loss of distraction before fusion has been the most common reported cause of failure in distraction-stabilization techniques (Trotter 2009).

Overall long term mortality rates for cervical stenotic myelopathy in dogs are reported to vary from 19 to 43% (Seim and Prata 1982; Dixon *et al*. 1996; Rushbridge *et al*. 1998; McKee *et al*. 1999; de Risio *et al*. 2002). Ability to walk prior to surgery and rapid response to surgery have been shown to improve the likelihood of success.

1.5 Pathology of the human cervical spine

Cervical vertebral arthrodesis techniques using plates and cages are commonly performed in humans as treatment for degenerative conditions of the vertebrae, traumatic instability (such as following vertebral fractures) and other conditions (such as cervical spondylosis) (Dvorak *et al*. 2005). *In vitro* mechanical testing of implants designed to promote vertebral fusion, has been performed in a large number of human studies reviewed in 1999 (McAfee).

The application of plates to the anterior aspect of affected cervical vertebrae has been widely performed in humans since the technique was first reported (Bohler *et al*. 1980). Plates are commonly used in the treatment of degenerative disorders of the cervical spine, neoplasia, trauma and deformity. Cervical disc degeneration (CDD) is a common condition in humans; the estimated annual surgical treatment for the condition in the USA in 2005 was 50-60 per 100,000 inhabitants (Patil *et al*. 2005). Surgical treatment of CDD involves anterior cervical discectomy with fusion (ACDF) and the current fusion methods of choice are either: using an autologous iliac crest graft (AICG) or using an artificial cage (commonly made of polyetheretherketone (PEEK)). Research has shown that plate application results in higher fusion rates when multilevel ACDF is performed (Wang *et al*. 2000; Wang *et al*. 2001; Samartzis *et al*. 2003). The benefit of anterior plating for single site spondylotic conditions in humans is less clear; studies have shown that plating fails to result in increased union rates compared to use of autograft alone (Wang *et al.* 1999; Samartzis *et al.* 2004; Grob *et al.* 2001). This highlights a major difference between horses and humans, as the use of implants to provide stability during arthrodesis of an equine cervical articulation is currently considered essential.

Plates are also used in humans to provide additional stability following removal of part of the cervical vertebral body (corpectomy), which is commonly performed to reduce compression on the spinal cord and/or spinal nerves. It is reported that plating over one or two corpectomy sites (i.e. 2-3 vertebrae) generally leads to acceptable outcomes. However, using plates to span greater than two corpectomy sites has been reported to result in high failure rates (Rhee *et al.* 2005). Interestingly, clinical series of plated multilevel corpectomies have been associated with higher graft complication rates than the unplated counterparts (Emery *et al.* 1998; Vaccaro *et al.* 1998). Biomechanical studies have been performed, the results of which suggest that long-plated constructs are more prone to losing stability under fatigue loading and result in altered load transfer through the surgery sites making them mechanically inferior (Isomi *et al.* 1999; DiAngelo *et al.* 2000). As a result it has been recommended that additional (posterior) stabilisation, or alternative anterior constructs are used for human cases undergoing corpectomy of greater than 2 sites.

A variety of plates have been used in human cervical vertebral surgery. Rigid plates with fixed angle screws were historically the first ones used in the cervical spine (Figure 3).

Figure 3: A “Synthes” cervical locking plate using fixed angle screws, locked to the plate with secondary inner set screws.

The application of a plate to the anterior aspect of the vertebrae prevents extension and supports the region of the vertebrae that has been operated on. However, rigid fixation has been shown to retard healing by preventing compression and loading of the graft, so alternative techniques have been investigated: Buttress plating, in which the plate is used simply to hold the graft in place allows loading of the graft site, however because they are not firmly anchored, these constructs can result in anterior graft extrusion leading to complications (Smith and Bolesta 1992; Riew *et al.* 1999). Dynamic plates, which allow for bidirectional or unidirectional subsidence, allow more controlled loading of the graft site, however because of their ability to move following insertion have resulted in plates overlapping and injuring adjacent disc spaces, as well as kyphosis (pathological curving of the spine), stenosis of the foramina and construct failure. An alternative is to use plates without slots but with variable angle screw; these allow more controlled load sharing of the graft.

Overall, a wide variety of implant designs and techniques have been used successfully in human cervical surgery. Complications have been reported with all described techniques and despite in-depth research to try and identify the best technique, it is reasonable to conclude that different implants and combinations of techniques are necessary to deal with the variety of pathology encountered.

1.6 Background and aims of the study

Cervical vertebral arthrodesis is performed regularly in horses; however the biomechanical properties of the cylindrical implants currently used have not been investigated. The use of cylindrical implants to promote arthrodesis are associated with some complications (discussed in section 1.3.1.1) and there are situations in which an alternative implant would be beneficial; cylindrical implants would not be suitable for fixation of certain cervical vertebral fractures and the ability to augment or replace failed KCC placement may be of benefit in some cases.

Plates are successfully used to provide support during cervical arthrodesis techniques in both dogs and humans and with the advent of a new locking compression plate (LCP) (Synthes), it is feasible that this could be used in horses in a similar fashion to the locking plates used in human surgery (Dvorak *et al*. 2005; Lehmann *et al*. 2005).

The findings of clinical series and biomechanical reviews from human and canine cervical surgery provide interesting insights into the techniques used; however the question as to whether these techniques are directly applicable to horses remains to be answered. There are major differences in size, anatomy, forces acting on the vertebrae and convalescence between humans, dogs and horses. Equine cervical surgery sites need to be able to withstand near normal (everyday) biomechanical forces immediately after recovery from anaesthesia, whilst in humans bed rest is relatively easy to enforce. In contrast to humans and dogs, equine recovery from anaesthesia has the potential to place enormous strains on the surgical site.

As background for this Master's research: A foal suffering from CSM, considered too small for a cylindrical implant for optimal fusion, was treated with a LCP and subsequently progressed well. Once suitable follow up had been obtained, a report of this case was produced and published in the veterinary literature (chapter two).

Questions regarding the suitability of the new technique were discussed, which led onto further investigation of the technique using biomechanical studies (described in chapters three and four). The aims of these studies were to compare the biomechanics of KCC constructs with LCP constructs in equine cadaver necks. Collaboration with biomechanical engineers at the University of the West of Scotland allowed access to materials testing machines for accurate measurement of the forces acting across the cervical vertebrae and implants and provided a novel insight into equine cervical vertebral fusion. Presented in chapters two, three and four are the publications that were achieved from the research, followed by a general discussion in chapter five.

Chapter Two

2. Case Report

“Ventral Locking compression plate for treatment of cervical stenotic myelopathy in a 3-month-old Warmblood foal“

Published in: Veterinary Surgery 2009 Jun; 38(4):537-42

ABSTRACT

Objective - To report a novel technique for cervical vertebral fusion in a foal with cervical vertebral malformation (CVM).

Study Design – Case report.

Methods – A 3 month old Warmblood filly with ataxia, weakness, and stenotic myelopathy at the level of the articulation of the sixth (C6) and seventh (C7) cervical vertebrae had a 7 hole broad locking compression plate (LCP) applied to the ventral aspect of C6 and C7 using seven 5.0mm locking screws. Revision surgery was required to replace the self-drilling screws, which had migrated, with longer non self-drilling screws. Fusion and growth of the vertebrae were monitored radiographically at 4, 10, and 16 months using radiography and the filly was followed for 32 months.

Results - The filly recovered well from the surgical procedures and by 30 months had improved by 2.5 neurologic grades. Ventral inter-central joint fusion was evident by 10 months. Continued vertebral growth occurred in all but the cranial physis of the C7 vertebral body.

Conclusions - A ventrally placed LCP provided adequate support for fusion and stability of cervical vertebrae.

Clinical relevance - Use of an LCP applied ventrally offers an alternative to basket use in small or immature horses for fusion of cervical vertebrae.

INTRODUCTION

Cervical stenotic myelopathy (CSM) is a developmental disorder that is a common cause of spinal ataxia in young horses. Cervical vertebral deformation leads to stenosis of the vertebral canal and spinal cord compression. CSM is commonly appreciated in horses between 6 months and 3 years of age and is more prevalent in male and Thoroughbred horses (Rush 2006).

Diagnosis of CSM is based on history, clinical signs, physical and neurologic examinations and radiographic evaluation of cervical vertebrae. Definitive diagnosis is achieved by myelography, which can also be used to differentiate dynamic (type 1) and static (type 2) compression. Conservative treatment involves nutritional adjustments (restricting energy and protein), systemic anti-inflammatory drugs (glucocorticoids, dimethyl sulfoxide and nonsteroidal anti-inflammatory drugs) and direct medication of the cervical vertebral articulations with glucocorticoids where appropriate. Dietary adjustments have been successful in some horses (Mayhew *et al.* 1993), but systemic anti-inflammatory drugs alone have not resulted in spontaneous recovery (Moore *et al.* 1993). Medication of the cervical articular process joints is only appropriate for arthropathies.

Surgical use of stainless steel cylinders to encourage bony fusion and stability between cervical vertebrae is the current treatment choice. The most frequently used implant is a partially or fully threaded cylinder (Kerf Cut Cylinder) which is a modification of the Bagby Basket (Wagner *et al.* 1979). It is estimated that ~2000 horses have had cylinder implantation for treatment of CSM (Walmsley 2005) with variable success; 43 – 79% return to ridden work (Grant *et al.* 1985; Nixon *et al.* 1985; Moore *et al.* 1993; Grant *et al.* 2003; Schuette 2005; Walmsley 2005).

Locking compression plates (LCP) have been used for cervical vertebral fusion in humans (Dvorak *et al.* 2005) and have a greater variety of sizes than the stainless steel cylinders. We report our experience with fusion of cervical vertebrae in a 3-month old Warmblood foal, using a ventrally placed LCP.

CLINICAL REPORT

A 200kg, 3 month old female Swiss Warmblood foal was admitted for evaluation of increasing signs of ataxia and weakness. The foal had become progressively stiff in the pelvic limbs over several weeks and in the week before referral, was recumbent most of the time and had multiple abrasions on the back and the hips because of recurrent falls.

Clinical examination revealed a Grade 4 pelvic limb ataxia (Mayhew *et al.* 1978a; Blythe 1987).On cervical spine survey radiographs, there was caudal epiphyseal flaring of the 6th cervical vertebrae (C6) and narrowing of the spinal canal at this level. There was subjective evidence of vertebral malformation, with caudal extension of the dorsal laminae and mild caudal epiphyseal flaring of C4 and C5. More quantitative evidence of narrowing of the canal was appreciated with intra-vertebral sagittal ratios measured as C5; 0.45 (normal >0.52), C6; 0.40 (normal >0.52) and C7; 0.40 (normal >0.56) (Moore *et al.* 1994).

On myelography, there was evidence of spinal cord compression at the C6-C7 intervertebral space with > 50% reduction in sagittal diameter of the dorsal and ventral dye columns, a 21% reduction in dural diameter and a dorsal contrast column of <2mm at that site. These myelographic findings were evident when the neck was in the neutral position, but were most pronounced with the neck in extension (Figures 4-6). No spinal cord compression was observed on the ventrodorsal views of the neck. Based on these findings a diagnosis of dynamic spinal cord compression between C6 and C7 was made (Van Biervliet *et al.* 2004).

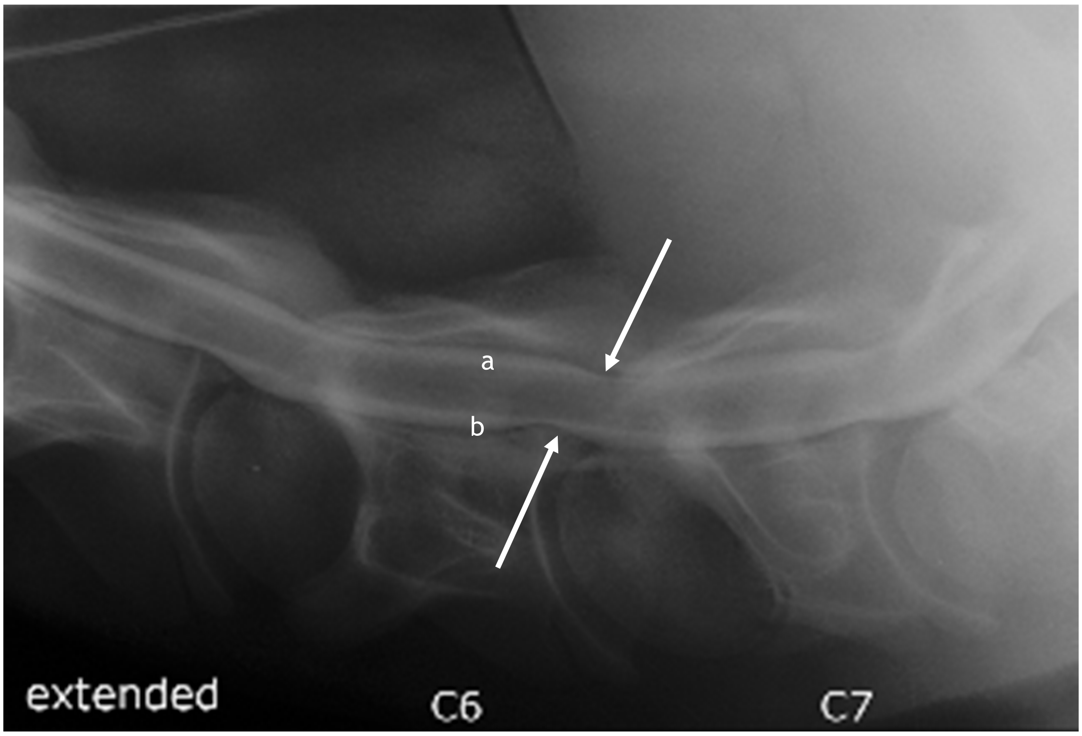


Figure 4: Myelographic study of the filly's cervical verterbrae in extension, before surgery showing spinal cord compression at the C6-C7 intervertebral space with > 50% reduction in sagittal diameter of the dorsal and ventral dye columns, a 21% reduction in dural diameter and a dorsal contrast column of <2mm at that site. a, is on the dorsal dye column; b, is on the ventral dye column; white arrows illustrate the site of major compression, from which the measurements were made.

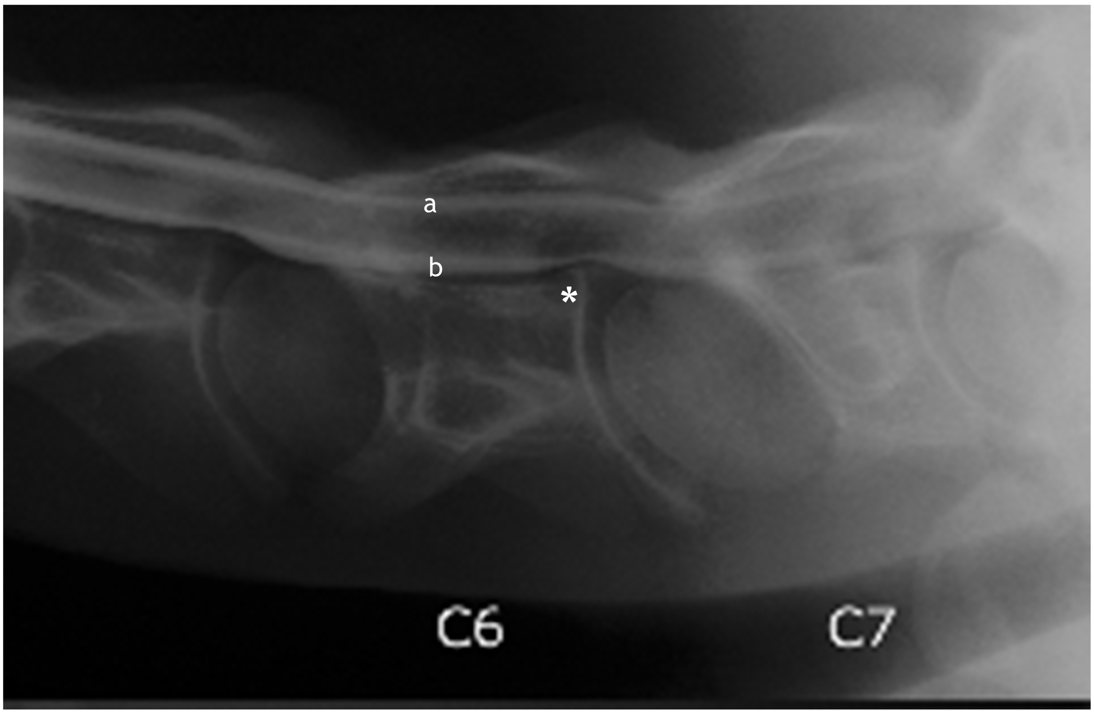


Figure 5: Myelographic study of the filly's cervical verterbrae in neutral position, before surgery showing milder compression of the dye columns than in the extended position.* is at the site of epiphyseal flaring on C6; a, is on the dorsal dye column; b, is on the ventral dye column.

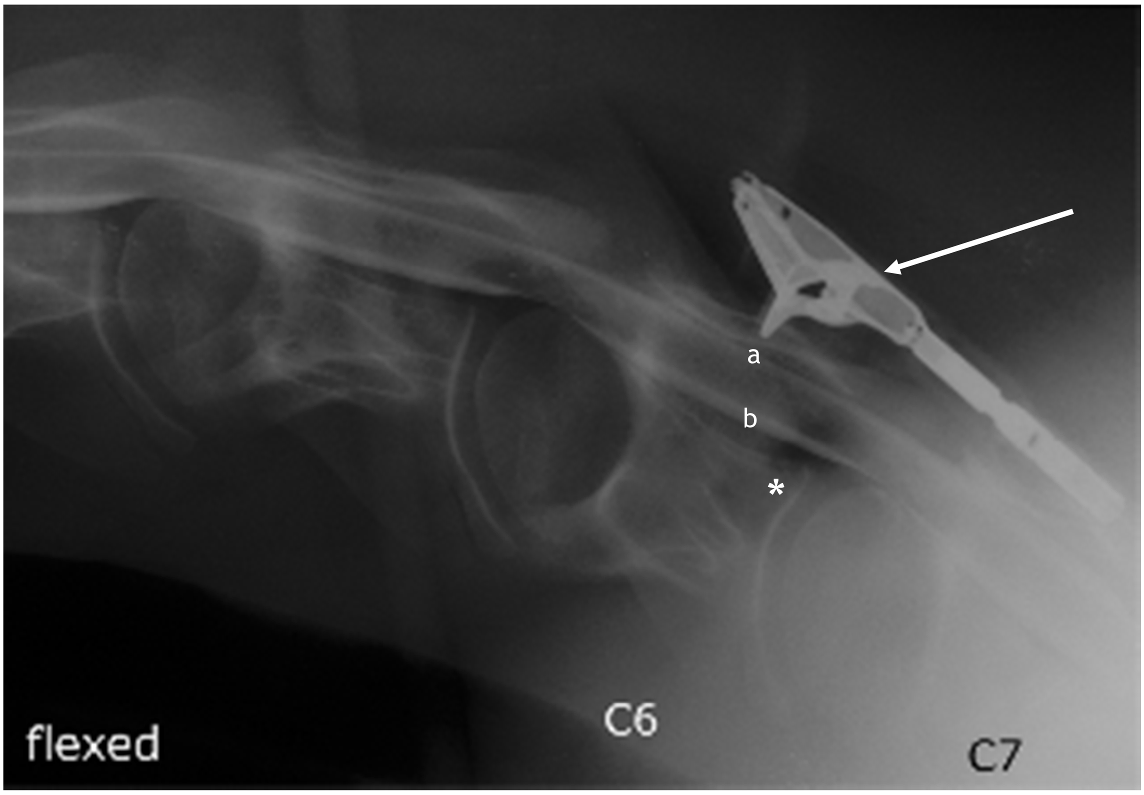


Figure 6: Myelographic study of the filly's cervical vertebrae in flexion, before surgery showing limited compression of the dorsal and ventral dye columns. * is at the site of epiphyseal flaring on C6; a, is on the dorsal dye column; b, is on the ventral dye column; white arrow shows the e.c.g. lead and clip.

Surgical Procedure

Forty minutes after administration of acepromazine (0.022 mg/kg intramuscularly [IM]), a combination of xylazine (0.6 mg/kg intravenously [IV]) and methadone (0.1 mg/kg [IM]) was administered. Anaesthesia was induced with diazepam (0.12mg/kg [IV]) and ketamine (2.2mg/kg [IV]) and maintained with isoflurane in oxygen. The filly was positioned in dorsal recumbancy on a Haico Telgte II (Eickemeyer, Tuttlingen, Germany) operating table with the neck extended on a carbon fibre board, held in position by a foam cushion and surrounded by an isocentric C-arm Siremobil C [3D] (Siemens Medical Solutions, Erlangen, Germany). The surgical site was clipped and aseptically prepared.

A 20cm skin incision was made on midline centred at the level of the C6-7 articulation (identified using radiographic guidance and the placement of a Backhaus towel clamp). The cutaneous musculature was incised with a scalpel blade. The sternohyoid then sternothyroid muscles were separated on midline to the level of the trachea which was retracted to the left side. Blunt dissection to the level of the longus colli muscle was performed allowing palpation of the ventral aspect of C6-7. An incision was made in the longus colli muscle which was retracted abaxially allowing access to the ventral aspect of the vertebrae. The ventral surface of C6 was flattened using an osteotome allowing access to the inter-central articulation, from which the disc material was debrided using a spoon curette. A broad 7 hole LCP was contoured to accurately appose the ventral aspect of the vertebrae, then 5 mm self-drilling and self-tapping locking screws were inserted under fluoroscopic guidance starting with a screw through the central hole over the inter-central articulation, followed by the 3 cranial screws starting closest to the joint, then the 3 caudal screws starting closest to the joint (Figure 7). The longus colli muscle was apposed using 3 metric monofilament glycomer 631 (Biosyn®) in a 2 layer mattress pattern. The ventral cervical musculature and subcutaneous tissues were apposed with 3 metric Biosyn® in simple continuous patterns. The skin edges were apposed using a skin stapler and a stent was applied over the incision. The filly was recovered in an uneventful hand assisted manner.

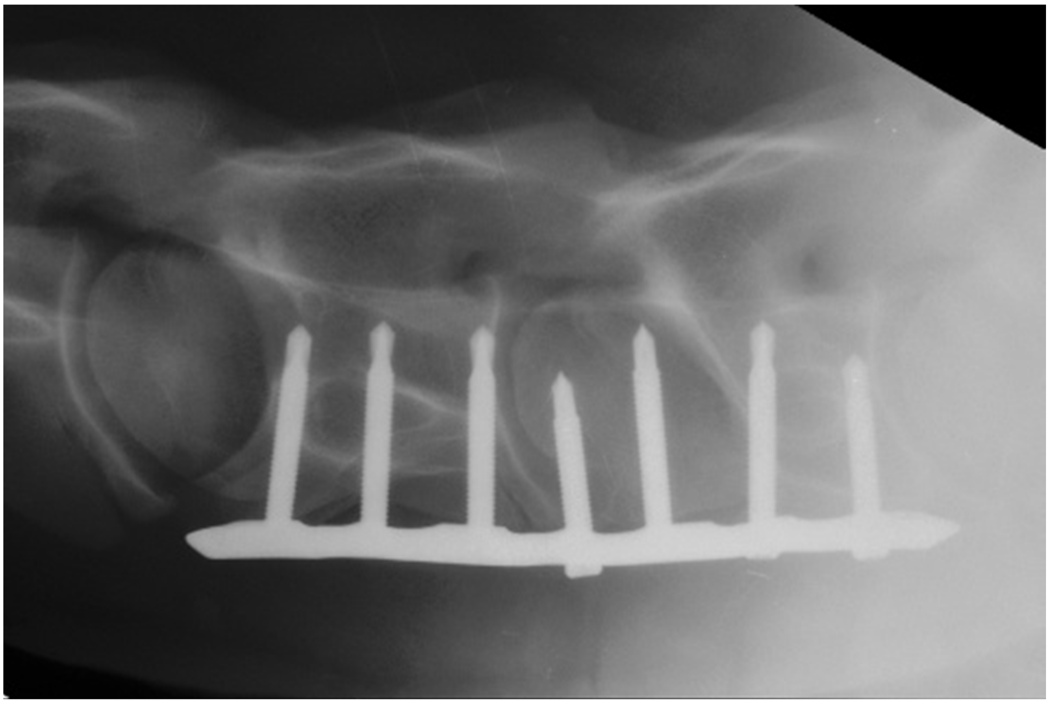


Figure 7: Laterolateral radiograph of C6 and C7 at 2 days after ventral fusion using a 7 hole LCP with self-drilling and self-tapping 5.0 mm Locking screws.

