Review Article

Global Spine Journal
2022, Vol. 12(7) 1596–1610
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DOI: 10.1177/21925682211063855
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A Review of Strategies to Improve Biomechanical Fixation in the Cervical Spine

Colby Oitment, MD[1], Patrick Thornley, MD[1], Frank Koziarz, BSc[2], Thorsten Jentzsch, Dr Med, MSc[3,4], and Kunal Bhanot, MD, MSc[3,4]

Abstract

Study Design: Systematic review.

Objectives: Review the surgical techniques and construct options aimed at improving the biomechanical strength of cervical constructs.

Methods: A systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A search of the MEDLINE, Embase, and Cochrane Library databases was performed to identify all studies examining biomechanical strategies utilized in the osteoporotic cervical spine. Screening was performed in duplicate for all stages of the review process.

Results: An initial search returned 3887 articles. After deletion of duplications and review of abstracts and full text, 39 articles met inclusion criteria. Overall, the surgical techniques reviewed aimed at obtaining rigid fixation in the setting of poor bone quality, or dispersing the forces at the bone-implant interface. We identified 6 key techniques to improve biomechanical fixation. These include bicortical fixation, appropriate screw selection (size and trajectory), PMMA augmentation, load sharing techniques, consideration of ancillary fixation around the occipitocervical junction, and supplementing the construct with post-operative collar or halo.

Conclusion: The summation of the literature highlights a framework of modalities available to surgeons to improve biomechanical fixation in the cervical spine. While these may improve construct strength in the setting of osteoporosis, there is a paucity of evidence available to make recommendations in this patient population.

Keywords
osteoporosis, spinal fixation, cervical

Introduction

Aging patient populations with associated osteopenia and osteoporosis pose a challenge for surgical intervention both in terms of hardware fixation intraoperatively as well as post-operative pullout and construct failure. Appropriate management of osteoporotic patients requires a thorough understanding of the pathology in the spinal column, methods of construct failure and options for addressing these issues perioperatively.

Spinal constructs may fail in a number of ways; however, in osteoporosis, failure occurs most frequently at the implant-bone interface or at the adjacent segment.[1] A mismatch exists between the elastic modulus of the screw and the adjacent bone, which creates stress fractures permitting cephalocaudal

[1]Division of Orthopedic Surgery, Hamilton General Hospital, McMaster University, Hamilton, ON, Canada
[2]Department of Graduate Studies, Health Research Methodology (HRM), and Epidemiology, McMaster University, Hamilton, ON, Canada
[3]Division of Orthopaedic Surgery, St Michael's Hospital, Toronto, ON, Canada
[4]Division of Neurosurgery, Department of Surgery, University of Toronto, Toronto, ON, Canada

Corresponding Author:
Dr Colby Oitment, MD, McMaster University, Department of Orthopedic Surgery, Hamilton General HospitalAffiliation, McMaster University, 1200 Main St West, Hamilton, ON L8S 4L8, Canada.
Email: colby.oitment@medportal.ca

toggling of screws.[1] This may lead to loosening and pullout or fracture of the thin lateral wall of pedicles in the thoracolumbar spine or lateral masses in the cervical spine. Alternatively, the increased force generated at the end of a fusion construct may lead to fracture at the upper instrumented vertebra (UIV), Lower Instrumented Vertebra (LIV) or the adjacent levels.[1,2]

In the thoracolumbar spine, multiple techniques have been employed to improve fixation and prevent hardware associated complications and failure. These include restoration of normal sagittal and coronal alignment which reduces strain on the construct.[3] Anchor points may be enhanced with multilevel fixation or using larger screws.[4] Fenestrated or hydroxyapatite coated screws,[5] undertapping,[6] and using convergent pedicle screws[7] with a straight-forward (rather than anatomic) technique[8,9] have been described. Other strategies include augments like vertebroplasty at the UIV + 1 or tethering of the adjacent vertebra[10] to prevent junctional failure. Decreasing the stiffness of the construct may thereby decrease the strain at the bone-implant interface to mitigate failure.[11]

In the cervical spine, however, osteoporosis poses a greater challenge due to the limited number of safe surgical techniques available to achieve rigid fixation. Commonly utilized techniques include bicortical fixation,[12-14] cervical pedicle screws,[13] and front and back fixation.[15,16] Here we present a scoping systematic review of fixation strategies that may be employed in the osteoporotic cervical spine with a qualitative synthesis of common strategies employed by surgeons to reduce failure in the setting of osteoporosis.

Methods

A systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statements as well as the Cochrane Collaborator handbook to identify all studies examining biomechanical strategies utilized in the cervical spine to improve fixation.

Literature Review

Using MEDLINE, Embase as well as the Cochrane Library databases, key words including "osteoporosis" OR "osteoporotic" OR "bone mineral density" AND "cervical" were queried to identify studies of interest. The search yielded results from January 1, 1996 to February 20, 2020. Hand search of included study references was undertaken to capture additional studies missed through the initial search strategy.

Data Extraction

Three authors (C.O, P.T., and K.B.) performed the initial screening for study eligibility. Eligible articles were written in English and included a biomechanical consideration or construct option for the cervical spine, which may improve biomechanical strength of a construct. All data was reviewed in duplicate and kappa agreeability scores were calculated. Disagreements were resolved via discussion and consensus amongst all authors. Authors independently abstracted data from included studies using data abstraction forms.

Articles are included if authors present direct or theoretical benefit for patients with osteoporosis. Articles with theoretical benefit for osteoporosis are those that have demonstrated improved biomechanical strength; however, have yet to be studied in osteoporosis. For example, biomechanical studies demonstrating improved pullout strengths for various screw configurations (with or without osteoporosis) are included for having theoretical benefit. For the purposes of obtaining all biomechanical options described in the literature, case reports are also included where surgeons have employed multiple techniques in an effort to improve biomechanical strength, with or without evidence of long term success. For a description of "actual" benefit, authors must have shown a comparison between normal and osteoporotic bone, with a particular technique or construct which demonstrated statistical significance favoring one particular technique or construct.

Cadaveric studies were included if the implants or constructs were specific to the cervical spine and demonstrated actual or theoretical benefit for osteoporotic bone. Mathematical modeling studies were included if they were specific to techniques within the osteoporotic cervical spine. While some posterior cervical constructs extend into the high thoracic spine, studies referencing thoracolumbar pedicle screw systems were not included. Letters to the editor, narrative reviews, and conference abstracts were excluded.

Results

The initial literature search produced 3887 results which after deletion of duplicates yielded 3271 results for abstract screening. Full text screening was completed for 68 articles, producing 39 studies which met inclusion criteria. The search strategy is presented in Figure 1. Kappa agreeability scores were .77 indicating substantial agreement between the reviewers. Eight case studies were identified, 11 retrospective case series, 19 cadaveric/biomechanical studies, and one mathematical modeling/finite risk analyses were included. Risk of bias was not assessed as all studies were low quality, based on expert opinion, case studies, or cadaveric/biomechanical studies. Included studies are listed in Table 1.

Overall, the surgical techniques reviewed within the included studies all aimed at obtaining rigid fixation in the setting of poor bone quality or dispersing the forces at the bone-implant interface. In an effort to synthesize the reported techniques in a systematic manner, 6 key fixation augmentation strategies emerged from the literature and are listed in Table 2. While the principles are broken into categories for comprehensibility, evidence is currently too limited to provide recommendations for use of any individual technique.