Postoperative Management

Potassium penicillin G (22,000 U/kg [IV] every 12 hours), gentamicin sulphate (6.6mg/kg, IV, every 24 hours), flunixin meglumine (1.1mg/kg, IV every 12 hours) and ranitidine (0.5mg/kg orally every 12 hours) were administered for 5 days. One fentanyl patch (10.0 mg), designed to deliver 100 μg/h, was placed over the lower back (total dose 0.5 μg/kg/hour). Morphine was administered 6, 12 and 18 hours after surgery (0.1 mg/kg).

For the first 24 hours, the filly had marked worsening of the ataxia, which gradually improved, but at 10 days, swelling associated with the incision became more pronounced and the filly had more pronounced ataxia of the pelvic limbs. On survey radiographs, the central and 2 caudal screws were backing out (Figure 8).The next day, the filly had revision surgery.

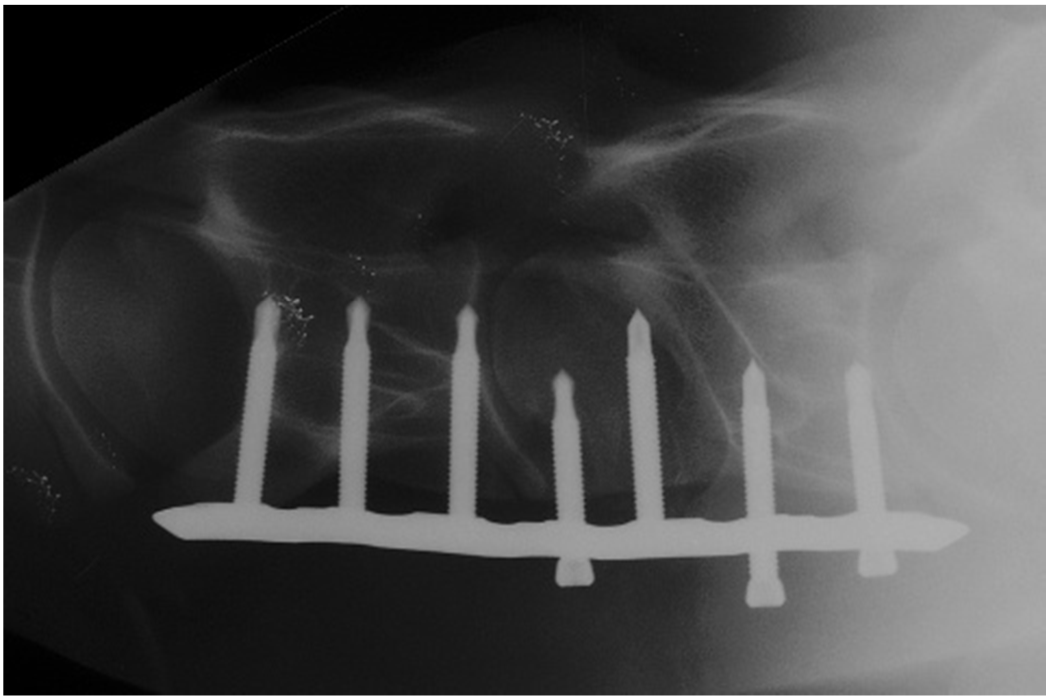


Figure 8: Laterolateral radiograph of C6 and C7 at 10 days after ventral fusion, demonstrating backing out of three screws.

Revision Surgical Procedure

The same approach was used and the implant and blood clots were removed. The broad 7 hole LCP was repositioned (moved slightly more cranially) to allow new drill holes for all 7 self-tapping screws. The middle screw was placed across the inter-central joint. The longest possible length was selected and application was performed under fluoroscopic guidance (Figure 9), then the incision was closed and the filly once again recovered in an uneventful, hand assisted manner.

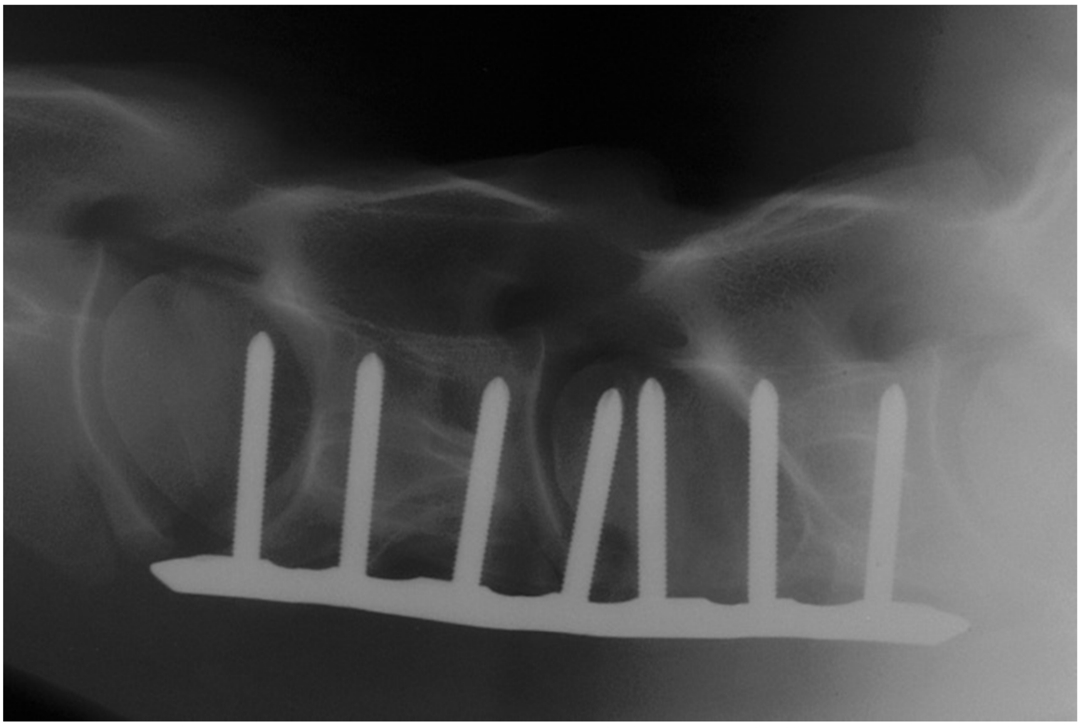


Figure 9: Laterolateral radiograph at 2 days after re-application of a 7 hole LCP with self-tapping 5.0 mm locking screw for ventral fusion of C6 and C7 (revision surgery).

Postoperative Management

Potassium penicillin G (22,000 U/kg [IV], every 12 hours), gentamicin sulphate (6.6mg/kg IV, every 24 hours), flunixin meglumine (1.1mg/kg IV every 12 hours) and ranitidine (0.5mg/kg PO, every 12 hours) were administered for 5 days. One fentanyl patch (10.0 mg), designed to deliver 100 µg/kg, was placed over the lower back (total dose 0.5 µg/kg/h). The filly gradually improved and was discharged 3 weeks later with instructions for stall rest for 8 weeks.

The filly was re-admitted after 12 weeks for investigation of a grade 2/5 left fore limb lameness that could not be localised up to the level of a median and ulnar nerve block. The lameness markedly improved the next day and no further investigation was undertaken. The filly still had grade 2 ataxia of the pelvic limbs. After discharge, the filly was turned out to pasture and was re-radiographed at 2, 4, 10, and 16 months (Figures 10-13).

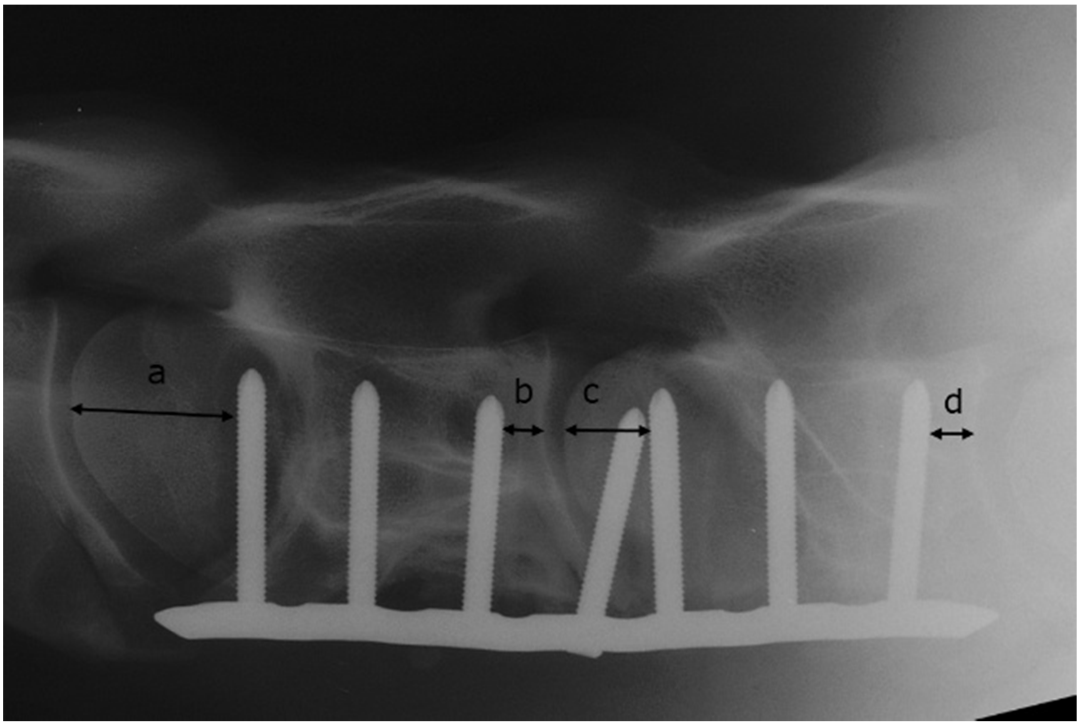


Figure 10: Laterolateral radiograph at 2 months after revision surgery showing details of measurements. a) cranial aspect of C6 to 1st screw, b) 3rd screw to caudal aspect of C6, c) cranial aspect of C7 to 5th screw, d) 7th screw to caudal aspect of C7.

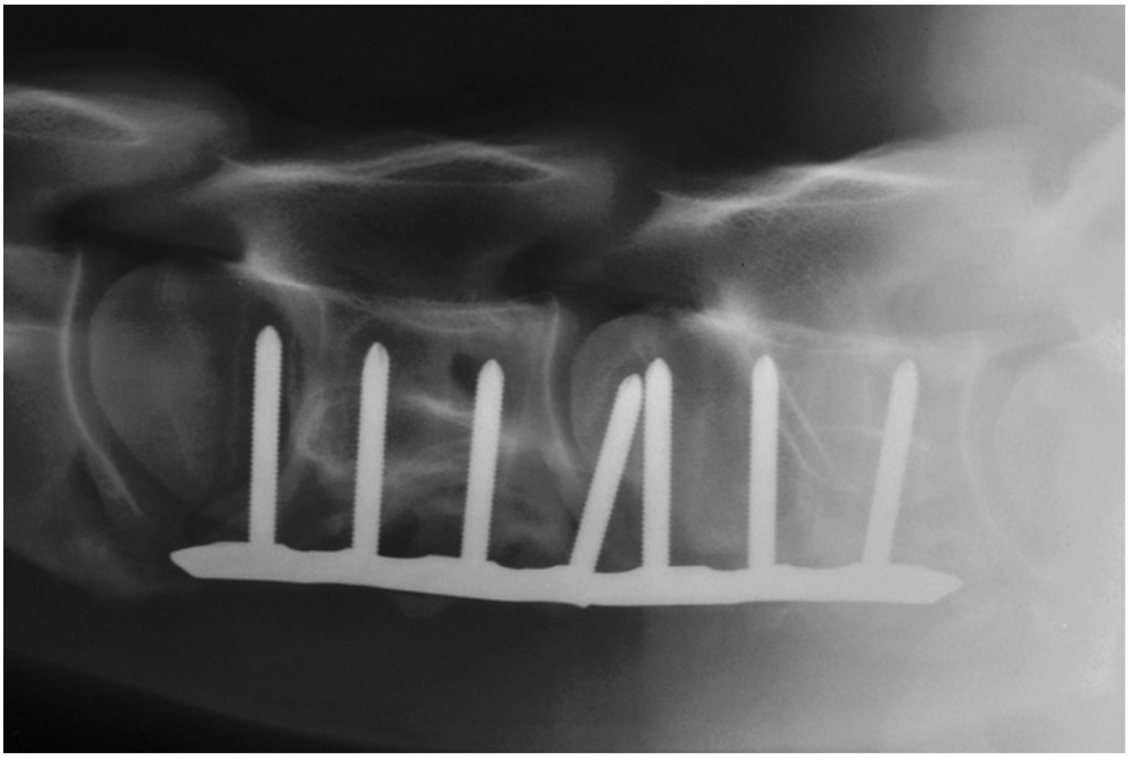


Figure 11: Laterolateral radiograph at 4 months after revision surgery.

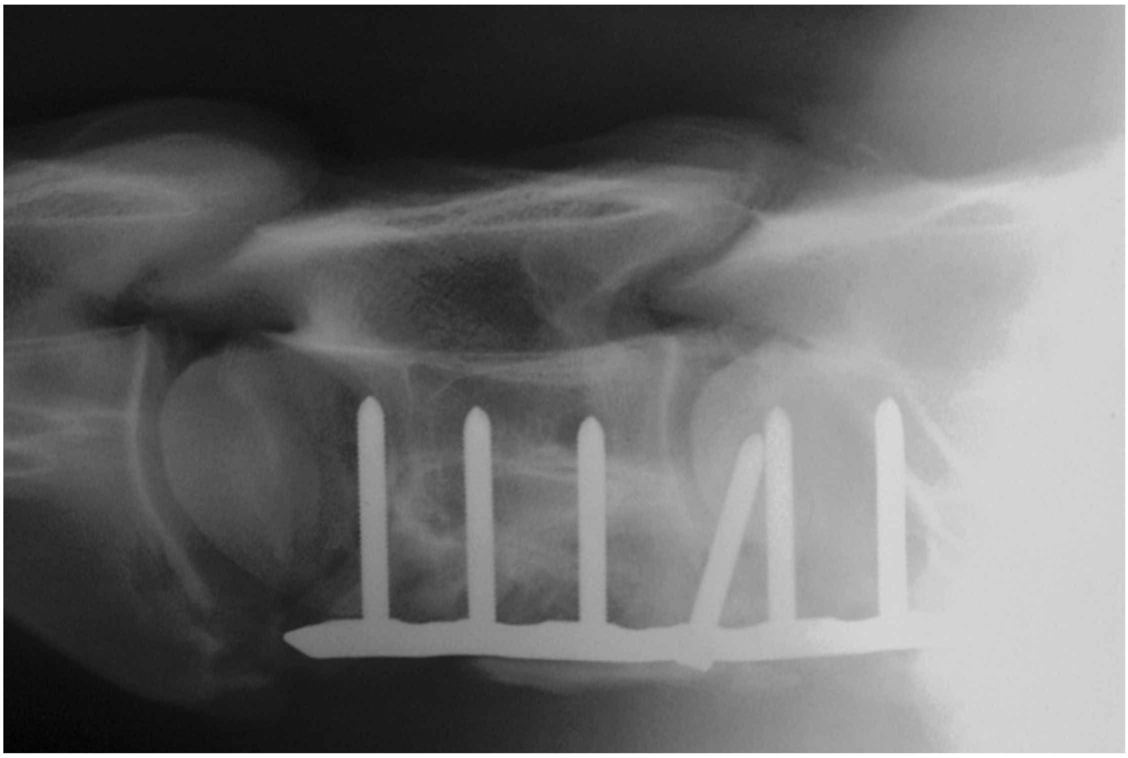


Figure 12: Laterolateral radiograph at 10 months after revision surgery.

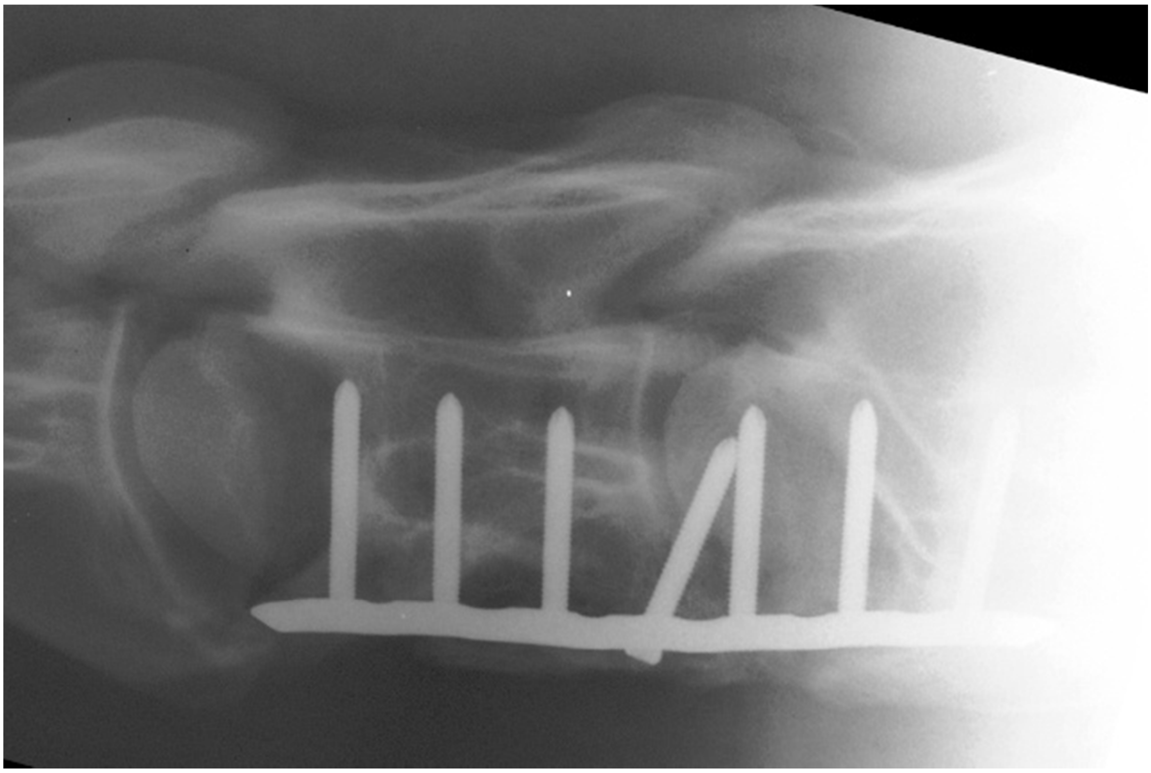


Figure 13: Laterolateral radiograph at 16 months after revision surgery.

At 2 months, there was radiolucency around the tips of the cranial 2 screws. The radiolucency was more visible at 4 months, but was no longer visible at 10 months and the plate remained in close contact with the ventral surface of the vertebrae throughout. Two months postoperatively there was radiographic evidence of backing out of the central screw, which became progressively more marked and was associated with alteration of the angle of the screw so that the dorsal tip of the screw progressed further caudally, to the extent that by 10 months the tip of the screw was at the level of the screw caudal to it.

New bone formation was apparent on the ventral aspect of C6 from 2 months and progressed to formation of callus around the plate (dorsal and ventral). By 10 months post operatively, callus was radiographically evident bridging the ventral aspect of the inter-central joint between C6 and C7 and the dorsal margin of the C6-C7 articular process joint had changed, showing evidence of new bone formation at this level (Figure 12).

Immediately postoperatively the cranial end of the LCP was in close association with the caudal ventral aspect of C5. There was a progressive increase in the gap between the plate and the caudal C5; however, there was also progressive new bone formation on the caudoventral aspect of C5 suggestive of interference.

The length and the depth of C5, C6 and C7 were measured at 4, 10 and 16 months using the length of the plate and the screws as calibration markers (Table 1). Measurements were made between the screws at either side of the vertebral bodies of C6 and the respective ends to assess effect on growth plates over 16 months (Figure 10)

Table 1: Radiographic Measurements of the Length and Depth of C5, C6 and C7 of a Foal with a Cervical Fusion of C6, C7 using a Locking Compression Plate.

	C5 (% of immediate postoperative dimension)		C6		C7	
	Length (mm)	Depth (mm)	Length (mm)	Depth (mm)	Length (mm)	Depth (mm)
Immediate Postoperative	687 (100%)	365 (100%)	667 (100%)	385 (100%)	585 (100%)	345 (100%)
4 months	766 (112%)	376 (103%)	732 (110%)	414 (108%)	628 (107%)	387 (112%)
16 months	815 (119%)	385 (105%)	751 (113%)	420 (109%)		

The percentage refers to relative length or depth compared to that measured immediately postoperatively (when the foal was 3 months of age).Vertebra C7 was collimated out of the 16 month post-operative films, so measurements could not be taken.

Between the cranial aspect of the cranial screw and the cranial aspect of C6 vertebral body there was a 41% increase in length (a, Figure 10), between the caudal aspect of the 3rd screw and the caudal aspect of C6 vertebral body there was a 108% increase in length (b, Figure 10), between the cranial aspect of the 5th screw and cranial aspect of C7 vertebral body there was an 8% decrease in length (c, Figure 10) and between the caudal aspect of the 7th screw and the caudal aspect of C7 vertebral body there was a 67% increase in length over 4 months (d, Figure 10).

At 2.5 years postoperatively, neurologic examination revealed a neurologic grade of 1.5 in the pelvic limbs. It is the intent of the owner to ride this horse in the future.

DISCUSSION

Successful surgical treatment of cervical spinal cord compression is dependent on early recognition. Rapid resolution of spinal cord compression is highly desirable and anecdotally the best results are reported when treatment is undertaken within 2 - 3 weeks of recognition (Grant *et al.* 2006). The Kerf Cut Cylinder has a diameter of 25mm and as such is not suitable for use in very small necks. Because the shorter cervical vertebrae C6 and 7 were affected in this young foal, we chose an alternative method of fixation. Use of an LCP allows greater variation in implant size, as plate and screw length can be varied.

Implant placement in very young animals has a questionable effect on the growth plates. There is a cranial physis from C3 to C7 (radiographically visible up to 4 years of age) and a caudal physis (radiographically visible up to 5 years of age). Cranial growth plate closure starts from ventrally in the cranial physis and from dorsally in the caudal physis. There is a lot of individual variability but it is expected that most of the growth activity is between the 3rd and 9th months of age (Dyce *et al.* 1991).

It was thought that this new construct was likely to have more of an effect on the vertebral growth than the cylinder implants. The growth plates in this foal were still open at initial surgery. Measurements of postoperative radiographs demonstrate continued overall growth in the C6 and C7 vertebrae and measurement in relation to the screws suggests continued growth at all but the cranial physis of C7, which was difficult to avoid with this or the basket technique. Because of the need for plate repositioning in this foal, the LCP was moved cranially to allow placement of alternate drill holes and as a result the LCP overlapped the caudal epiphysis of the 5th cervical vertebral body. The resultant new bone formation suggested that the plate was impinging on the C5 vertebral body during neck ventroflexion which would be something to avoid in future surgeries.

The new bone formation on the ventral aspect of C6 and C7 and evidence of inter-central joint bridging were encouraging. There were no radiographic features to suggest that the inter-central joint was fused dorsally. It has been suggested that complete removal of disc material is essential for good fusion

(Personal communication, Bagby G, January 2007) and it was thought likely that this material was not removed aggressively enough in this foal. If this articulation was not fully fused, this may be causing the residual neurologic deficit observed in this animal. It is also possible that the continued ataxia was a result of permanent damage to the spinal cord from the initial compression, or compression at an alternate site.

The LCP implant provides good radiographic visibility of the inter-central joint that was not possible with the cylinder implants, which may provide better monitoring of joint fusion and could be considered a benefit of this technique compared with the basket technique. In this single case it was found that the technique was technically demanding but was not thought to be more so than the placement of cylinder implants. Also the LCP technique does not require further specialist instrumentation other than a LCP kit. The C-arm made the technique quicker in this case, but was not essential.

Ventral plating in combination with a Bagby basket has been described as treatment for vertebral fractures (Nixon 1996). Plate fixation alone has been reported in a 1 month old foal (McCoy *et al*. 1984). In that case, 2 broad dynamic compression plates (DCP) were applied to the ventral surface of the 1st and 2nd cervical vertebrae, abaxial to the spinal canal. We would suggest that this construct would be too weak to be effective on more caudal vertebrae because of vertebral anatomy, with very little bone abaxial to the canal. The LCP provides a more stable construct than the DCP, allowing stabilization via the vertebral bodies ventral to the spinal canal. Based on the range of plates and screws available we believe that the LCP fusion technique would be applicable for any size of horse.

Application of the plate to the ventral aspect of the bone violates the principle of plating the tension side of a bone. As a result, flexion of the neck predisposes the fixation to failure by causing screw distraction from the bone. This may well be the reason for the central screw movement in this foal. In contrast, a Kerf Cut Cylinder would lock in extension while compressed. Biomechanical testing of cadaveric specimens would be interesting to compare these 2 techniques.

Complications of vertebral fracture and implant migration are reported when using cylinder implants (Walmsley 2005); these complications were not observed in this foal. It is thought that the LCP technique may help to avoid vertebral fracture by spreading the load over more of the vertebral surfaces and having a larger surface area hold in the bone than the cylinder implants. The backing out of screws from the plate observed after the 1st surgery is uncommon with LCP plates. This may have occurred in this foal partly because the screw heads were not locked adequately, which may have been because of the difficulty of drilling and tapping the screws at this site which was difficult to access. The initial choice of using self-drilling and self-tapping screws was based on the assumption that with accurate measurements there would be no risk of drilling too far into the spinal canal and would still result in enough stability for a vertical fusion of the joint. However by using self-drilling and self-tapping screws a considerable amount of threaded screw length was lost because of the drilling device at the tip of the screw. It was likely that the selection of too short screws and the difficulty in applying these correctly resulted in a loosening of implants and loss of stability.

We managed to re-apply the implant using different holes, with longer, self-tapping screws providing enough stability to eventually fuse the 2 vertebrae. Interestingly, the successful re-application of the implant is something that would be very difficult to achieve with the cylinder implants, with which comparably there are no second chances.

This LCP technique provides an alternative for cervical vertebral fusion. Use in other cases and long term follow up will provide more information regarding the viability of this technique.

Chapter Three

3. Initial Biomechanical Testing

“A pilot *in vitro* biomechanical comparison of Locking compression plate fixation and Kerf-cut cylinder fixation for ventral fusion of fourth and fifth equine cervical vertebrae”

Published in: Veterinary Comparative Orthopaedics and Traumatology 2009, 22(5):371-9

Introduction:

The surgical placement of implants to encourage bony fusion and stability between cervical vertebrae as a treatment of cervical spinal cord compression in horses was first reported in 1979 (Wagner *et al.* 1979). Since then the technique has been performed widely in North America and progressively more so in Europe. It has been estimated that up to 2000 horses have had the cervical fusion surgery (Walmsley 2005). The technique has progressed from implantation of a homologous bone dowel to the implantation of a stainless steel cylinder with bone graft (Cloward Bagby basket) (Wagner *et al.* 1979b) and to the more recent open-ended threaded stainless steel kerf cut cylinder (KCC) (Walmsley 2005).

Clinical assessment following the procedures report varying success; the rate of return to ridden work has been shown to range from 43% to 79% (Walmsley 2005; Grant *et al.* 1985; Nixon and Stashak 1985; Moore *et al.* 1993; Trostle *et al.* 2003; Schuette 2005). However the complication rate associated with the procedure is high, with a fatality rate of 9% in one report (Moore *et al.* 1993). The major reported complications associated with the techniques are ventral migration of implant and vertebral fractures.

Vertebral fusion techniques are commonly performed in humans as treatment for degeneration, traumatic instability and other conditions (Dvorak *et al.* 2005). Between 1994 and 1999 more than 80,000 lumbar interbody fusion cages were implanted across the world (McAfee 1999). Recently, locking plates have been used for trans-cervical fixation techniques in man (Dvorak *et al.* 2005; Lehmann *et al.* 2005), the mechanical properties of which have been tested in a human cadaveric model (Dvorak *et al.* 2005). The successful use of a locking compression plate (LCP) (Synthes®) for fracture repair and cervical vertebral fusion in a three month old foal in which a cylindrical implant was considered inappropriate was described in chapter 2 and published (Reardon *et al.* 2009).

In vitro mechanical testing of implants has been performed in a large number of human studies reviewed in 1999 (Lehmann *et al.* 2005). Biomechanical testing has been done in calf, sheep and human cadaveric studies (McAfee 1999), but no such testing has been performed on equine cervical spines.

The purpose of this preliminary *in vitro* study was twofold:

1. To establish a testing module for biomechanical testing of cadaveric equine fourth and fifth cervical vertebral (C4-C5) articulations.
2. To compare the biomechanical properties of the equine C4-C5 articulation stabilized with a KCC to those stabilized with a ventrally placed 4.5/5.0 LCP or a ventrally placed 3.5 LCP construct.

Materials and methods

Specimens

Twenty four equine cervical spines were collected within 24 hours of death from cadaveric adult horses that were aged by dentition. Ponies and draught breeds were excluded. The major external musculature was removed to the level of the intertransversarii cervicis muscles from the C3 to C6 (disarticulated between C2-C3 and C6-C7) spinal segment; joint capsules were left intact. The specimens were placed in sealed plastic bags and frozen to -20^{o}C.

Implants

Group 1: The KCC (Figure 14) (Wilson tool and Manufacturing Co., Washington, USA) with the following features were used: height 26mm, internal diameter 23mm, external unthreaded diameter 26mm, external threaded diameter 30mm. Each implant had four evenly spaced rows of twelve 4mm diameter circular holes.

Figure 14: Photograph of a Kerf Cut Cylinder.

Group 2: Standard 4.5/5.0 broad 8 hole LCP plates (Synthes reference 226.581) with six 5.0mm, self-tapping, locking screws. Screw length ranged from 32-55mm (Synthes ref VS502.032 to .055).

Group 3: Standard 3.5 broad 11 hole LCP plates (Synthes reference VP4045.11) with eight 3.5mm, self-tapping, locking screws. Screw length ranged from 30-45mm (Synthes ref VS303.032 to .045).

Study design

Using a random number generator (Excel 2003, Microsoft, USA) the spines were randomly allocated equally into four groups: groups 1-3 with the implants described above and group 4 without any implant.

The length of the vertebral body and height of the cranial vertebral body were measured for C4 and C5 from calibrated radiographs of the specimens, as described elsewhere (Rush Moore *et al.* 1994). Specimen length was defined as the combined lengths of C4 and C5 (Figure 15). Specimen height was defined as the mean height of the two vertebral body heights. Overall specimen size was defined as specimen length multiplied by specimen height.

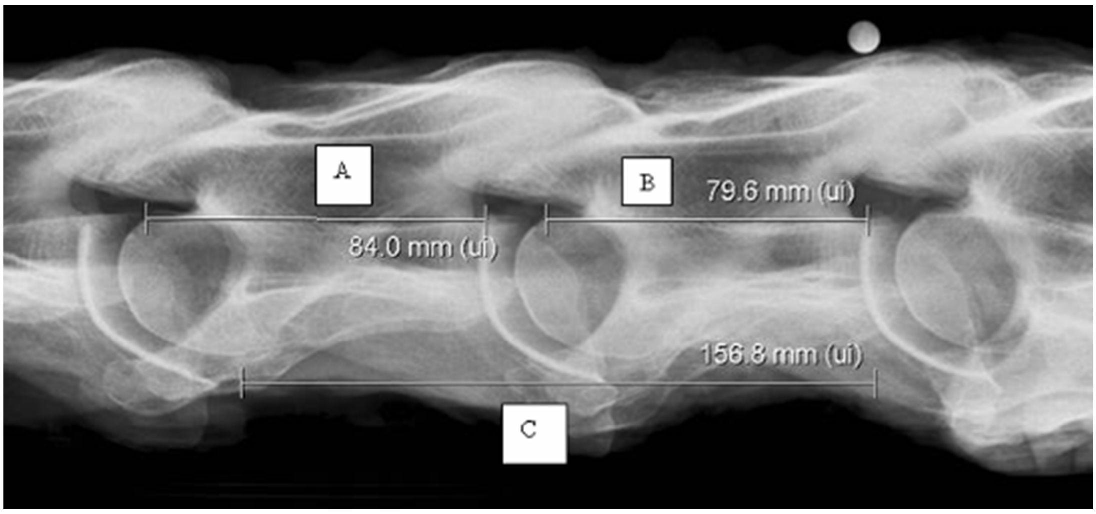


Figure 15: Radiograph demonstrating how vertebral size was measured in chapters three and four.

The spinal specimens were thawed at room temperature (20-22^{o}C) over a period of 12 hours prior to implant placement and resin fixation, subsequently they were re-frozen as before.

Kerf Cut Cylinder placement (group 1)

Specimens were secured on a wooden board with a 23mm deep pad of dense foam placed under the dorsal aspect of the C4-C5 articulation. The intertransversarii cervicis musculature over the ventral surface of C4 and C5 was sharply dissected. The ventral process of C4 was removed using an osteotome allowing access to the intervertebral disc. The KCC were placed using specialised equipment to drill and tap a cylindrical implant site between the bodies of C4 and C5, then screw the cylinder into place as described elsewhere (Grant *et al.* 2006) (Figure 16 shows the equipment required for KCC placement). Placement was performed under radiographic guidance using an isocentric C-arm (Ziehm Vision, Nürnberg, Germany) by the same clinician (JPW) for all 6 spines. (Table 2 shows the steps used for KCC placement.). Each implantation was timed with a stop watch from initial incision to end of implantation.

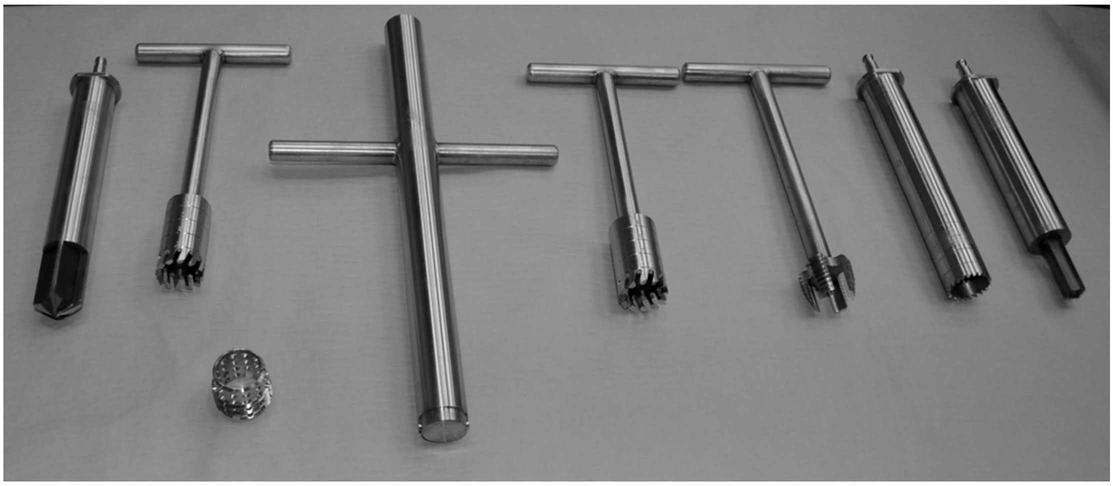
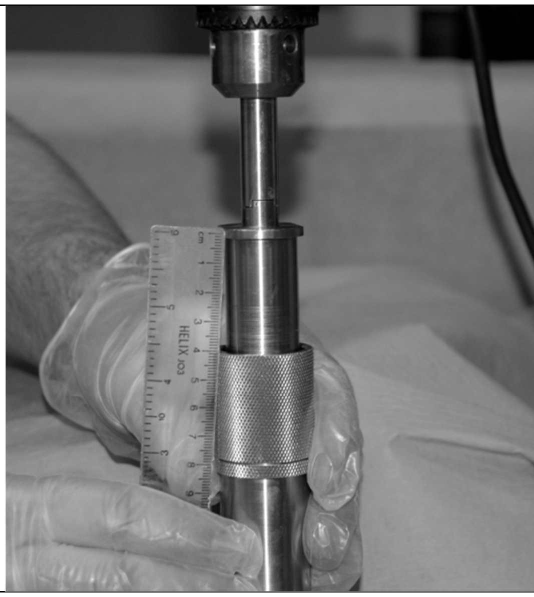
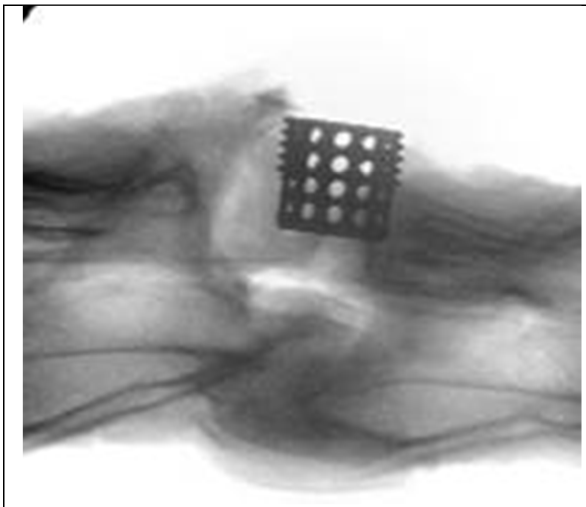


Figure 16: Equipment required for Kerf cut cylinder placement.

Table 2: Photographic views demonstrating the Kerf Cut Cylinder placement technique.

	
1. The ventral process of C4 is removed with a chisel	**2. The guide is positioned and sequential drilling is performed**

	
3. Fluoroscopic guidance is used to ensure accurate placement of the guide and depth of the core saw	**4. Manual measurements are also made using the drill guide and a ruler**
	
5. Further fluoroscopy is used to assess the depth of the bed cutter	**6. A specialised tap is then used to prepare the site**
	
7. The depth of the tap is also checked fluoroscopically	**8. The Kerf cut cylinder is then screwed into place with a specialised instrument**



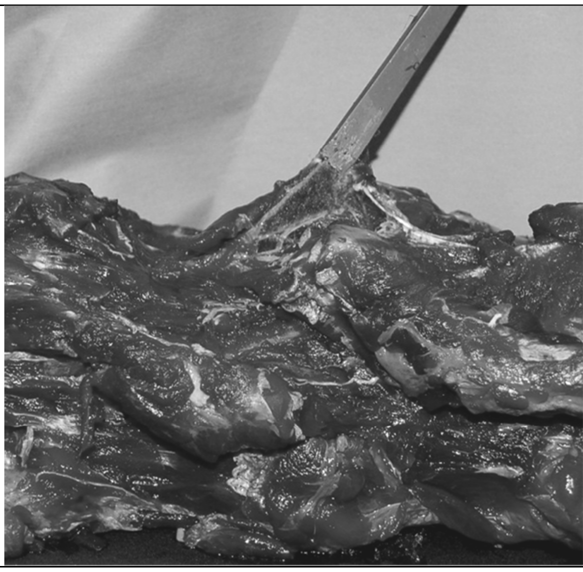
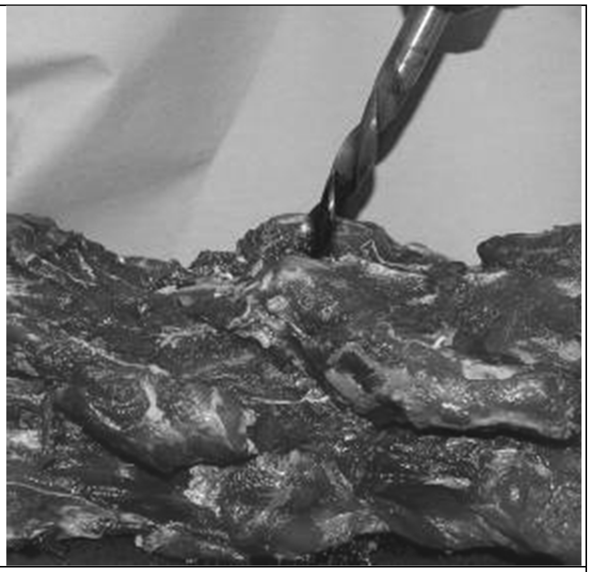
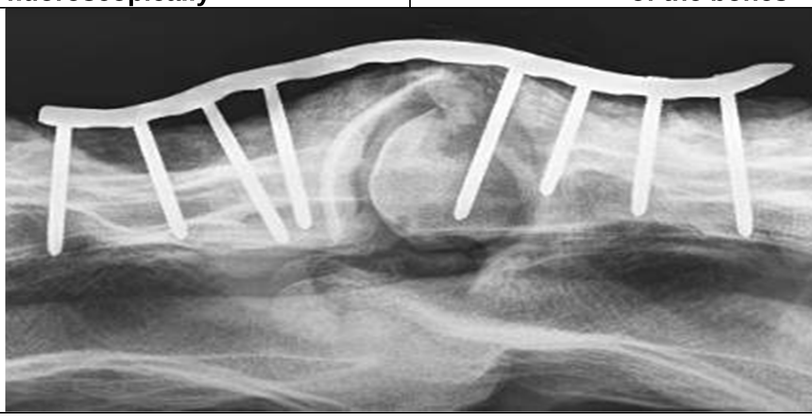
9. The position of the Kerf cut cylinder is checked fluoroscopically

10. The Kerf cut cylinder in position, viewed from ventrally

Locking Compression Plate placement (groups 2 and 3)

Specimens were secured and prepared as for group 1 as far as removal of the ventral process of C4. A drill with 15mm bit was used to remove material from the ventral half of the intervertebral disc, under radiographic guidance. The LCP were contoured to appose the ventral midline of C4 and C5. Screws were placed under radiographic guidance. For group 2: 5.0mm locking, self-tapping screws were applied to the screw holes (numbered sequentially from cranial to caudal on the plate) in the following order: 3,6,1,8,2,7 (the two centre holes were left empty). For group 3: 3.5mm locking, self-tapping screws were applied to the screw holes (numbered sequentially from cranial to caudal on the plate) in the following order: 4,8,1,11,2,10,3,9 (the three centre holes were left empty). For both groups screw placement was performed ensuring that screws did not interfere with any articulation, or the spinal canal. All plates were applied in the same fashion, using standard AO techniques relative to LCP placement, by the same clinician (CJL) for all 12 spines. (Table 3 shows the steps used for KCC placement). Each implantation was timed with a stop watch from initial incision to end of implantation.

Table 3: Photographic views demonstrating the Locking Compression Plate placement technique

	
1. A chisel is used to remove the ventral process of C4	**2. A 15mm drill bit was used to debride the C4-C5 inter-central articulation**
	
3. The position of the drill bit was checked fluoroscopically	**4. Plate was contoured to the ventral surface of the bones**
	
5. Radiograph following application of a 3.5mm broad 11 hole LCP	

Spine fixation

Two (4mm thread, 50mm length) coated high grade steel screws were placed in a craniomedio-caudolateral direction across the centre of each of the articular process joints between C3-C4 and C5-C6. Two (5mm thread, 100mm length) hardened, zinc plated, steel screws were placed in a cranioventral-caudodorsal direction in a sagittal plane across the intervertebral disc between C3-C4 and C5-C6.

Resin Fixation

Specimens were then supported over a specially designed 15cm^3 cuboid mould and fixed in polyester resin (Nord composites, Picardie, France) to the level of the necks of the cranial articular processes of C4 cranially and to the level of the necks of the caudal articular processes of C5 caudally in order to include the C3-C4 and the C5-C6 articulations in the resin. Resin fixation of both ends took less than 6 hours. The top inside edges of the resin blocks were trimmed to allow greater movement relative to the inner support points. A radiograph of a spine fixed with screws and resin is shown in Figure 17. Specimens were thawed at room temperature (20-22^{o}C) for 12 hours prior to testing, and during testing they were kept moist with water. The time from collection to test period (freezer time) was limited to a maximum of three months.

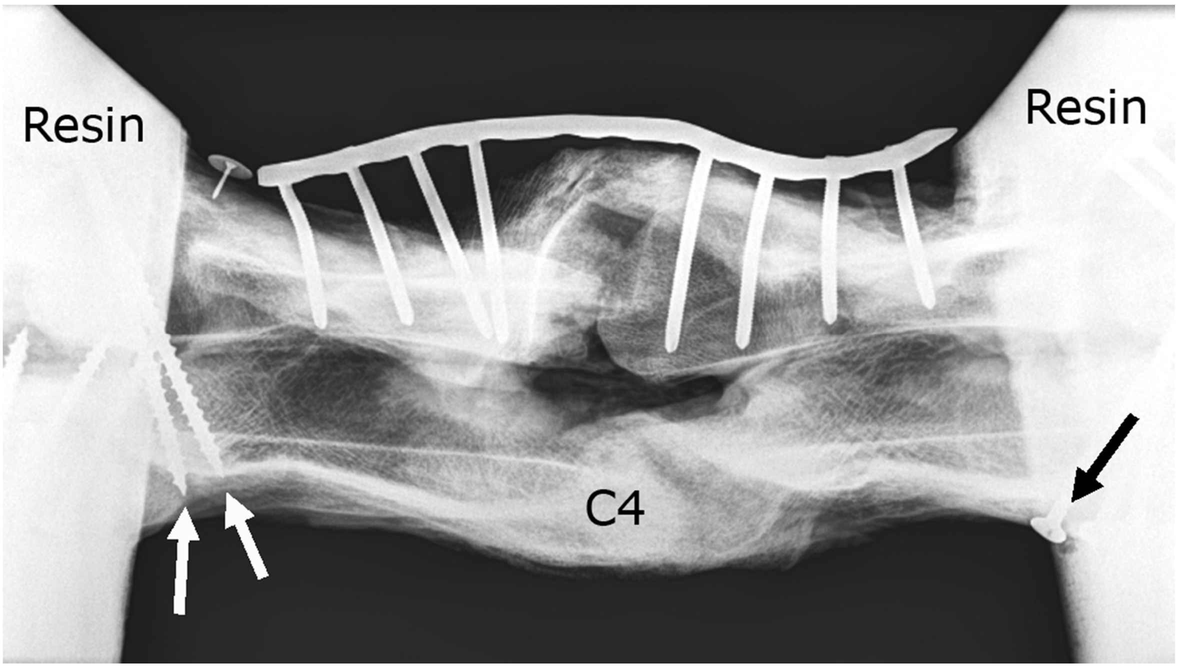


Figure 17: A spine fixed in resin post testing. White arrows point to the tips of the two 100mm screws extending from cranioventral to caudodorsal across the C3-C4 intervertebral disc. The black arrow points at one of the fixation screws extending from craniomedial to caudolateral across the centre of one of the articular process joints between C5 and C6.

Biomechanical testing

The resin blocks of the specimens were secured in steel boxes. Specimens were placed in a four point bending fixture within a materials testing machine (DARTEC 9500 Servo Screw Universal Testing Machine, Zwick, UK) (Figure 18). The outer support points were located on centrally placed pivot wheels on the outside of the steel boxes holding the resin. The outer support span was measured for each test specimen. The inner loading span was 100mm in all cases. The inner loading points were applied equidistant on either side of the C4-C5 articulation. The inner support points consisted of 10mm thick metal plates that were rounded on the C4 and wedge shaped on the C5 contact edges and had 20mm wide x 40mm deep central sections removed, which gave clearance for the plate ventrally. The inner contact points differed in shape because it was thought that the wedge shaped point might prevent movement in a cranial caudal plane, whilst the rounded contact would allow horizontal gliding movement around it without preventing normal flexion of the articulation. Because of the difficulty in fixing the C3-C4 and C5-C6 joints, the inner load points could not be more widely spaced and they contacted the bone within the span of the plate for groups 2 and 3.

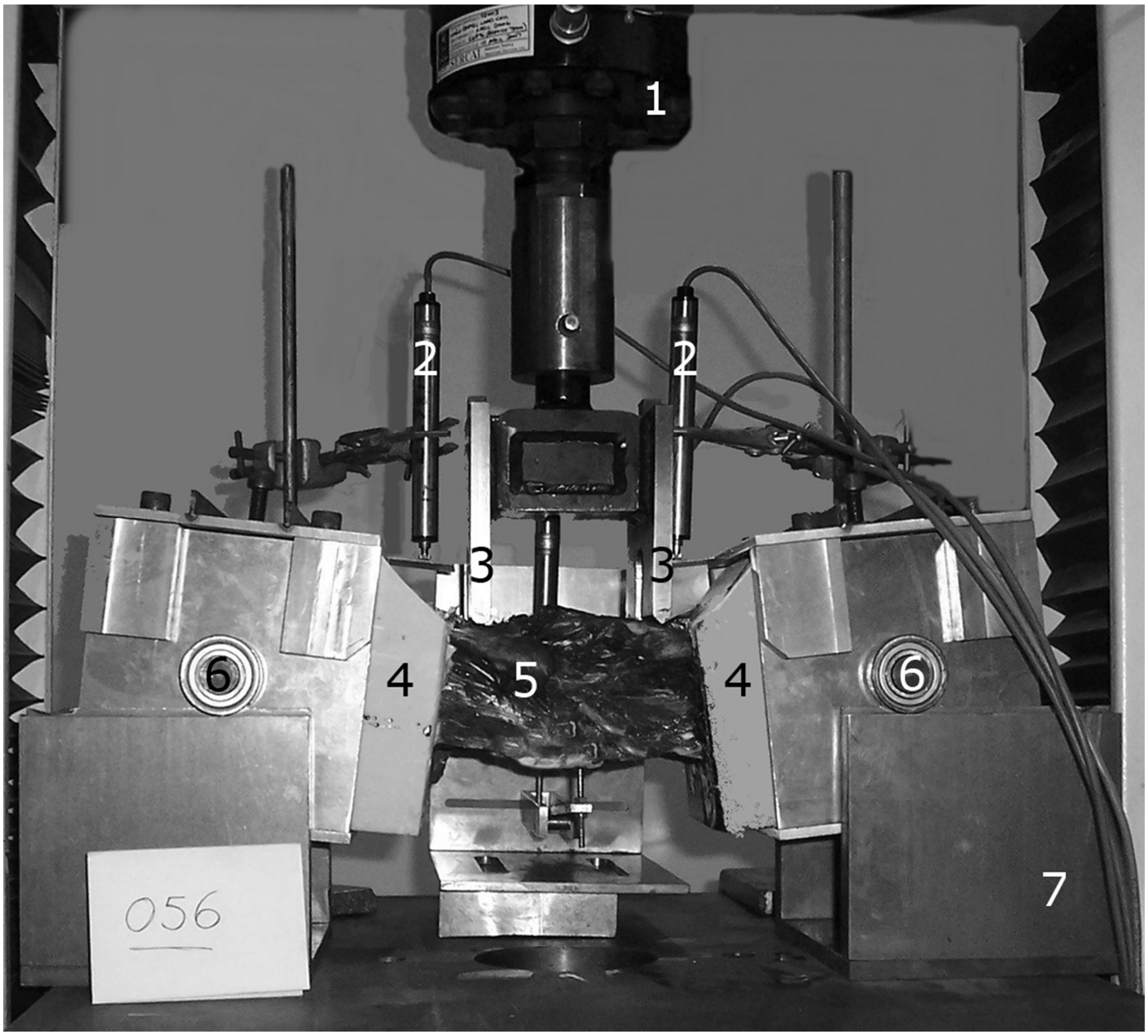


Figure 18: A spine secure in the load cell prior to testing. 1: Load cell; 2: LVDT; 3: Inner Support Points; 4: Resin Block; 5: Specimen; 6: Pivot Wheel / Outer Support; 7: Support.

Bending tests were performed in a ventral plane over a single cycle under displacement control at a constant rate of 0.1mm/s to failure. Three linear variable differential transformers (LVDT) were placed on the testing apparatus: one on the inside edges of each fixing box and one on the dorsal aspect of C4. Using an Orion S1 3531D Data Acquisition Data Logger, data was acquired at 0.1 second intervals throughout the test by A/D conversion and stored in a computer data file. Failure was defined as the point at which the load stopped increasing, despite continued displacement.

Data Analysis

Moment-angular displacement (4-point bending (15)) curves were constructed for each test. The slope of a simple linear regression of the linear (elastic) portion of each curve was used to determine stiffness in Nm/deg. Failure load and associated displacement were determined from the point of ultimate failure, that is, the highest point reached on the load-deformation curve.

Bending moment M was calculated using the following formula: M = (FL)/2

Where: F is the force (yield load or failure load) applied to the specimen;
L is (S-T)/2
S is the distance between the outer supports and T is the distance between the loading edges (Figure 19).

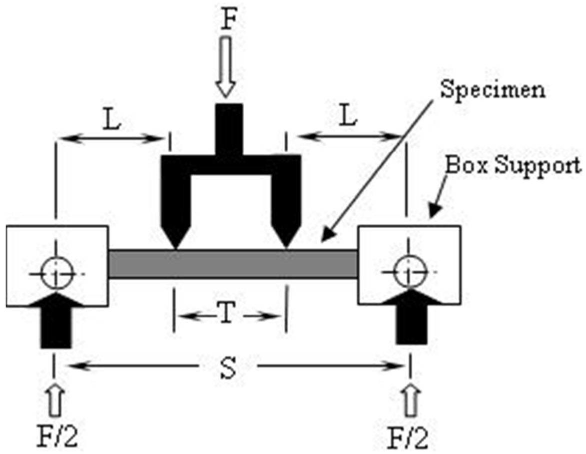


Figure 19: Diagram representing the forces applied through the test apparatus. F = force (yield load or failure load) applied to the specimen; L = (S-T)/2; S = distance between the outer supports and T = distance between the loading edges.

Angular displacement θ was calculated by using the formulas:

$\theta = \tan^{-1}(U/X)$ and $\theta_T = \theta_1 + \theta_2$

Where: θ is the angular displacement;

U is the displacement of the LVDT and

X is the offset of the LVDT from the pivot support,

θ_T is the total rotational displacement of the joint and

θ_1 and θ_2 are the rotations at each support (Figure 20).

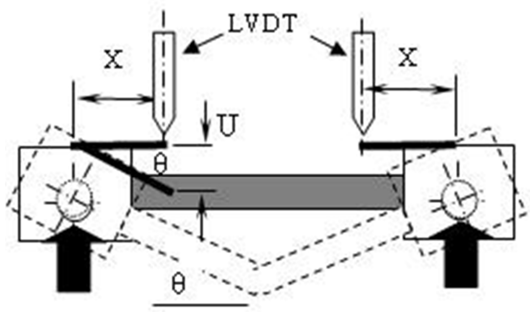


Figure 20: Diagram representing the angular displacement of the specimen. LVDT = linear variable differential transformer; θ = angular displacement; U = displacement of the LVDT and X = offset of the LVDT from the pivot support, θ_T = total rotational displacement of the joint and θ_1 and θ_2= rotations at each support.

Failure Mode:

Each specimen was examined thoroughly pre- and post-testing and the site of failure, when evident, was identified and recorded. Digital photographs (Kodak CX6330) of the test set up were taken at the start and end of each test. Latero-lateral (62 kV, 10 mAs) and dorso-ventral (68 kV, 10 mAs) radiographic projections centred on the C4-C5 articulation were taken prior to testing using computed radiography (CR MD 4.0 cassettes in a CR 35-X digitizer, Agfa, Agfa-Gevaert, Mortsel, Belgium). Latero-lateral, flexed (supported between blocks allowing the C4-C5 articulation to flex in a ventral direction) and dorso-ventral radiographic projections centred on the C4-C5 articulation were taken post testing (Figure 21). When it was not possible to accurately identify failure mode on the radiographs, implants were removed and CT images were collected (exel 2400 elite, Elscint, Phillips Medical Systems, Surrey, UK) of the C4 and C5 vertebrae.

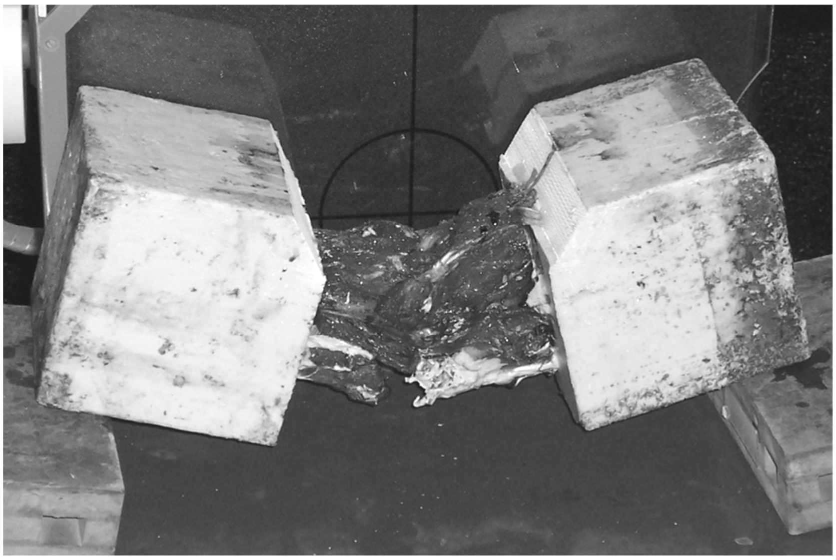


Figure 21: Post-testing radiography of a specimen, supported by blocks to stress the articulation

Statistical analysis

Mean (± SD) stiffness and moment to failure were calculated for each of the test groups.

Two general linear models were undertaken one for stiffness as the outcome and one for moment to failure as the outcome: Age, size and group were included as predictors and group was fitted as a random effect. The final models were specified using a stepwise algorithm and based on Akaike's Information Criterion (AIC). As the sample size for this study was convenience-based, a post-hoc power calculation, using the standard deviations calculated from the residuals of each fitted model was undertaken. Statistical significance was set at $P<0.05$. Statistical analyses were undertaken using R (16) and post-hoc power calculation undertaken using statistical software (nquery Advisor, version 6, Statistical Solutions, Saugus, MA, USA).

Results

Specimens

The cadaver specimens were collected from horses of ages ranging from 5 to 20 with a median age of 12 years. The final general linear models fitted age and size as predictor but group was dropped from both models (Table 4).

Table 4: Results of generalised linear models for stiffness and moment to failure

Outcome	Variable	Coefficients	Standard Error	P value
Stiffness$^{\#}$	Intercept	4.964	7.681	0.5251
	Age	-0.693	0.459	0.1463
	Size	0.304	0.142	0.0438*
Moment to failure$^{\#\#}$	Intercept	116.609	110.030	0.3013
	Age	-14.281	6.583	0.0417*
	Size	5.689	2.030	0.0107*

* significant at $P<0.05$
$^{\#}$ Adjusted $R^2 = 0.2185$
$^{\#\#}$ Adjusted $R^2 = 0.1072$

Age was found to be significantly associated with moment to failure (P=0.042) but not stiffness. It was found that for any given sized horse, an increase in age by one year will result, on average, in a decrease in moment to failure by 14.28 Nm.

The calculated length of specimens ranged from 16.2 to 22.8 cm with a median length of 18.3 cm. The calculated height of the specimens ranged from 2.6 to 4.2 cm with a median height of 3.3 cm. Calculated size ranged from 41.5cm^2 to 95.1cm^2 with a median of 62.2cm^2. Size was found to be statistically associated with stiffness (P=0.044) and moment to failure (P=0.011). For a horse of any given age, an increase in size by 1 cm^2 will result, on average, in an increase in stiffness by 0.30 Nm/deg and an increase in moment to failure by 5.69 Nm. The results of generalised linear models assessing association between age and size and stiffness and moment to failure are shown in Table 5.

Implant placement time:

KCC Placement

Time taken for KCC placement decreased. The first implant took 1 hour 10 minutes, whilst placement of the 6th implant took just 28 minutes. In one specimen, placement of the KCC resulted in fracture of a small cranial ventral part of the central bone pinnacle (the ventral part of the C4 vertebral body left in the centre of the KCC from cutting with the cylindrical core saw) (Figure 22).

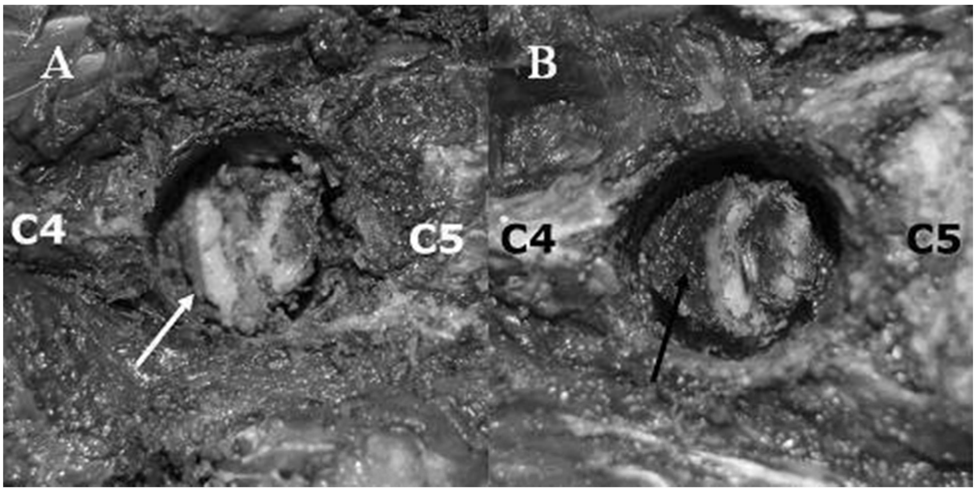


Figure 22: Images of the ventral aspect of the C4-C5 articulation after cutting with the core saw. A: specimen in which the ventral C4 part of the bony pinnacle fractured and has been removed (white arrow). B = specimen in which the bony pinnacle is intact (black arrow).

LCP Placement

The time taken to place the LCP implants decreased. The first implant in group 2 took 50 minutes, whilst placement of the 6th implant took 24 minutes. The first implant in group 3 took 45 minutes, whilst placement of the 6th implant took 30 minutes. Two specimens (one from each of groups 2 and 3) required replacement of one screw with a longer one, following radiographic assessment.

There was no significant difference between the three groups in the time taken for implant placement.

Mechanical test results

Following placement in the test unit, prior to load application, ventral flexion of the C4-C5 articulation was appreciated in the spines without implants but not in groups 1-3.

In all tests, an initial period of lower stiffness was apparent on the moment-angular rotation graphs (Figure 23).

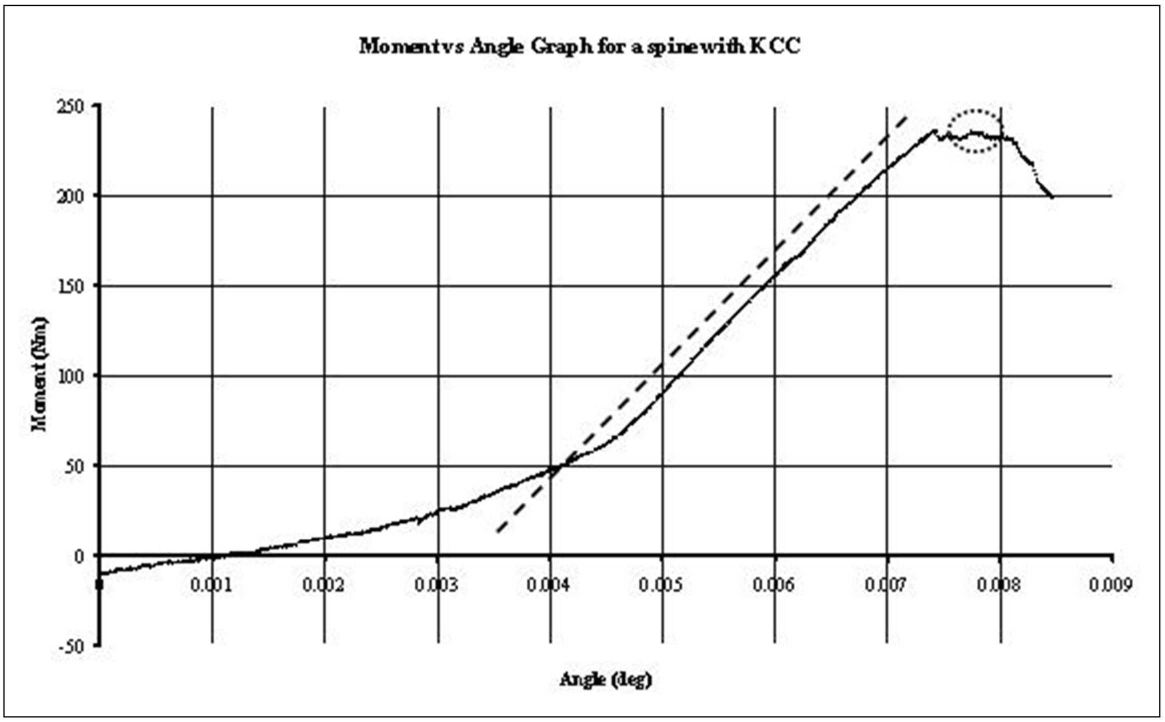


Figure 23: Moment vs. angle graph from Group 1 demonstrating initial shallow incline followed by steeper incline. Dashed line represents the stiffness of the construct; dotted circle represents the failure point. Nm = Newton meter, deg = degree.

A review of the moment to failure and stiffness for each of the groups are shown in Table 5 and represented graphically in figures 24 and 25.

Table 5: Mean, standard deviation (±) and (range) of stiffness and moment to failure for each group. Nm = Newton meter, deg = degree.

	Stiffness (Nm/deg)	Moment to Failure (Nm)
Group 1 KCC	**13.4** (± 4.3) (8.5 – 18.8)	**211.3** (± 51.6) (121 – 250)
Group 2 8 Hole	**15.7** (± 4.8) (9.2 – 21.8)	**337.8** (± 83.4) (216 – 448)
Group 3 11 Hole	**11.9** (± 6.7) (7 – 24.9)	**340.3** (± 162.4) (198 – 642)
Group 4 None	**19.8** (± 11.4) (8.7 – 38.4)	**274.6** (± 108.3) (167 – 436)

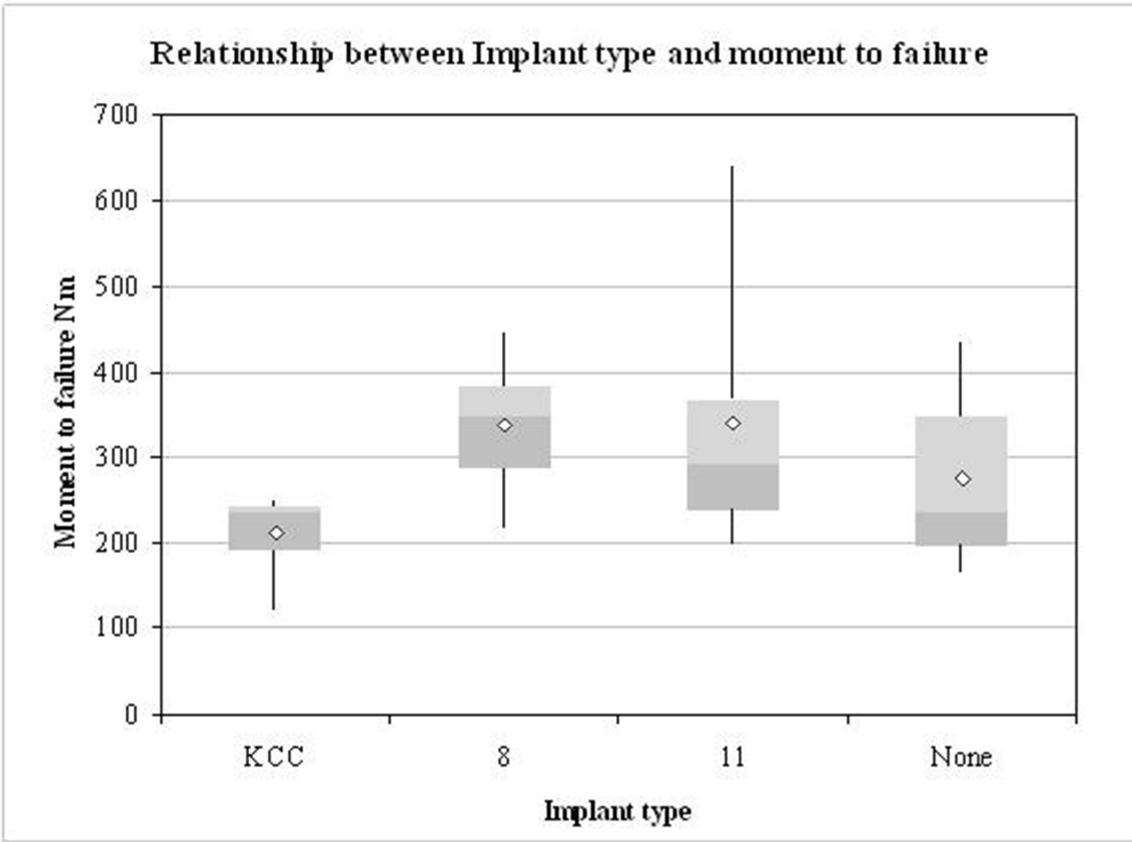


Figure 24: Relation of group with respect to moment to failure. Centre line is the median; interquartile ranges and total ranges are represented by the box and whiskers respectively. White diamonds represent the mean.

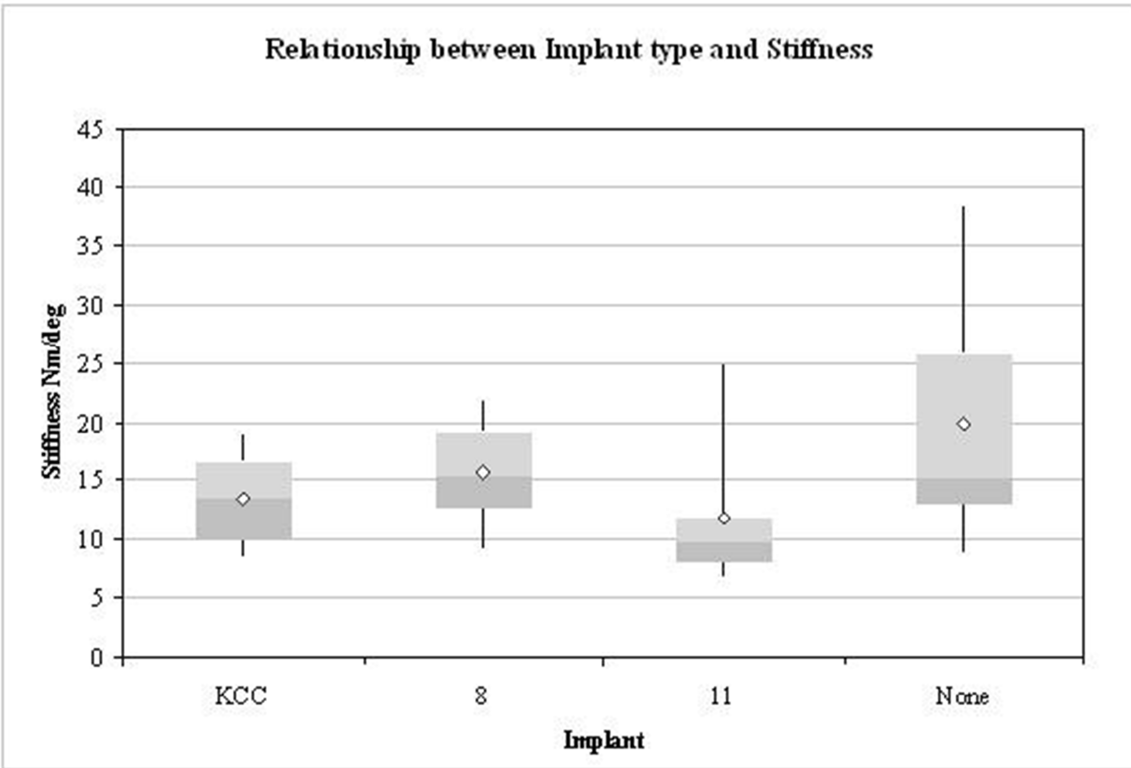


Figure 25: Relation of group with respect to stiffness. Centre line is the median; interquartile ranges and total ranges are represented by the box and whiskers respectively. White diamonds represent the mean.

There was no significant difference in the failure load or stiffness between any of the groups tested. The post-hoc power calculation revealed that, with 80% power to detect an effect based on the variance between means and at a significance of 0.05, 149 spines would be required for each group for the moment to failure model and over 2,000 would be required for the stiffness model. Based on these findings, to detect a difference between fixation method for groups of ten specimens, there would need to be a greater than 30% difference in either moment to failure or stiffness.

Failure modes

Group 1. KCC failure mode. Five of six of the KCC constructs failed via fracture of the C5 vertebral body between the caudal aspect of the cylinder and the vertebral canal (Figure 26). The other specimen failed by ventral migration of the cylinder. Two of the specimens were imaged in the CT scanner to confirm failure site; one was the spine in which KCC migration had occurred, and the other demonstrated a fracture line in a similar position to those observed in the other fractured specimens. The specimen that failed via migration of the KCC did not demonstrate any change in stiffness or moment to yield compared to the other KCC implanted specimens.

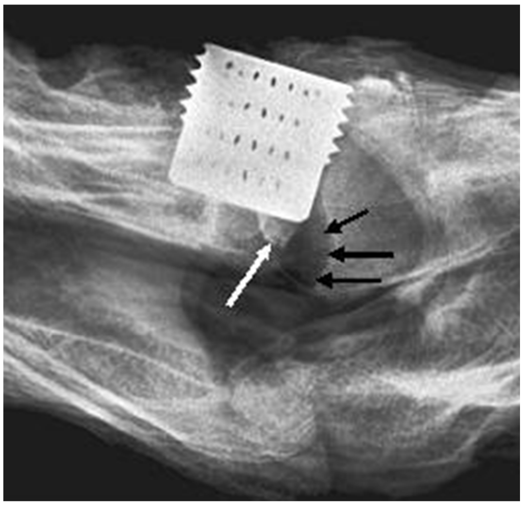
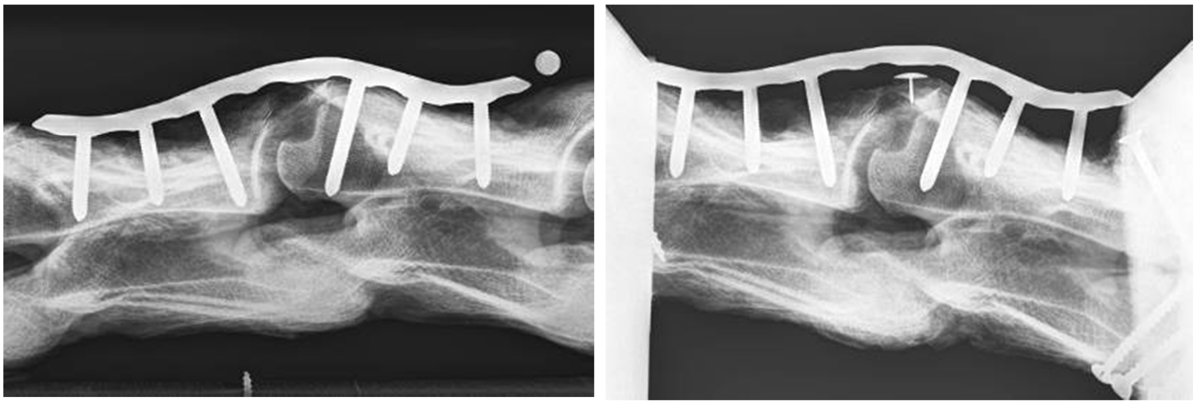


Figure 26: Post testing latero-lateral radiograph of the C4-C5 articulation from group 1. Left is cranial, top is ventral. Black arrows indicate the caudal end of the fracture line; white arrow shows the fracture fragment from the cranial body of C5.

Group 2. 4.5 Broad LCP failure mode. All constructs failed via screw pull out, which was most notable from C5 in 4 of the 6 cases. Minimal plate bending was appreciated (Figure 27 demonstrates a case of failure from screw pull out). In one case the cranial screw was bent. None of the spines fractured.

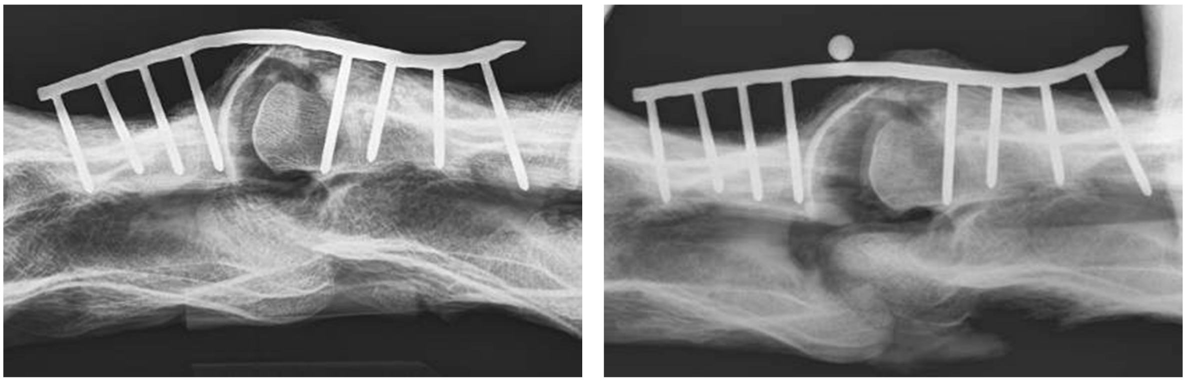


A B

Figure 27: Radiographs before (A) and after (B) testing of a 4.5mm Locking Compression Plate demonstrating screw pull out.

Group 3. 3.5 Broad LCP failure mode.

All but one of the constructs failed via screw pull out. Screw pull-out occurred primarily from C5. Plate deformation occurred in all but one of the cases. In three of the cases, screw bending was observed ranging from 2 to 6 screws. In the case where screw pull out did not occur, the plate, two cranial and all four caudal screws were deformed. The spine that failed without screw pull out demonstrated a markedly higher stiffness (double that of any of the other spines in this group), though the plate did ultimately bend. None of the spines fractured. (Figure 28 demonstrates a case of plate deformation.)



A B

Figure 28: Radiographs before (A) and after (B) testing of a 3.5mm Locking Compression Plate demonstrating plate deformation.

Group 4. No implant failure mode. All six spines without implants failed via disarticulation at C4-C5.

Discussion

This study reports a successful method for applying consistent load across a single equine cervical vertebral articulation. Multiple pilot studies were performed to ensure movement occurred only at the C4-C5 articulation. The anatomy of the cervical vertebrae makes fixation and application of load across a single articulation difficult. Resin fixation of the specimens of just C3 and C6, insertion of metal rods in the spinal canal across the C3-C4 and C5-C6 articulations and leaving C3-C4 and C5-C6 unfixed all led to inconsistent failure outside the C4-C5 articulation. Furthermore, load application through a variety of different load points, including adjustable inner support points and loading arms led to inconsistent contact and specimen failure. Three point bending was successful, but necessitated load application on either C4 or C5 and was deemed inferior to 4 point for examination of the mechanical properties of the constructs at this articulation. The final test model required placement of screws across the C3-C4 and C5-C6 articulations. Radiographic projections in two planes confirmed that these screws did not impinge upon the constructs in any of the cases, as they were abaxial and cranial or caudal to them. None of the spines fractured at sites associated with the screws used for fixation of these articulations, suggesting they did not have an adverse effect on the vertebral structure.

The results of the study suggest that the mechanical properties of the LCP constructs are comparable to those of the KCC. Although differences were observed in the mechanical properties between implants, these were not statistically significant, which is likely to be partially the result of variability in the specimens, the small sample size and consequent relatively large standard deviation for each of the groups. However, it was determined that unreasonably large sample sizes would be required to find a significant association between fixation technique and moment to yield or stiffness (149 and over 2000 spines per group respectively) and as such implies that if an association were to exist, it is unlikely to be mechanically important. A limitation of the study is that the testing involved high load application in only one plane, which may be comparable to forces acting on a horses’ neck during a fall, such as during anaesthetic recovery, but does not emulate the forces acting on the neck during normal movement. Others have recognised single cycle loading as a useful way to obtain information about the stability of implants (Elce *et al*. 2006; Fitzpatrick *et al*. 2008). Repetitive loading of spines at physiologically representative loads would provide useful information about the potential long term stability provided by the implants.

We chose to test to failure in ventral flexion because this tests the weakest configuration for the LCP constructs (compression side for the plate). The comparable mechanical properties of the LCP with the KCC implants despite this are encouraging. Further testing in dorsal and lateral flexion is needed. The higher mean stiffness and moment to failure of the spines without implants may be a result of the greater contact between the C4 and C5 vertebrae and the presence of the intact inter-central joint capsule in these specimens. It is also hypothesised that the implants in groups 1-3 stop the facets and inter-central joints from articulating, which leads to a less stable communication between the vertebrae and a different method of failure.

For all tests, the moment-angular rotation graphs demonstrated two distinct gradients (Figure 23): An initial shallow gradient followed by a steeper gradient. Construct stiffness was calculated from the second of these two lines in each case, as this was considered most likely to represent the true stiffness of the construct. Although the exact cause of the early lower stiffness is unknown, it has been observed in other clinical studies (Arnott *et al*. 2008). It is hypothesised that the initial stiffness relates to a “bedding in” effect of the test apparatus, which occurs as the inner contact points meet the specimen and any residual movement in the C4-C5 articulation is taken up. The consistent nature of this finding is encouraging as it adds weight to the repeatability of the testing.

Placement of KCC occurred with minimal complications, which reflects the experience of the clinician undertaking the placement. The complication during KCC placement of ventral cranial bone pinnacle fracture (Figure 22) has previously occurred during surgery performed by one of the authors on clinical patients, without apparent ill effect and as a result the specimen was included in this study. Implantation of LCPs was straight forward. Contouring of the plates to the ventral surface of the vertebrae was simple once the ventral process of

C4 had been adequately removed. Two spines required screw replacement, which was performed without difficulty and may highlight a benefit of the LCP system over the KCC, where revision implant placement is not feasible.
The rapid decrease in implantation time over the six specimens for each of groups 1-3 was primarily as a result of operator experience (both surgeon and technicians). The comparable implantation time between KCC and LCPs was encouraging, however access to the surgical site is far easier in these dissected specimens than it is *in vivo*. Although implantation of 8 screws takes longer than 6, the comparable implantation times between groups 2 and 3 observed in this study is a reflection of the speed of screw placement once radiographic measurement had been performed and the fact that group 3 implants were placed when the implant technique was most practised.

The failure modes differed between the groups. The relatively consistent fracture of the cranial articular end of the body of C5 in group 1 was interesting. To the authors' knowledge, this complication has not been previously reported. This may be because the spines were being placed under far higher loads in this testing than they experience *in vivo*, or because the fractures are relatively hard to see, requiring stressed radiographic projections for detection in some of these cases. It is also possible that the instability in the articulation caused by these small fractures is sufficiently supported by the extrinsic musculature to allow fracture healing without causing a clinical problem.
None of the LCP constructs resulted in vertebral fracture though the failure mode differed between the 4.5/5.0 and the 3.5 constructs. Screw and plate bending was observed frequently in group 3 compared with the bending of just a single screw in group 2. This reflects the size difference and hence different mechanical properties of the screws and plates. All but one of the LCP constructs failed via screw pull out, which commonly occurred from vertebra C5. This failure mode is likely as a result of the direction of flexion, with the construct on the compression side of the joint. The spine that failed by plate and screw deformation alone demonstrated a higher stiffness than all the other implanted spines, suggesting that construct stiffness may be closely related to pull out strength of the screws for the LCP constructs. Construct failure by screw pull out would be highly undesirable in a clinical case, but may not preclude revision surgery and implant replacement (Reardon *et al*. 2009). By re-

positioning the plate more cranially, caudally or abaxially, new holes could be drilled or different sized plates or screws employed. Failures of KCC implanted spines could also be revised but if fractures had occurred at the implant site an alternative technique, such as use of a ventrally placed plate might be required to supplement it.
The spines without implants all failed via disarticulation, no fractures were appreciated in this group. This highlights one possible adverse effect of the KCC implant which weakens the vertebra and alters the load distribution across the articulation.

The use of cadaveric specimens does not accurately emulate conditions *in vivo*, in which external soft tissue structures provide stability and compression around the cervical articulations and healing mechanisms stabilise the implant site with new bone proliferation. However, through the use of a standardised technique in which the same external support structures were removed for all cases, it is hoped that the tested samples were comparable. Many other studies have used cadaveric specimens for preliminary work (Dvorak *et al*. 2005; Lehmann *et al*. 2005; Elce *et al*. 2006; Fitzpatrick *et al. 2008*) as useful information can be obtained without the risk of animal morbidity or mortality.

Quite a large amount of variation in stiffness and moment to failure was appreciated within the groups in this study. There are numerous possible causes for this. The use of cadaveric specimens introduces uncontrollable variability as the anatomy and physiological structure of the bone and soft tissues inevitably varies. Use of fresh specimens may have been preferable to frozen ones and due to the constraints on collection; freezer time did vary between specimens. However specimens were handled in a consistent fashion; previous studies have used frozen cadavers for biomechanical testing (Glazer *et al*. 1996). It has been shown that freezing has little effect on the biomechanical properties of bone (Linde and Sorenson 1993) and one study using pig cervical vertebrae concluded that freezing resulted in no change in stiffness or displacement at failure (Callaghan and McGill 1995). Although specimens were kept moist externally, some drying of internal tissue was likely, which has been shown to effect mechanical properties (Costi *et al*. 2002). In this study, specimens from younger horses were found to have significantly higher moment to failure than those from older horses. Equine bone microarchitecture has been shown to vary with age (Furst *et al.* 2008), which likely explains this finding. Age of specimens in this study was elucidated from dentition, which has been shown to be not entirely accurate (Richardson *et al.* 1995) so the ability to accurately predict moment to failure from age is probably questionable. The association of increasing spine size with increasing moment to failure and stiffness is unsurprising.

Conclusions

This pilot study describes a technique for testing the equine C4-C5 articulation and provides some preliminary data regarding its mechanical properties. In this study group the mechanical properties of articulations fixed with the LCP construct were comparable in ventral flexion, to spines fixed with the KCC construct, which may justify LCP use in clinical cases. Future work could involve investigation of the mechanical properties of spines in different planes of flexion, the effects of cyclical loading and extrinsic musculature and the investigation of alternate implants and implantation techniques.

Chapter Four

4. Further Biomechanical Testing

"An *in vitro* biomechanical comparison of a Locking compression plate fixation and Kerf-cut cylinder fixation for ventral arthrodesis of fourth and fifth equine cervical vertebrae"

Published online in: Veterinary Surgery 2010 (Sep 29).

INTRODUCTION

Cervical spinal cord compression in horses can occur from developmental (e.g. cervical vertebral malformation [CVM] (Wagner *et al.* 1987; Mayhew *et al.* 1978a; Reed *et al.* 1981)) and acquired (e.g. fractures (Pinchbeck and Murphy 2001), osteoarthritis of the articular process joints (Rush 2006)) causes. Compression of the spinal cord can sometimes be relieved by stabilizing the cervical vertebrae involved (Wagner *et al.* 1979a, Wagner *et al.* 1979b; Grant *et al.* 1985a, Grant *et al.* 1985b; Rush Moore *et al.* 1993). A technique using surgical implants to encourage bony fusion and stability between cervical vertebrae as a treatment of cervical spinal cord compression in horses was reported in 1979 (Wagner *et al.* 1979a). The technique has evolved from implantation of a homologous bone dowel to implantation of a stainless steel cylinder with bone graft (Cloward Bagby basket) (Wagner *et al.* 1987) to an open-ended threaded, stainless steel cylinder (Kerf Cut Cylinder [KCC]). The technique is now widely used for treatment of cervical stenotic myelopathy in North America and the UK. It has been estimated that up to 2000 horses have had cervical vertebral arthrodesis surgery (Walmsley 2005).

Clinical assessment after surgical stabilization of the cervical vertebrae report varying success; return to ridden work has been shown to range from 43% - 79% (Rush Moore *et al.* 1993; Wagner *et al.* 1979a; Walmsley 2005; Nixon and Stashak 1985; Trostle *et al.* 2003; Schuette 2005). The complication rate associated with these procedures is high, with major complications associated with the techniques being ventral migration of implant and vertebral fractures. One review reported a 9% fatality rate (Rush Moore *et al.* 1993).

Vertebral arthrodesis techniques are commonly performed in people as treatment for degenerative conditions of the vertebrae, traumatic instability (after vertebral fractures) and other conditions (such as cervical spondylosis) (Dvorak *et al.* 2005). More than 80,000 lumbar interbody fusion cages (metallic cages, providing support, whilst allowing bony in growth between lumbar vertebrae during fusion) were implanted across the world in the 5 years leading up to 1999 (McAfee 1999). *In vitro* mechanical testing of implants designed to promote vertebral fusion, has been performed in a large number of human studies reviewed in 1999 (McAfee 1999). The recent advent of Locking

Compression Plates (LCP) have provided an alternate fixation technique and these plates have been used for trans-cervical fixation techniques in people (Dvorak *et al*. 2005; McAfee 1999). LCP has allowed fracture repair and successful cervical vertebral arthrodesis in horses where a cylindrical implant would not have been suitable, because the horse was considered too small for the cylindrical implant (Reardon *et al*. 2009). In addition, cylindrical implants would not be suitable for fixation of certain cervical vertebral fractures and the ability to augment or replace failed KCC placement may be of benefit in some cases.

Preliminary *in vitro* testing of the LCP fixation technique has already been performed. A preliminary cadaveric study demonstrated a successful testing module for biomechanical testing of equine cervical vertebrae and compared 2 sizes of LCP with KCC implanted cervical vertebrae during flexion (Reardon *et al*. 2009); however to our knowledge, no study has investigated the mechanical testing of equine cadaver specimens in extension or left lateral bending or compared KCC and LCP implants in those directions.

Cervical vertebral arthrodesis is performed regularly in horses; however, the biomechanical properties of the currently used implants have not been investigated. Current arthrodesis techniques are associated with complications and there are situations in which an alternative implant would be beneficial (Reardon *et al*. 2009). Thus, our purpose for this *in vitro* study was: 1) to determine mechanical properties in flexion, extension and left lateral bending of the C4-C5 articulation of a group of equine cadaveric specimens, and 2) to compare biomechanical properties of the 4^{th} and 5^{th} equine cervical vertebral articulation when stabilized with a KCC compared with that stabilized with a ventrally placed 4.5 LCP. We hypothesized that LCP implanted cervical vertebrae would be stronger and stiffer than cervical vertebrae with KCC implants or without implants. We also hypothesized that biomechanical variables would differ with loading direction and that failure mode would differ between implant type and loading direction.

MATERIALS AND METHODS

Specimens

Equine cervical spines (n = 54) from C3 - C6 (disarticulated between C2-C3 and C6-C7) were collected from adult horses (range, 5 - 20 years; median, 12 years). Ponies and draught breeds were excluded. Cervical vertebrae were collected from cadaver specimens of unknown histories (aged by dentition) within 24 hours of death. Major musculature was removed to the level of the intertransversarii cervicis and longus colli muscles; joint capsules were left intact. Specimens were stored in sealed plastic bags and frozen to -20^{o}C. Specimens were frozen twice: once after collection and once after implantation. Specimens were thawed at room temperature (20-22^{o}C) for 12 hours twice: once before implantation and once before biomechanical testing. Collection to test period (freezer time) was limited to a maximum of 4 months.

Study Design

Cervical vertebrae were numbered and divided into 3 age groups: 5-10 years, 11-15 years and 16-20 years, to ensure distribution of different ages. Then, using a random number generator (Excel 2003, Microsoft) cervical vertebrae were allocated within the age groups to 1 of 3 implant groups: KCC, LCP, and Intact. From these groups using the same random number generator the specimens were then equally subdivided into 1 of 3 test directions for 4 point bending: a) flexion; b) extension; c) left lateral bending, leaving 6 specimens in each group.

Length of the vertebral body (measured from the midpoint of the cranial articular surface to the midpoint of the caudal articular surface (Figure 29, line A) and height of the cranial vertebral body (measured from the ventral aspect of the cranial vertebral body to the ventral aspect of the vertebral canal, at the widest point (Figure 29, line B) were measured for C4 and C5 from calibrated radiographs as described elsewhere (Rush Moore *et al*. 1994). Specimen length was defined as the combined lengths of C4 and C5. Specimen height was defined as the mean height of the 2 vertebral body heights. Because vertebral shape varies; vertebral length and height are not predictably related, so to produce a numerical indicator of overall specimen size this was defined as specimen length multiplied by specimen height.

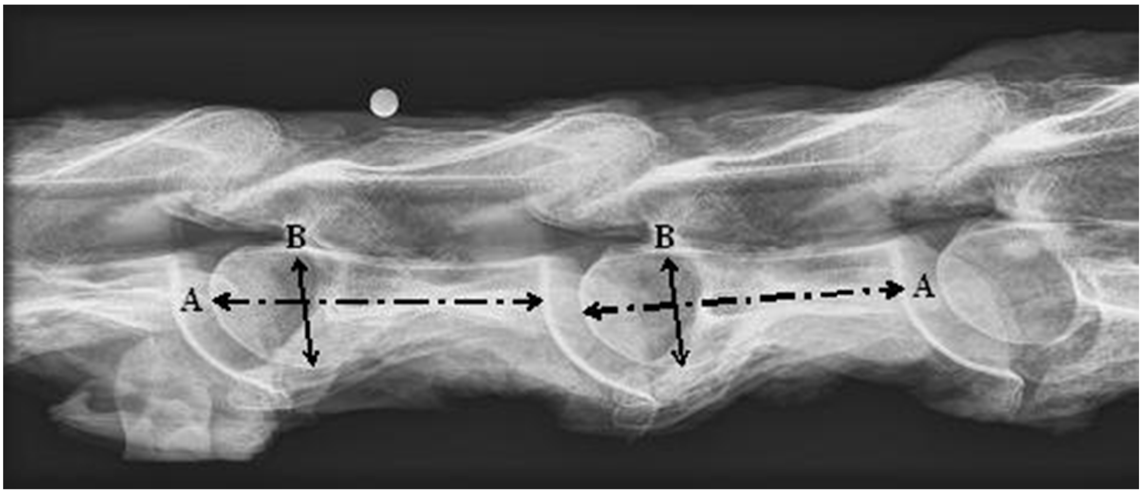


Figure 29: Left-right laterolateral radiographic projection centred on the C4-C5 articulation of a specimen, demonstrating measurements collected for specimen sizing. Radiodense structure on dorsal C4 is a ball bearing placed on midline, used for calibration. A = length of vertebral body. B = height of cranial vertebral body. Left = Cranial; Top = Dorsal.

Kerf Cut Cylinder placement (KCC group)

Implants. KCC obtained (Wilson Tool and Manufacturing Co, Spokane,WA) with the following features: height 26mm; internal diameter 23mm; external diameter 26mm (unthreaded), 30mm (threaded); with 4 evenly spaced rows of twelve 4mm diameter circular holes.

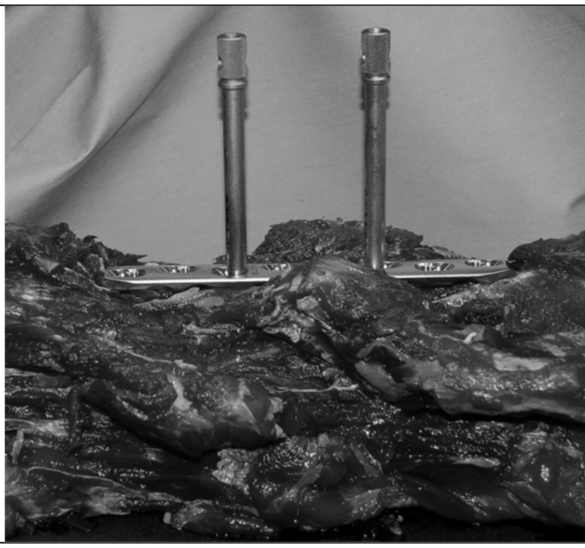
Specimens were secured on a wooden board with a 23mm deep pad of dense foam placed under the dorsal aspect of the C4-C5 articulation. The longus colli musculature over the ventral surface of C4 and C5 was sharply dissected. The caudal midline ventral crest of the C4 vertebral body was removed using an osteotome allowing access to the inter-central articulation. Under radiographic guidance (using an isocentric C-arm, Ziehm Vision, Nürnberg, Germany), the intervertebral disc was debrided with a Volkmann spoon curette, a bed for the KCC implant was drilled and tapped using specialized equipment (Wilson Tool and Manufacturing Co) and the KCCs were inserted, (full details of the technique are described elsewhere (Grant *et al*. 2006). KCC implants were placed by the same clinician (JPW) for all 18 specimens. Time from initial incision (start of muscle debridement) to end of implantation was recorded.

Locking Compression Plate placement (LCP group)

Implants. Standard 4.5 broad 8 hole LCP plates (Synthes®, Solothurn, Switzerland; reference 226.581) with six 5.0mm, self-tapping, locking screws. Screw length ranged from 32-55mm (Synthes ref VS502.032 to .055, Synthes)

Specimens were secured and prepared as far as removal of the ventral process of C4, as for the KCC group. A drill with 15mm bit was used to debride the disc material from the ventral half of the inter-central articulation, under radiographic guidance. Plates were not contoured, but were applied straight. Screws were placed under radiographic guidance: 5.0mm locking, self-tapping screws were applied to the plate holes (numbered sequentially from cranial to caudal on the plate) in the following order: 3,6,1,8,2,7 (the 2 centre holes were left empty). Plates were positioned so that the 4th and 5th holes spanned the C4-C5 articulation. Consistent positioning was achieved by ensuring that the screw 3rd from cranial, consistently engaged the caudal most part of the body of C4, without interfering with the articulation. Screw placement was performed ensuring that screws did not interfere with any articulation, or the spinal canal. All plates were applied in the same fashion, using standard AO/ASIF techniques relative to LCP placement, by the same clinician (CL) for all 18 specimens (Table 6 demonstrates steps in LCP placement that differed from chapter 3). Time from initial incision to end of implantation was recorded.

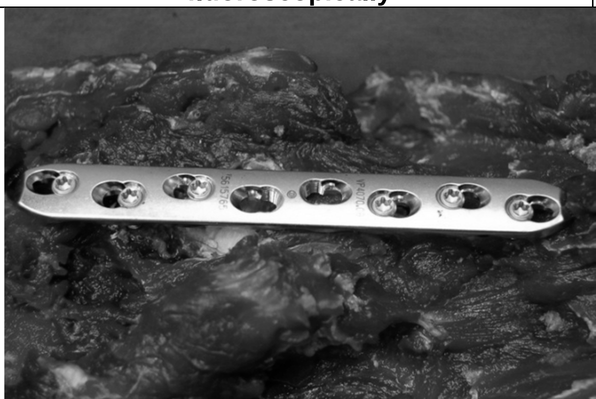
Table 6: Images of steps in Locking Compression Plate placement that differed from those used in chapter three.



1. **An uncontoured 8 hole 4.5mm broad Locking compression plate was placed over the articulation**

2. The position of the LCP was checked fluoroscopically

3. Screw holes were drilled under fluoroscopic guidance



4. Screws were placed sequentially until all but the two central holes were filled

5. Screws were all placed under fluoroscopic guidance

After implant placement, specimens were placed in sealed plastic bags and frozen to -20^{o}C

Preparation of Specimens for Mechanical Testing

Two (4mm thread, 50mm length) coated steel screws were placed in a craniomedial-caudolateral direction across the centre of each of the articular process joints between C3-C4 and C5-C6. Two (5mm thread, 100mm length) hardened, zinc plated, steel screws were placed in a cranioventral-caudodorsal direction in a sagittal plane across the intercentral joints between C3-C4 and C5-C6. Specimens were then supported over a specially designed 3375cm^3 cuboid mould and fixed in polyester resin (Nord composites, Picardie, France) to the level of the necks of the cranial articular processes of C4 cranially and to the level of the necks of the caudal articular processes of C5 caudally in order to include the C3-C4 and the C5-C6 articulations in the resin. Resin fixation of both ends took <6 hours. The top inside edges of the resin blocks were trimmed to allow greater movement relative to the inner support points.

Mechanical Testing

The resin blocks were secured in steel boxes. Specimens were placed on a bending fixture within the materials testing machine (Figure 30). During testing specimens were kept moist with water. Outer support points were located on centrally placed pivot wheels on the outside of the steel boxes holding the resin, which were free to move along the bottom supports (Figure 30, label 7). The outer support span was measured between the centre of these pivot wheels for each case. The inner support points were applied equidistant on either side of the C4-C5 intercentral articulation. The inner support span was 100mm in all cases. For flexion and extension the inner support points consisted of 10mm thick metal plates. The plates were rounded on the C4 and wedge shaped on the C5 contact sides and had 2cm wide x 4cm deep central sections removed, which spanned the plate or bone ventrally and the dorsal spinous process dorsally. For left lateral bending the inner support points consisted of 10mm thick metal plates, rounded on the C4 and wedge shaped on the C5 contact sides and contacted the lateral aspect of the neural arch. The inner contact points differed in shape because it was thought that the wedge shaped point might prevent movement in a cranial caudal plane, whilst the rounded contact would allow horizontal gliding movement around it without preventing normal flexion of the articulation. Because of the difficulty in fixing the C3-C4 and C5-C6 joints the inner support points could not be more widely spaced and contacted the bone within the span of the plate for the LCP group. Before testing, accurate apposition of the inner support points to the vertebrae was checked – discrepancies in height were adjusted using metal spacers placed under the metal supports (Figure 30, label 7).

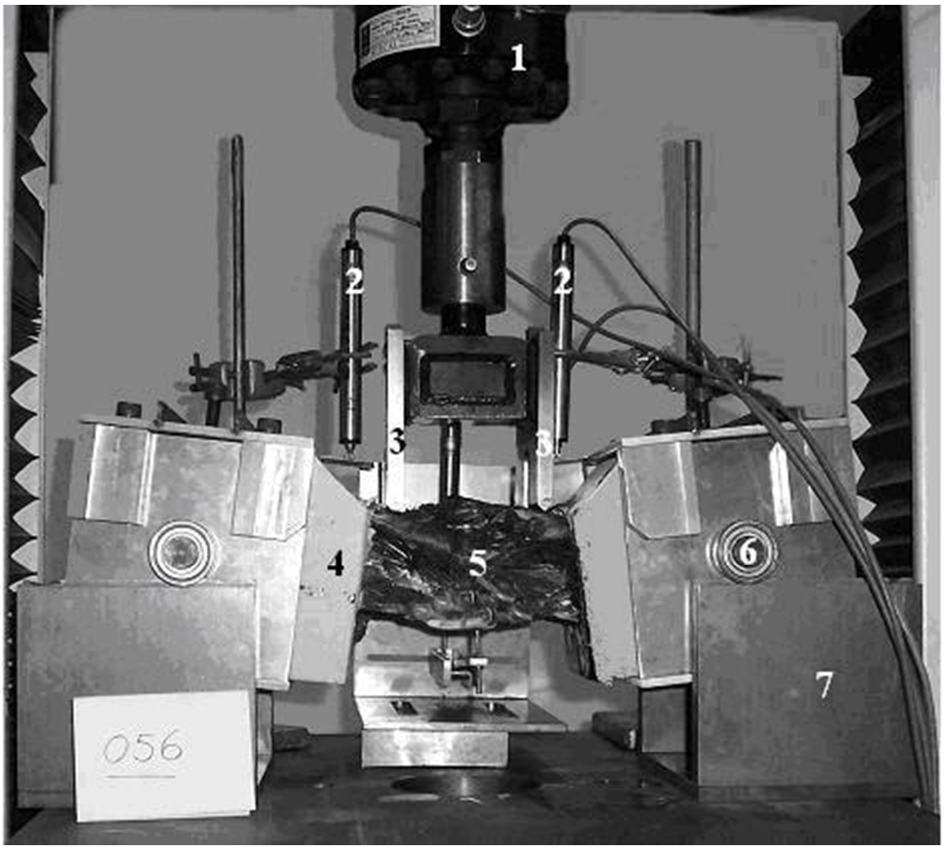


Figure 30: Cervical vertebrae secure in the load cell before testing (Left = cranial, Top = ventral). 1: Load cell; 2: LVDT; 3: Inner Support Points; 4: Resin Block; 5: Specimen; 6: Pivot Wheel / Outer Support; 7: Support.

Bending tests were performed in flexion, extension or left lateral directions over a single cycle under displacement control at a constant rate of 1mm/s to failure. A DARTEC 9500 Servo Screw Universal Tensile Testing Machine (Zwick, Leominster, UK) was used. Three Linear Variable Differential Transformers (LVDTs) (AML, IE Series; Berkshire, UK) were placed on the testing apparatus: one on the inside edges of each fixing box and one on the caudal, lowest aspect of C4. Using an Orion S1 3531D Data Acquisition Data Logger (Ametek; Farnborough, UK), data was acquired at 0.1 second intervals throughout the test by A/D conversion and stored in a computer data file. Failure was defined as the point at which the load stopped increasing, despite continued applied displacement.

Data Analysis

Moment-angular displacement (4-point bending (Dowling 2007)) curves were constructed for each test. The slope of the linear (elastic) portion of each curve was used to determine stiffness Nm/deg. Yield point was defined as the point on the moment-angle curve where stress was no longer proportional to strain (defined as the point where deviation from the calculated stiffness decreased by 20%).

Bending moment M was calculated using the following formula: $M = (FL)/2$

Where: F is the force (yield load or failure load) applied to the specimen;
L is the distance from the outer to the inner support $(S-T)/2$
S is the distance between the outer supports and T is the distance between the inner supports (Figure 31).

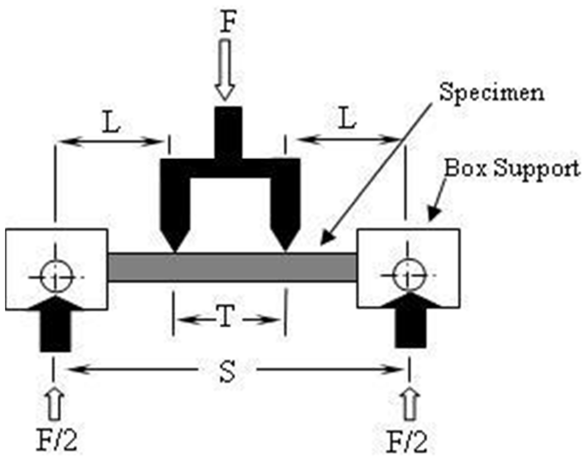


Figure 31: Diagram representing the forces applied through the test apparatus: F= force (yield load or failure load) applied to the specimen; L = distance from the outer to the inner support; S is the distance between the outer supports; T is the distance between the inner supports.

Angular displacement θ was calculated by using the formulas:

$\theta_1 = \tan^{-1}(U_1/X)$, $\theta_2 = \tan^{-1}(U_2/X)$, and $\theta_T = \theta_1 + \theta_2$

Where: θ_1 and θ_2 are the angular displacement of C4 and C5 respectively;
U_1 and U_2 are the displacement of the LVDT's and
X is distance of the LVDT from the pivot point of the outer support,
θ_T is the total rotational displacement of the C4-C5 articulation and
θ_1 and θ_2 are the rotations at each support (Figure 32).

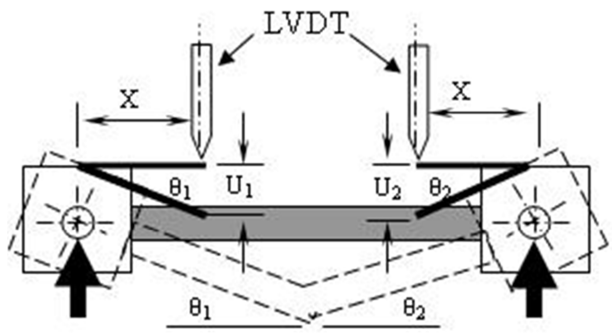


Figure 32: Diagram representing the angular displacement of the specimen. U_1 and U_2 represent the displacement of the LVDT's, X is the distance of the LVDT from the pivot point of the outer support and θ_1 and θ_2 represent the rotations at each support.

Failure Mode

Each specimen was examined thoroughly pre- and post-testing and site of failure, when evident, was identified and recorded.

Digital photographs (Kodak CX6330; Hemel Hempstead, UK) of the test set up were taken at the start and end of each test. The testing procedure was filmed using a digital video camera (Digital Handycam HDR/HC1E, Sony, Switzerland). Latero-lateral (62 kV, 10 mAs) and dorso-ventral (68 kV, 10 mAs) radiographic projections centred on the C4-C5 articulation were taken before testing using computed radiography (CR MD 4.0 cassettes in a CR 35-X digitizer, Agfa, Agfa-Gevaert, Mortsel, Belgium). Laterolateral, flexed (supported between blocks allowing the C4-C5 articulation to bend in the direction of loading) and dorsoventral radiographic projections centred on the C4-C5 articulation were taken post testing. When it was not possible to accurately identify a bony abnormality that might explain the specimen failure on the radiographs, implants were removed and CT images were collected (exel 2400 elite, Elscint, Phillips Medical Systems, Surrey, UK) of the C4 and C5 vertebrae.

Statistical Analysis

Mean ($\pm$ SD) stiffness, yield bending moment and failure bending moment were calculated for each of the test groups. Three general linear models were undertaken with stiffness, yield bending moment and failure bending moment as the respective outcomes. Age, size, test direction and implant (KCC, LCP or none) were included as predictors, with test direction fitted (flexion, extension or lateral flexion) as a random effect and age and size as covariates. All models were fitted using stepwise forward inclusion and post-hoc calculations were undertaken using the Bonferroni method. Statistical significance was set at $P<.05$ and all statistical analyses were performed with software (Minitab version 15, Minitab Inc, State College, PA).

RESULTS

Specimens

The calculated length of C4 and C5 vertebral bodies ranged from 14.8 - 22.8 cm with a median length of 17.7 cm. The calculated height of C4 and C5 vertebral bodies ranged from 2.4 - 4.2 cm with a median height of 3.2 cm. Calculated size ranged from 38.9 cm^2 to 95.1 cm^2 with a median of 57.3 cm^2.

Implant Placement

KCC Placement. Placement of the 1st implant took 70 minutes, while placement of the 18th implant took just 14 minutes (median implant placement time: 30 minutes). Placement of 2 of the KCC implants resulted in fracture of a small cranial ventral part of the central bone pinnacle (the ventral part of the C5 vertebral body left in the centre of the core saw).

LCP Placement. Placement of the 1st implant took 48 minutes, while placement of the 18th implant took 12 minutes (median implant placement time: 22 minutes). One specimen required replacement of 1 screw (6th hole from cranial) with a longer one, after radiographic assessment.

Mechanical Test Results

In all tests a “toe-region” (lower stiffness) was apparent on the moment-angular displacement graphs (Figure 33). A review of failure bending moments and stiffness for each of the groups is shown in Table 7 and graphically in Figures 34 and 35.

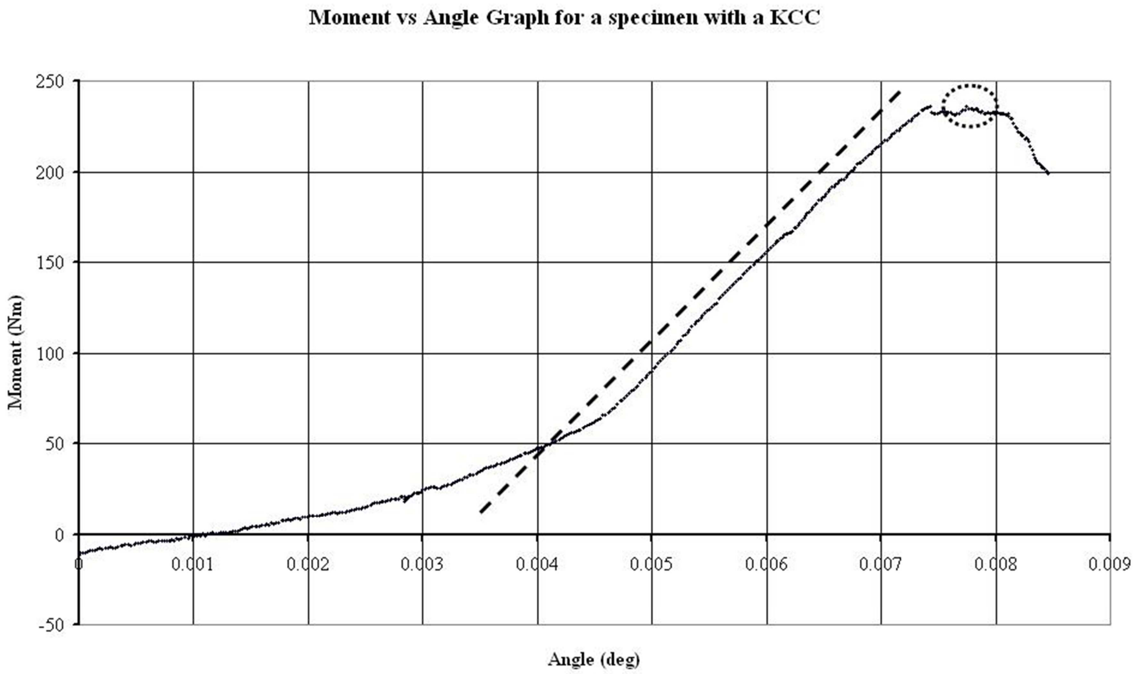


Figure 33: Moment vs. angle graph from Group 1 demonstrating "toe-region" followed by steeper incline. Dashed line represents the stiffness of the construct; dotted circle represents the failure point. Nm = Newton meter, deg = degree.

Table 7: Mean ± SD (range) of Moment to Yield, Ultimate Failure Load and Stiffness for Flexion, Extension and Lateral Bending.

	LCP	**KCC**	**None**
Flexion			
Stiffness (Nm/°)	20 ± 3 (16 - 24)	16 ± 4 (12 – 22)	22 ± 9 (11 - 36)
Moment to yield (Nm)	323 ± 96 (187 - 445)	239 ± 76 (113 – 328)	265 ± 95 (191 – 437)
Failure load (Nm)	332 ± 87 (219 – 445)	250 ± 77 (121 – 329)	284 ± 99 (191 – 437)
Extension			
Stiffness (Nm/°)	26 ± 10 (10 - 37)	18 ± 9 (9 – 35)	22 ± 16 (8 - 50)
Moment to yield (Nm)	433 ± 169 (232 - 638)	207 ± 72 (132 – 344)	229 ± 167 (90 – 550)
Failure load (Nm)	440 ± 173 (232 – 661)	211 ± 72 (137 – 347)	242 ± 159 (115 – 550)
Lateral bending			
Stiffness (Nm/°)	35 ± 13 (20 - 58)	19 ± 8 (9 – 33)	17 ± 6 (12 - 29)
Moment to yield (Nm)	411 ± 129 (276 - 594)	260 ± 95 (167 – 426)	304 ± 142 (108 – 462)
Failure load (Nm)	445 ± 126 (276 – 640)	266 ± 92 (174 – 426)	312 ± 138 (120 – 467)

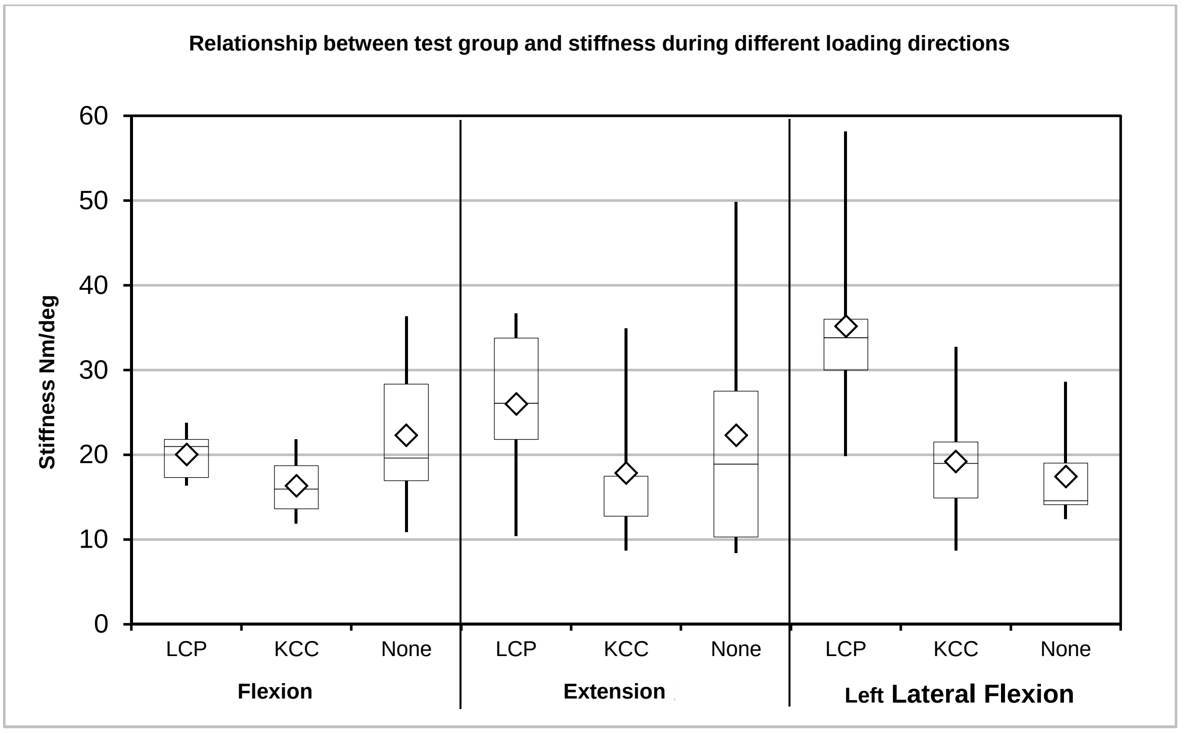


Figure 34: Relation of group and loading direction with respect to stiffness. Centre line is the median; interquartile ranges and total ranges are represented by the box and whiskers respectively. White diamonds represent the mean. KCC = Kerf Cut Cylinder; LCP = Locking Compression Plate; Nm = Newton meter; deg = degree.

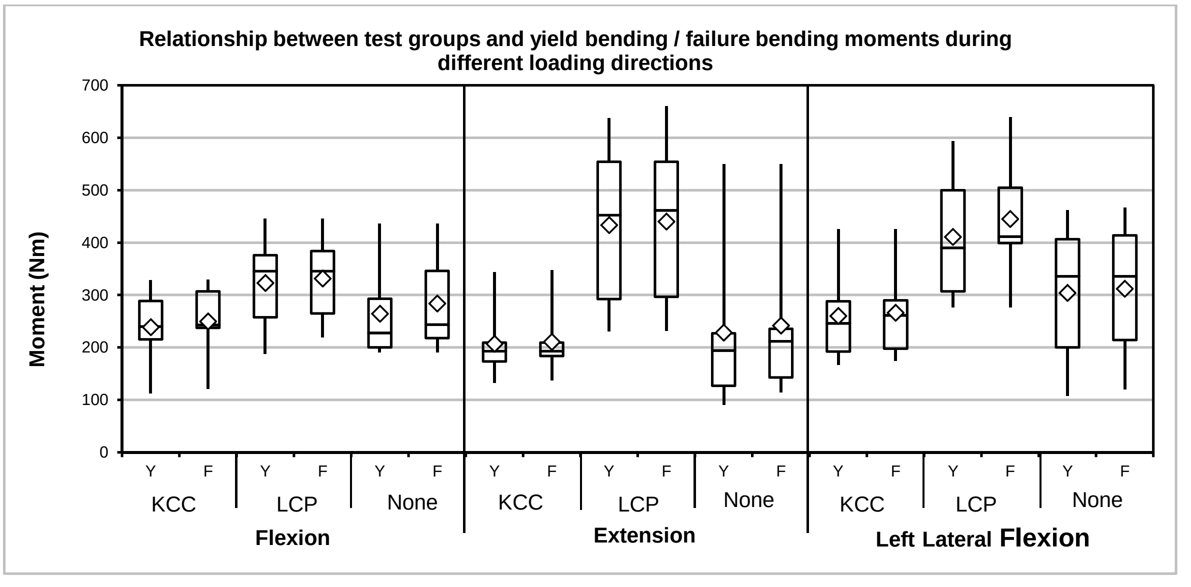
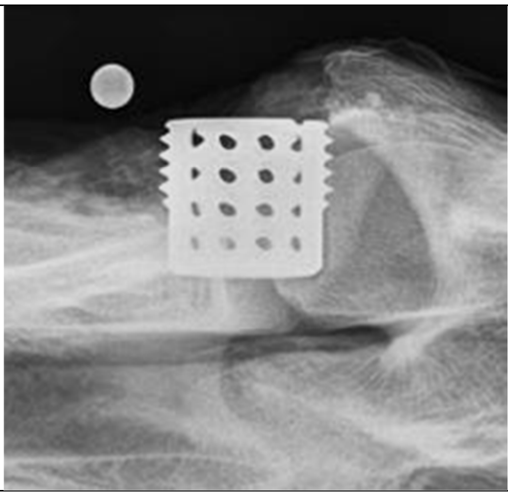


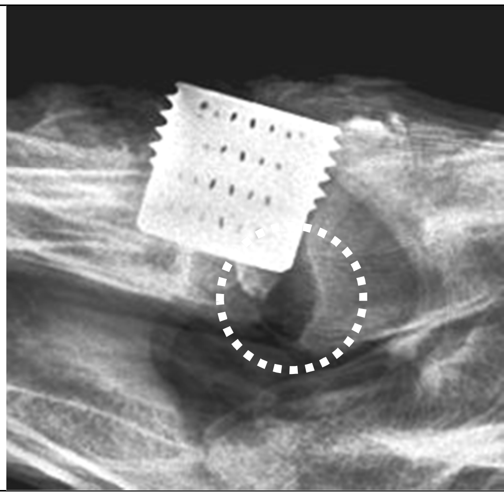
Figure 35: Relation of group and loading direction with respect to yield bending and failure bending moments. Centre line is the median; interquartile ranges and total ranges are represented by the box and whiskers respectively. White diamonds represent the mean. Y = Yield bending moment; F = Failure bending moment; KCC = Kerf Cut Cylinder; LCP = Locking Compression Plate; Nm = Newton meter.

Failure Modes

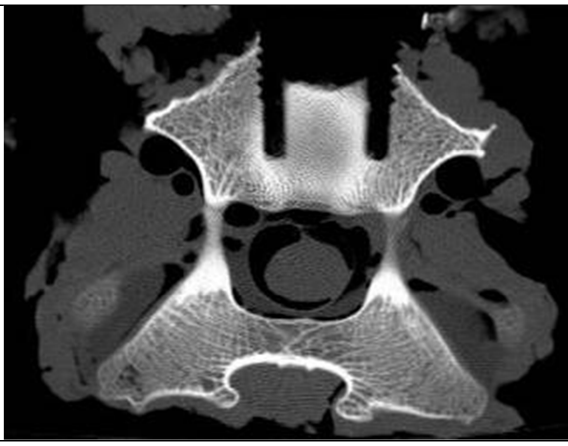
KCC Group. Seventeen of 18 of the KCC constructs failed by fracture of the C5 vertebral body between the caudal aspect of the cylinder and the vertebral canal (Figure 36). The other specimen (loaded in flexion) failed by ventral migration of the cylinder. Nine of the 18 specimens were imaged in the CT scanner to confirm failure site, one of which was the neck where the KCC migration had occurred. The specimen that failed by migration of the KCC demonstrated no significant difference in stiffness or yield bending moment compared to the other KCC implanted specimens.



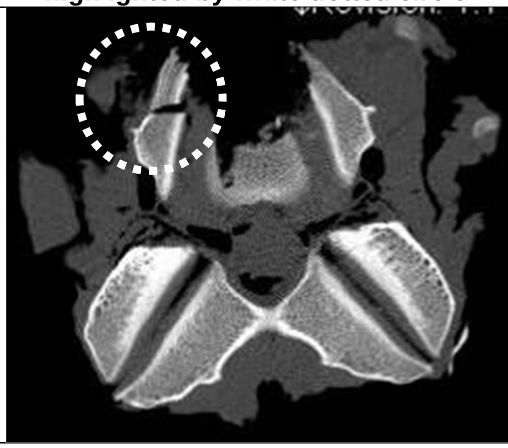
1. KCC in place prior to flexion testing



2. Following flexion testing – fracture site highlighted by white dotted circle



3. CT image of C4 with KCC removed



4. CT image showing part of fracture site (white dotted circle)

Figure 36: Radiographs and CT images demonstrating some of the Kerf Cut Cylinder failure modes.

LCP Group. Failure varied with loading direction. Subjectively, minimal plastic plate bending was appreciated during testing; none of the plates remained deformed at the end of the tests. Eight of the 18 specimens were imaged in the CT scanner to confirm failure site.

When the failure site wasn't clear from the radiographs, CT scans were performed. Figure 37 shows an example of a CT scan performed of a LCP failure.

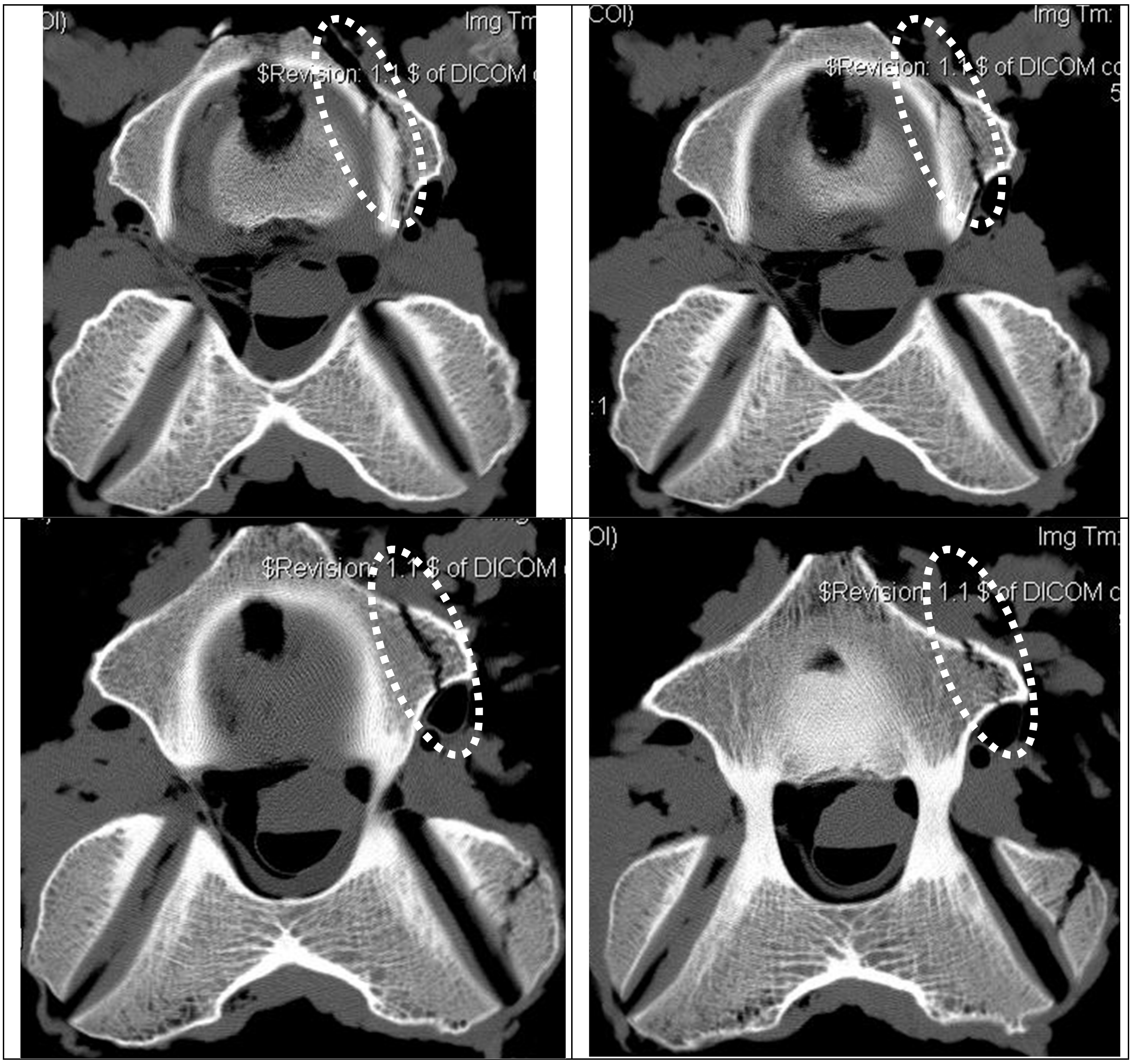


Figure 37: Sequential CT images demonstrating the fracture site following testing of a specimen with a LCP implant. The fracture occurred in a sagittal plane along the caudal inter-central articulation of C4. Images run sequentially from left to right in a cranial to caudal progression. Fracture highlighted by a white dotted ellipse.

During 4 of 6 tests in flexion, pull out of the 2 middle screws occurred at a point distinct from the point on the moment-angle chart deemed as the failure point and was evident on the moment angle chart as a drop in the curve followed by a return to the previous incline. None of the LCP implanted cervical vertebrae fractured during flexion.

During extension, 4 of 6 specimens fractured; 2 fractured through the body of C4 (1 at the level of the cranial screw and 1 between the 2nd and 3rd screws from cranial) and 2 fractured through the body of C5 (1 between the 4th and 5th screws from cranial and 1 caudal to the 6th screw from cranial (Figure 38).

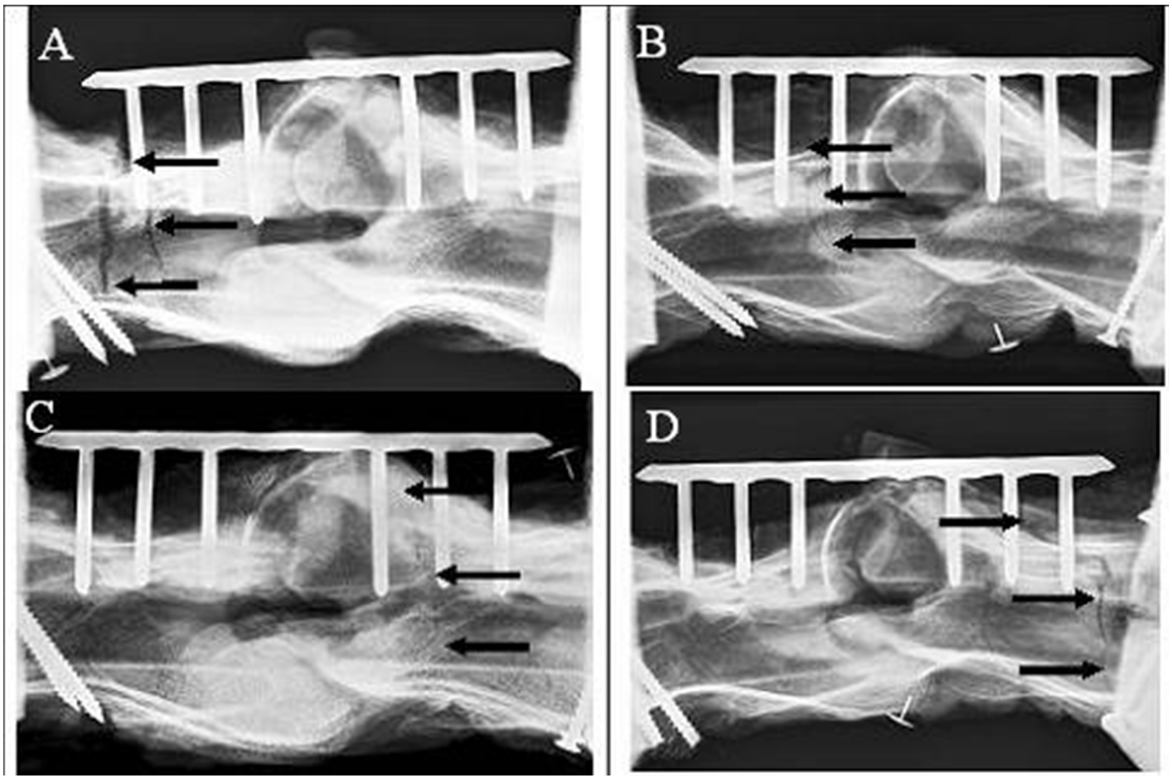


Figure 38: Post testing right-left latero-lateral radiographic projections demonstrating the fractures (black Arrows) observed in LCP group following loading in extension. A: Fracture through the body of C4 at the level of the cranial screw. B: Fracture through the body of C4 between the 2nd and 3rd screws from cranial. C: Fracture through the body of C5 between the 4th and 5th screws from cranial D: Fracture through the body of C5 extending from between the 5th and 6th screws from cranial to caudal to the 6th screw.

During left lateral bending all 6 specimens fractured in C4 between the left lateral caudal articular surface and the left lateral vertebral body just caudal to the lateral process (Figure 39).

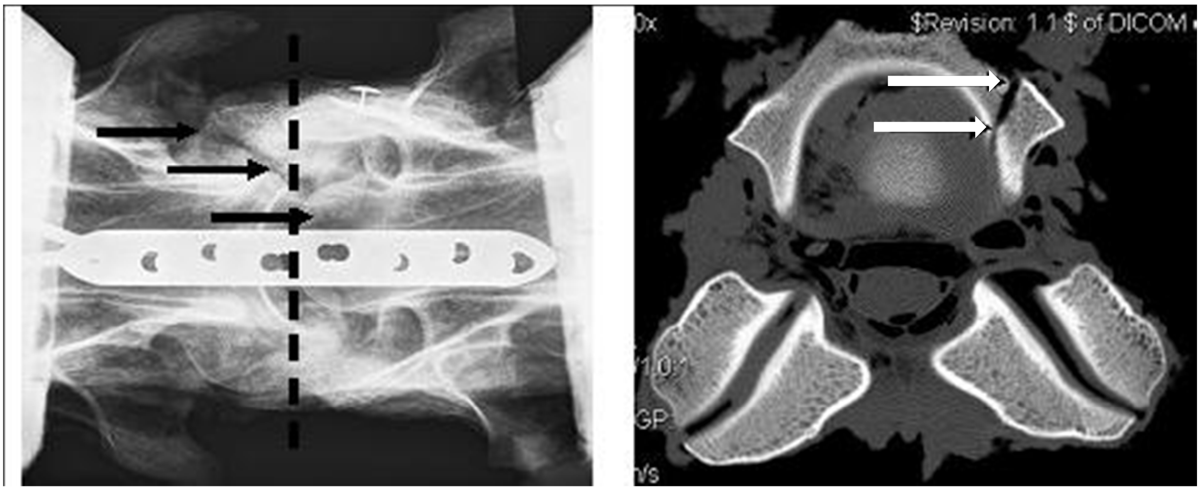


Figure 39: Post testing DV radiograph (Left of image = cranial) and CT (Top of image = ventral) scan of specimen from the LCP group that failed during lateral flexion. Black and white arrows highlight the fracture line on the compression side, extending from the left lateral caudal articular surface at the intercentral articulation to the left lateral vertebral body just caudal to the lateral process. The dashed line represents the level of the CT slice (right hand image).

Intact Group. Four of the 18 specimens were imaged in the CT scanner to confirm failure site. Sixteen of 18 specimens without implants failed by subluxation of the C4-C5 intercentral articulation. During left lateral bending 2 specimens fractured at C4; 1 extending from the right caudal vertebral body to the left mid body at the level of the caudal edge of the lateral process and 1 extending across the caudal aspect of the articular surface obliquely from cranial left to caudal right (Figure 40).

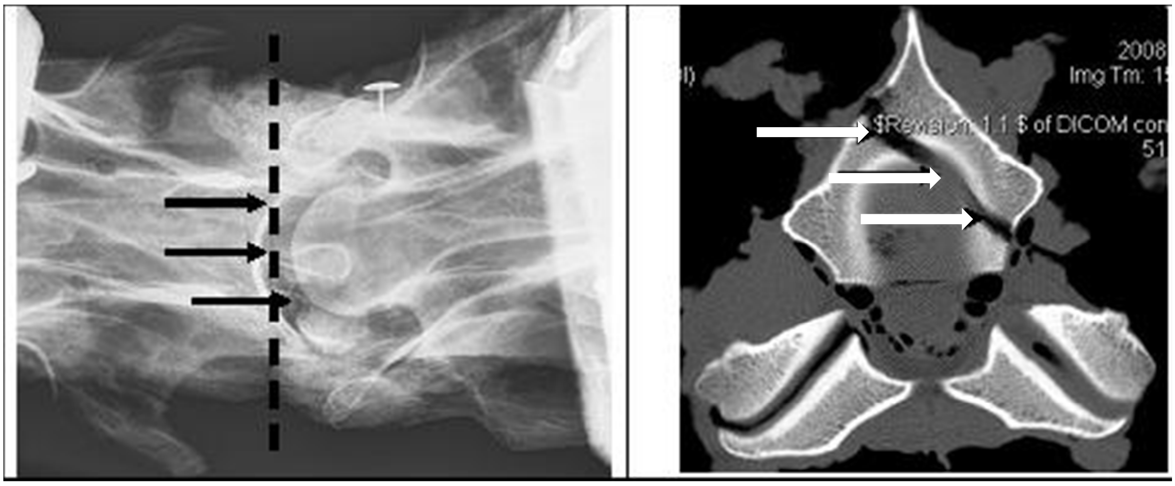


Figure 40: Post testing flexed DV radiograph (Left of image = cranial) and CT scan (Top of image = ventral) of specimen from intact group that failed on the compression side during left lateral loading. Black and white arrows highlight the fracture line in C4; extending across the caudal aspect of the articular surface obliquely from cranial left to caudal right. The dashed line represents the level of the CT slice (right hand image).

Statistical Analysis

Variables found to have a significant effect on the outcome variables were: Implant, which significantly affected stiffness, yield bending moment and failure bending moment; and age which significantly affected yield bending moment and failure bending moment. The final models are displayed in Table 8.

Table 8: Results of general linear models fitted, using forwards stepwise inclusion, with outcome variables of 1) stiffness, 2) yield bending moment and 3) failure bending moment and explanatory variables of Implant type (LCP, KCC or none), Age, Test direction (Ventral, Dorsal or Lateral, included as a random effect) and Size.

Model	Explanatory variable	Coefficient	SE Coefficient	p	R^2(adj)
1 (Stiffness)	Implant*			0.02	10.92
2 (Yield)	Implant*			0.001	27.04
	Age*	-8.763	3.969	0.032	
	Loading Direction			0.288	
3 (Failure)	Implant*			<0.001	29.10
	Age*	-8.144	3.932	0.044	
	Loading Direction			0.234	

* denotes significance at p<0.05

Bonferroni post-hoc comparisons for each model showed that there were no significant differences in stiffness between cervical vertebrae without an implant and those with a KCC (p =0.76) or those with an LCP (p = .11), but significantly greater stiffness was found for cervical vertebrae with LCP implants than those with KCC implants (mean difference = 9.27 Nm/deg, p = .01). Yield bending moment was found to be greater for cervical vertebrae with LCP when compared to cervical vertebrae without implants (mean difference = 120.24 Nm, p = <.01) and those with KCC implants (mean difference = 154.24 Nm, p = .0004) and failure bending moment was also found to be greater for LCP implanted cervical vertebrae than for cervical vertebrae without an implant (mean difference = 123.60 Nm, p = <.01) and those with KCC implants (mean difference = 163.68 Nm, p = <.01).

DISCUSSION

Having accounted for the potential confounders of age, size of cervical vertebrae and loading direction, cervical vertebrae with LCP implants had significantly greater stiffness than cervical vertebrae with the KCC implants and significantly greater yield bending moment and failure bending moment than cervical vertebrae with the KCC implant and cervical vertebrae with no implants. The greater mean stiffness recorded for the cervical vertebrae with no implants when tested under flexion represented the only measured mean outcome variable that was higher than the LCP group. It could be argued that flexion tests the weakest configuration for the LCP constructs (compression side for the plate), which could be a possible explanation for why they did not perform as well in this direction. The greater mean stiffness of the cervical vertebrae without implants may also be partly as a result of the intact inter-central joint in these specimens. Whilst the LCP constructs demonstrated superior biomechanical properties in this study, in a live animal the KCC constructs might be expected to result in increased stability over time, as bony in growth occurs through the holes in the cylinder. Biomechanical comparison of cervical vertebrae fused with the different techniques *in vivo*, at variable times post-operatively would be interesting.

Statistical modelling was performed to try and elucidate the significance of the recorded variables in combination. Test direction was included as a random effect because it was considered difficult to directly relate specific test direction to the *in vivo* situation, where neck movement is multi-planar. Although test direction was not found to have a significant effect on the outcome variables, it was included in the final models 2 and 3 because it improved the fit of models (measured by R^2). This suggests that test direction did not have an effect of its own, but accounted for some of the effect of the other variables in the model.

For all tests, the moment-angular displacement graphs demonstrated 2 distinct gradients (Figure 33), which has been observed in other clinical studies (Arnott *et al.* 2008). Whilst observing the post-testing videos the initial shallow gradient appeared to be associated with a “bedding in” of the test apparatus, as such construct stiffness was calculated from the 2nd (steeper) gradient. The consistent nature of the finding adds some weight to the repeatability of the testing. The middle screw pull out observed in 4 of 6 of LCP Group specimens in flexion, resulted in a consistent change in the moment-angle graph (Figure 41). The reduction in, then return to previous stiffness, suggests that the construct continued to provide some support despite initial failure, which may be beneficial clinically. This step in the moment angle graph was not observed during testing of the other specimens. Neck failure was observed on the moment angle graphs as either a decline in stiffness (from the yield point) followed by increased angle with a decreased load (commonly observed where cervical vertebrae subluxated) or a specific point where increased angle became associated with decreased load (observed in cervical vertebrae subsequently found to have fractured).

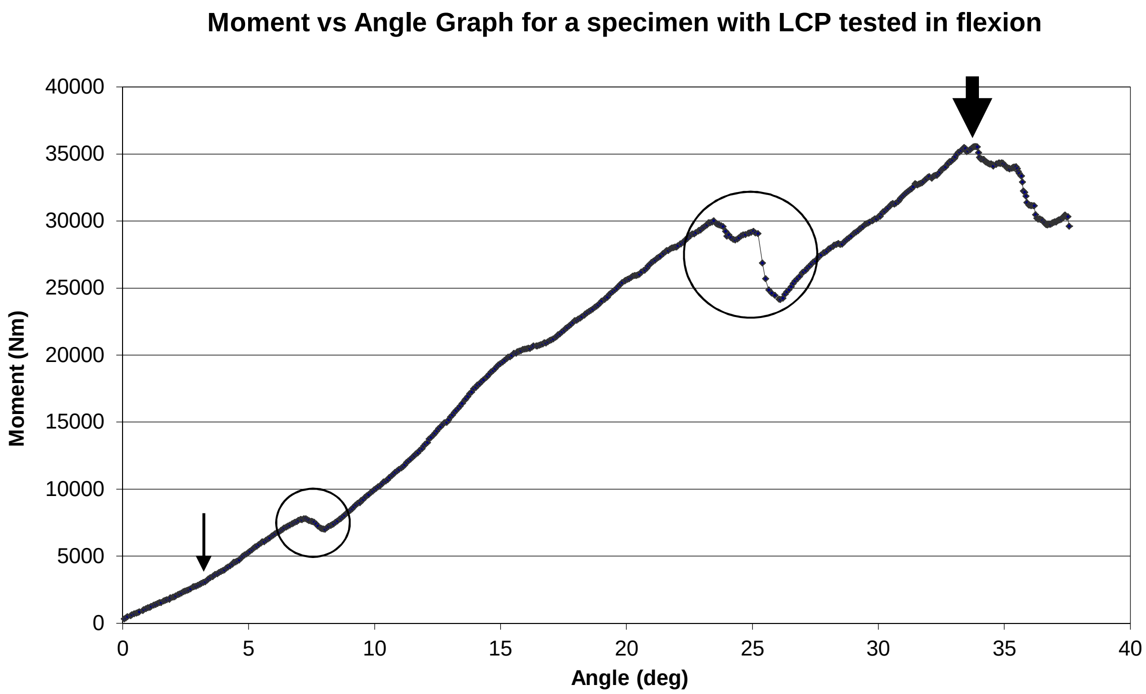


Figure 41: Moment vs. angle graph from a specimen in the LCP group in flexion demonstrating the alterations in stiffness. Nm = Newton meter, deg = degree. The changes in stiffness at 8º and 25º (circled) corresponded with screw slippage from the construct. The change from the "toe-region" to the construct stiffness is highlighted by the thin arrow. The failure point is highlighted by the thick arrow.

Placement of KCCs occurred with minimal complications. The fracture of ventral cranial part of the bone pinnacle (the centre left by the core saw) during KCC placement has occurred (to 1 author, JPW) in clinical patients without apparent ill effect and it is thought that this bone pinnacle is unlikely to contribute significantly to the mechanical properties of the construct, as a result the specimens were included in this study and were found to have similar mechanical properties to the other cervical vertebrae with KCC implants. Implantation of LCPs was straight forward.

Nonlinear finite element analysis modelling (ANSYS software, Cononsburg, PA.) of the LCP alone, demonstrated superior mechanical properties of an uncontoured plate compared to one which had been contoured, which was why the plates were applied uncontoured. It could be suggested that contoured LCP plates would provide a mechanically stronger construct. Research has shown that distances between the bone and the LCP plate of >2mm (that occurred in some of the screws in this study), reduce the stability of the construct (Ahmad *et al.* 2007). Also, screw placement in multiple planes caused by plate contouring, might be expected to increase the holding strength of the implants. One neck from the LCP group required screw replacement, which was performed without difficulty and may highlight a benefit of the LCP system over the KCC, where revision implant placement is potentially more difficult. The rapid decrease in implantation time over the 18 specimens for each of the implant groups was primarily as a result of operator experience (both surgeon and technicians). The comparable implantation time between KCC and the new LCP technique may be of interest, when considering using the technique in clinical patients; however access to the surgical site is far easier in these dissected specimens than it is *in vivo*. Potentially a longer incision is required for LCP placement, with the associated increased potential for postoperative morbidity.

Unfortunately the inner support points contacted the vertebrae within the span of the LCP. Although this may have affected the biomechanical properties and failure mode of these constructs, this was considered acceptable because the mechanical properties of the C4-C5 articulation could still be studied.

The failure modes differed between groups. The fracture of the cranial articular end of the body of C5 in the KCC group was a consistent finding in all loading directions. This may be because this implant technique results in a weakness in the bone at this site (a narrow bony pinnacle) or causes particular stress to become focused at this site. To our knowledge, this complication has not been reported previously. This may be because the cervical vertebrae were being placed under far higher loads in this testing than they experience *in vivo*, or because the fractures are relatively hard to see, requiring stressed radiographic projections or CT imaging to observe them in some of these cases (Figure 42). It is also possible that the instability in the articulation caused by these small fractures is sufficiently supported by the cervical musculature to allow fracture healing without progressing to cause further neurological issues.

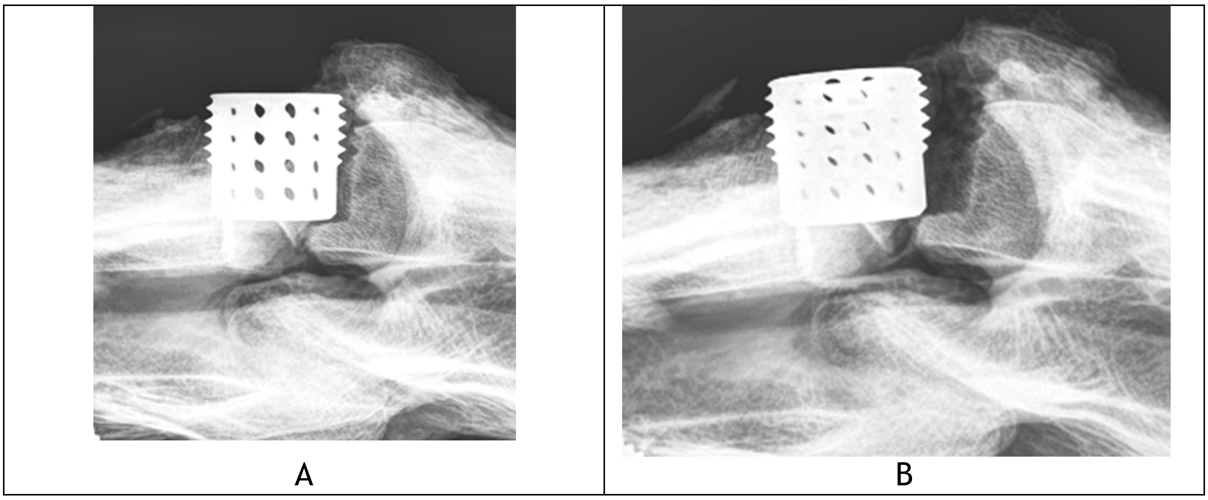


Figure 42: Radiographs post mechanical testing. A=in neutral position; B=with specimen in stressed position, highlighting the fracture site.

Failure mode of the LCP group varied with loading direction. The screw pull out during flexion resulted from movement of the C4-C5 articulation away from the implant. The fractures observed during extension all consisted of complete fractures of the vertebral body, indicating bony rather than implant failure in comparison to the testing in flexion. The 2 fractures located near the ends of the plates may indicate that these plates were not long enough for the neck specimens (the specimen that fractured through C4 at the cranial screw was the largest in that group, but the neck that fractured through C5 at the caudal screw was the smallest in that group); however, in this loading direction fractures also occurred through the bodies of the vertebrae away from ends of the plates, suggesting that this may not be significant. Further testing of different neck and plate sizes would be indicated to investigate this.

It is hypothesized that the fractures observed in the LCP group during lateral flexion, occurred because the relatively thin bone of the caudal lateral end of the C4 articulation contacts the denser bone of the cranial articular process of

C5 and is unable to distract because of the presence of the LCP. Similar fractures of the caudal aspect of C4 were observed in 2 of the specimens in the intact group during left lateral bending, though for both of these greater angulation in the cervical vertebrae occurred before failure, than was observed for the LCP specimens in left lateral bending. The other 16 specimens in the intact group failed by subluxation, highlighting the effects of the implants on the mechanism of failure.

The C4-C5 articulation was chosen for this study for convenience, as C3 and C6 were easier to fix in resin than C2 (narrow) or C7 (short) and because a repeatable means of testing this articulation had already been defined (Reardon *et al.* 2009). A large amount of variation in stiffness, yield bending moment, and failure bending moment was appreciated within the groups in this study. As well as this, statistical modelling demonstrated low R^2 values for all models, suggesting that a lot of the variability in these measures was not accounted for by the variables that we recorded. There are numerous possible causes for this. The setup of the testing unit meant that the metal cases and resin were part of the tested construct and despite consistent technique in preparation, variations in these (specifically the resin), may have affected the results. The use of cadaveric specimens introduces uncontrollable variability as the anatomy and physiologic structure of the bone and soft tissues inevitably varies. Use of fresh specimens may have been preferable to frozen ones and because of constraints on collection, freezer time varied between specimens. However, specimens were handled in a consistent fashion, previous studies have used frozen cadavers for biomechanical testing (Glazer *et al.* 1996), it has been shown that freezing (including several freeze-thaw cycles) has little effect on the biomechanical properties of bone (Linde and Sorenson 1993) and one study using pig cervical vertebrae concluded that freezing resulted in no change in stiffness or displacement at failure (Callaghan and McGill 1995). Although specimens were kept moist externally, some drying of internal tissue (such as the intervertebral disc) was possible; this has been shown to affect mechanical properties (Costi *et al.* 2002).

Horse age was found to significantly affect the yield bending moment and failure bending moment. The coefficient for age is interpreted as for every 1 year increase in age; there is an 8.763 Nm reduction in yield bending moment and an 8.144 Nm reduction in failure bending moment (Table 9). This could be partly explained by the fact that equine bone micro architecture has been shown to vary with age (Furst *et al*. 2008); however, this finding should be interpreted with care as age of specimens in this study was determined from dentition, which has been shown not to be entirely accurate (Richardson *et al*. 1995).

This study describes a technique for testing the mechanical properties of the equine C4-C5 articulation in 2 planes of movement. Our results indicate that the LCP constructs had favourable mechanical properties compared to the cervical vertebrae with KCC implants and the cervical vertebrae with no implants, which may justify LCP use in clinical cases. Future work could involve investigation of the mechanical properties of cervical vertebrae during cyclical loading to evaluate long term holding strength of implants during joint ankylosis. Computer modelling of vertebrae based on CT images, could allow investigation of the effects of extrinsic musculature on the implant stability. Alternate implants such as the cervical spine locking plates used in people and alternate techniques such as fixation of the articular process joints in addition to the intercentral joints could be investigated.

Chapter Five

5. General Discussion

Since the inception of a surgical technique for treatment of cervical stenotic myelopathy (Wagner et al. 1979a), there has been a general trend towards greater acceptance of the procedure, which is now performed widely in North America and in a number of hospitals in the U.K. (Walmsley 2005). Pathology of equine cervical vertebrae can have an important impact on equine welfare; from developmental defects in young horses (as demonstrated in the case report) to cervical fractures or arthritis in older athletic animals, all potentially leading to neurological defects. Any additional techniques that safely facilitate reduction in the morbidity and/or mortality caused by these neurological defects are to be encouraged.

The series of publications submitted here, provide information regarding a novel technique for treatment of cervical pathology in horses. The information presented in the case report demonstrated that it is possible to use a locking compression plate (LCP) in place of the traditional cylindrical implant for successful treatment of CSM in a juvenile equine. The subsequent biomechanical testing in chapters three and four indicated that the LCP construct provides equivalent to superior mechanical stability than the kerf cut cylinder (KCC) implants, albeit in adult cadaver necks under laboratory conditions.

In the case report (chapter two), the LCP was chosen for fixation because of the flexibility of implant size in a foal. The case had a successful outcome, although potential flaws with the technique were highlighted:

1. Use of self-drilling screws was found to be inappropriate as they provided insufficient bone holding in the narrow vertebral bodies; which may have been of even more importance in the relatively soft bone of a foal. As a result it was concluded that these screws are not appropriate for the LCP technique for cervical vertebral arthrodesis, despite the time they would potentially save during application.

2. Because the LCP construct spanned more of the vertebrae than a KCC construct, a question of whether it would have an adverse effect on the growth plates in a young animal arose. In the case report, based on radiographic measurements it was concluded that the LCP construct had no more adverse effect than a KCC construct would have, however this should be monitored in other cases. It is likely that if the implant interferes with a physis it has the potential to adversely affect growth and it would be prudent to try and avoid implant contact with physes distant from the arthrodesis site if possible.

3. Plate positioning, avoiding impingement of the end of the plate on adjacent vertebrae was observed to be important. In the case report, following necessary plate repositioning; the LCP overlapped the caudal epiphysis of the cervical vertebral body cranial to it and it was surmised that resultant new bone formation was as a result of impingement of the plate during neck ventro-flexion. Fortunately, the horse was not observed to demonstrate adverse clinical signs (such as a stiff neck) following the procedure, but further monitoring of the case will be performed to see if this develops.

4. It was concluded that adequate removal of disc material from the joint being arthrodesed was important. In the case report, although new bone formed on the ventral aspect of the treated vertebrae (C6 and C7) (evidence of inter-central joint bridging), there were no radiographic features suggesting fusion of the joint dorsally. It was suggested that the disc material was not removed aggressively enough, resulting in incomplete fusion, which may have accounted for the residual neurologic deficit in that case. As such, complete removal of disc material in future cases is advocated.

A number of potential benefits of the LCP technique were observed in chapter two:

a. It allowed good radiographic visibility of the inter-central joint (during arthrodesis), which is not possible with the cylinder implants. This would potentially enable better monitoring of the progression of arthrodesis post-operatively.

b. No specialised instrumentation other than the LCP kit was required; whilst a specialist kit is required for implantation of the KCC – different sized kits for different sized cylinders.
c. The risk of vertebral fracture was potentially reduced because the force over the joint being arthrodesed is spread over a larger area, than the focal positioning of the KCC.
d. The plate can potentially be re-applied if it comes loose, as seen in chapter two. This re-application has not been reported in KCC cases and considering the intricacy of the implantation procedure, KCC re-application is likely to be very challenging in all cases and impossible in some.

Having identified a new successful technique for cervical vertebral fusion with potential advantages; it was decided that further examination of the technique was required. To facilitate effective arthrodesis, joint stability is essential, as such it was decided that a major question regarding the new LCP construct was whether it could provide enough mechanical stability around the joint being arthrodesed. The results of the case report suggested that the LCP did provide enough stability to allow arthrodesis in a young animal, however the forces experienced by the cervical vertebrae in an adult were thought likely to be considerably higher. Also the LCP position on the ventral aspect of the cervical vertebrae, which would be on the compression (or weaker) side during neck (ventral) flexion, was a potential issue. So, biomechanical investigations using cadaver specimens were performed (chapters three and four) to investigate the mechanical properties of the new construct in adult cadaver specimens.

The normal loads experienced by the equine neck have not been reported: It is very difficult to predict them because there is multiplanar and rotational movement at each articulation and because there is movement on either side of each vertebra. However, as an approximation: a 500kg mass (horse's body) one metre (1m long neck) from a fixed point (head in a fixed position, such as stuck in the corner of the recovery box) would exert a moment of 4900Nm. Interestingly, this moment is significantly higher than the failure loads recorded during testing, which might suggest that this level of moment is not experienced in the live animal.

There have been no published descriptions of a technique for mechanical testing of equine cervical vertebrae, so the initial part of the study involved devising a technique for consistent, repeatable load application to a single cervical vertebral articulation (described in chapter three - discussion). This was crucial to allow accurate investigation of the mechanical properties of the different implants. Following discussion with the surgeons, implant placement of both KCCs and LCPs was performed with a foam wedge extending the inter-central articulation. This was performed because; this position is preferred by JPW for KCC implantation in live animals and it was decided that this positioning would be appropriate for implantation of LCPs, as it allows good access to and alignment of the intercentral joint.

The C4-C5 articulation was chosen for these studies for convenience, as C3 and C6 were easier to fix in resin than the narrow C2 or short C7. Despite a variety of different loading mechanisms, because of the relative short length of the vertebrae, the final set-up required load application through inner support points within the span of the LCP. Although this may have affected the biomechanical properties and failure mode of these constructs, this was considered acceptable because the mechanical properties of the chosen articulation could still be studied. It was also considered that this setup would be more likely to under- rather than over-estimate the mechanical properties of the LCP construct, because less of the plate experienced the full load between the inner support points and this under-estimation was considered preferable when investigating a new technique.

Another difficulty experienced whilst developing a technique for mechanical testing involved ensuring that the adjacent articulations did not move during testing. It was determined that screw placement across the adjacent inter-central and articular process joints combined with resin fixation, led to rigid fixation of these joints during testing. There were concerns regarding the potential for these screws to affect the mechanics of the vertebrae, specifically during failure, so careful radiographic analysis was performed prior to testing to ensure these screws did not impinge upon the constructs and radiographic and computed tomographical analysis was performed post testing to ensure that vertebral failure was not related to the position of these screws in any of the cases. The final test module could be used for further biomechanical testing; application of repetitive loads has been discussed and may provide some useful additional information in the future. However, because it is impossible to accurately emulate the effect of living tissue i.e. healing bone, in the laboratory, the cost of further testing cannot currently be justified.

In chapter three, where two sizes of LCP and KCC were compared under ventral flexion, no statistically significant differences were observed between the mechanical properties of the different construct types and it was concluded that unfeasibly high numbers of tests would be required to be able to identify such a difference. In chapter four, one size (4.5mm) of (non-contoured) LCP constructs were compared with KCC constructs under flexion, extension and lateral bending and were found to have greater stiffness than cervical vertebrae with the KCC implants and significantly greater yield bending moment and failure bending moment than cervical vertebrae with the KCC implant and cervical vertebrae with no implants. The identification of a significant difference between implant groups in chapter four, compared to chapter three suggests that one of the different variables used in chapter four had a large effect on the biomechanics. It is considered likely that this variable was “test direction”, although other variables may have been important. As discussed in chapters three and four; flexion tests the LCP constructs in the weakest configuration, which would explain why no significant difference was observed in chapter three (where all the constructs were tested in flexion) compared to chapter four.

The decision to use the broad 4.5mm rather than the 3.5mm LCP in the further biomechanical testing in chapter four, was based on a number of considerations:

1. It had similar biomechanical properties to the narrow 3.5mm plate.
2. Subjectively, it deformed less than the 3.5mm plate during mechanical testing, which we considered made it less likely to be adversely affected by repetitive loading in the live animal.
3. Fewer screws were required making the implantation faster (fewer holes to drill) and cheaper (fewer screws to buy).

4. The 4.5 mm system is more commonly used for large animal osteosynthesis than the 3.5mm system so we considered that it might be more available in equine clinics.

It was of interest that in both chapters three and four; cervical vertebrae without implants were found to have greater mean stiffness than either of the construct groups in flexion. The reason for this is not known but thought likely to be a result of the greater contact between the tested vertebrae (C4-C5) and the presence of the intact inter-central joint capsule in these specimens. The normal loads experienced by the equine cervical spine have not been reported and because of the flexibility of the equine neck and load sharing between articulations they are difficult to predict. However, as an approximation: a 500kg mass (horse's body) one metre(1m long neck) from a fixed point (head in a fixed position, such as stuck in the corner of the recovery box) would exert a moment of 4900Nm, which is significantly higher than the failure loads recorded during testing. The fact that more failures are not reported following KCC surgery suggests that the equine vertebral articulations are not experiencing this sort of load. Whilst the LCP constructs demonstrated superior biomechanical properties in this research, in a live animal the KCC constructs might be expected to result in increased stability over time, as bony in growth occurs through the holes in the cylinder. Biomechanical comparison of cervical vertebrae fused with the different techniques *in vivo*, at variable times post-operatively would be interesting, but would require suitable specimens, which would either take a long time to collect, or require study horses and euthanasia, which is currently hard to justify.

Placement of all implants occurred with minimal complications, which was likely as a result of the experience of the clinicians performing the procedures, the easy surgical access afforded by using cadaver specimens and the access to specialist equipment such as the C-arm. In chapter three, contouring of the LCPs to fit the ventral aspect of the vertebrae was considered straight forward, but is likely to be more challenging in a live patient where access is more difficult. In the cases which required screw replacement during LCP implantation, this was performed without difficulty, highlighting a potential benefit of the LCP system over the KCC, in which KCC re-positioning is very difficult once the site is cut.

Despite consistent technique in implant placement and mechanical testing, a large amount of variation in stiffness, yield bending moment and failure bending moment were appreciated within the groups in both biomechanical testing chapters. Statistical modelling demonstrated low R^2 values for all models, suggesting that a lot of the variability was not accounted for by the variables that were recorded. Potential causes for this include: variations in resin quality and placement, the use of cadaveric specimens, the use of frozen specimens and the drying of specimens during testing or implantation, all of which have been discussed and were considered unavoidable during this research.

For all tests in both biomechanical testing chapters, the moment-angular displacement graphs were observed to demonstrate two distinct gradients, which have also been observed in other clinical studies (Arnott *et al*. 2008). This was ascribed to "bedding in" of the test apparatus. Attempts were made to determine associations between these graphs and alterations in construct position from video footage of the testing, however because the screws and KCCs were obscured by the specimens it was not always possible to see which parts were moving. Use of fluoroscopy or high speed computed radiography might allow more in depth investigation of specimen failure if further testing is carried out.

Failure modes differed between groups: Fracture of the cranial articular end of the body of C5 in the KCC group was a consistent finding in all loading directions and it was surmised that this may be because this implant technique resulted in weakness in the bone or particular stress focus at that site. That complication had not been reported previously, which may be because the cervical vertebrae were being placed under far higher loads during testing than they experience *in vivo*, or because the fractures are relatively hard to image and have minimal clinical effects in live animals. Failure mode of the LCP group varied with loading direction and plate size from; plate bending (3.5mm plate) and screw pull out during flexion to fractures in extension and lateral flexion. The fractures observed in the LCP groups would potentially have more adverse clinical effect than those observed in the KCC group, however whether the vertebrae of a live horse are likely to undergo the high focal forces required to cause these fractures is unknown. The presence of significant supporting soft tissues such as strap muscles would be likely to have a major protective effect on the equine cervical spine in a live animal.

In chapter three LCPs were contoured to the surface of the ventral aspect of the cervical vertebrae. Following nonlinear finite element analysis modelling of the LCP alone, superior mechanical properties of an uncontoured plate compared to a contoured one were determined. As a result, in chapter four uncontoured plates were applied. However, it could be suggested that contoured LCP plates would provide a mechanically stronger construct because research has shown that distances between the bone and the LCP plate of greater than 2mm (which occurred in some parts of the uncontoured plates) reduce construct stability (Ahmad 2007) and screw placement in multiple planes (a result of plate contouring), might be expected to increase the holding strength of the implants. Based on the mechanical properties observed in chapters three and four, it would seem reasonable to use either technique, although contouring the plate is thought to be the most advisable current practice.

The comparable implantation time between KCC and the LCP technique is of interest when considering using the technique in clinical patients, however it is important to remember that access to the surgical site is far easier in dissected specimens than it is *in vivo*. It was also concluded that based on the experience in chapter two and considering the implant length, a longer incision is likely to be required for LCP placement, with the associated increased potential for post-operative morbidity.

Other variables found to have an effect on outcome were horse age and size: in chapter four horse age was found to significantly affect the yield bending moment and failure bending moment, which was hypothesised to be partly explained by the fact that equine bone microarchitecture varies with age (Furst *et al*. 2008) and in chapter three, horse size was found to affect moment to failure and stiffness – likely because increased mass will require increased energy to achieve movement.

Chapter Six

6. Conclusions

The chapters presented here provide information about an exciting new technique. Many questions remain about its use in adult horses, specifically how the LCP construct would perform under the repetitive cyclical loading and forces experienced in an adult equine neck whilst fusion occurs and how easy it would be to apply in a live adult animal. The question as to whether the technique could be recommended in preference to the KCC technique based on this research is still hard to answer. However, the author would suggest that it would be reasonable to use the technique in clinical cases, particularly if there were other mitigating factors, such as small patient size or presence of a cervical fracture. Ultimately though, more clinical cases are needed to assess the efficacy of the technique in adult horses.

The research has already paved the way for plate application in equine cases with cervical pathology in which KCC implants were deemed inappropriate. At a recent meeting of the European College of Equine Surgeons; results of two adult equine cases treated with ventrally applied plates were presented – one case of cervical fracture and one a case with CSM, both of which are making good preliminary progress (Mespoulhes-Riviere and Rossignol, 2010). With the size flexibility afforded by the LCP constructs, it is hoped that others will find the technique a useful and reliable one that can be applied to a variety of different cases and as a result improve the health and welfare of horses.

Chapter Seven

7. Appendix

Details of the publications achieved during the course of this research:

1. Reardon R, Kummer M, Lischer C. Ventral locking compression plate for treatment of cervical stenotic myelopathy in a 3-month-old Warmblood foal. Vet Surg. 2009 Jun;38(4):537-42.

Co-author input for 1:

Kummer – provided details of the case and follow up, assisted with the surgery and helped review the final case report.

Lischer – performed the surgery and assisted with reviewing the case report.

2. Reardon R, Bailey R, Walmsley J, Heller J, Lischer C. A pilot *in vitro* biomechanical comparison of locking compression plate fixation and kerf-cut cylinder fixation for ventral fusion of fourth and fifth equine cervical vertebrae. Vet. Comp. Orthop. Traumatol. 2009;22(5):371-9.

3. Reardon RJ, Bailey R, Walmsley JP, Heller J, Lischer C. An *in vitro* biomechanical comparison of a locking compression plate fixation and kerf cut cylinder fixation for ventral arthrodesis of the fourth and the fifth equine cervical vertebrae. Vet. Surg. 2010 (online Sep 29).

Co-author input for 2 and 3:

Bailey – Provided advice on mechanical testing, helped design the load application set-up and provided access to the testing equipment.

Walmsley – Applied the KCC implants and helped review the paper prior to submission

Heller – Provided statistical advice; specifically for choice of statistical analysis and interpretation of results.

Lischer – Came up with the idea for the research, obtained funding and collaboration. Helped with reviewing results and publications.

Non-refereed publications:

Reardon R. J. M., Bailey B., Walmsley, J.P., Lischer C. An *in vitro* biomechanical comparison of a locking compression plate fixation and kerf cut cylinder fixation for ventral fusion of fourth and fifth equine cervical vertebrae. Proceedings of the annual convention of the European College of Veterinary Surgeons, Basel, 2008.

Reardon R. J. M. An In Vitro Biomechanical Comparison of a Locking Compression Plate Fixation and Kerf Cut Cylinder Fixation for ventral fusion of fourth and fifth Equine cervical vertebrae. Proceedings of the annual convention of the American College of Veterinary Surgeons, San Diego, 2008.

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