Bicortical Fixation

Bicortical fixation may be achieved in the keel of the occiput, C1 lateral mass, subaxial lateral masses posteriorly[12,13,17] or

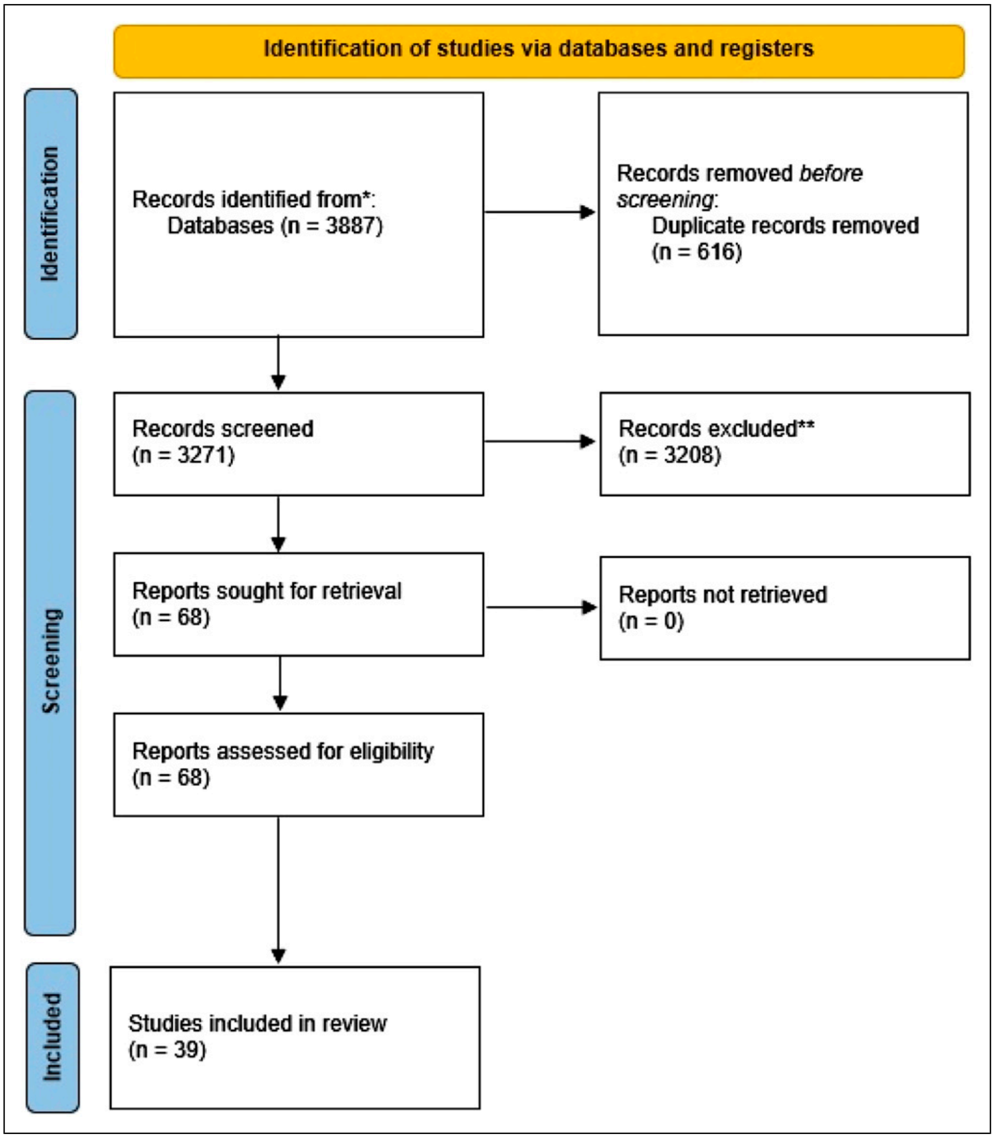

Figure 1. PRISMA Flow Diagram of Search Strategy.

anteriorly in the vertebral body.[21] In biomechanical analyses, mean pullout strength of C1 bicortical lateral mass fixation is 807N compared to 588N for unicortical fixation.[12] Bicortical fixation in the occipital keel has 50% greater pullout strength compared to unicortical fixation.[47] Subaxial bicortical lateral mass fixation according to Park et al. achieved higher pullout strength than unicortical fixation (519N vs 565N) but did come with significantly higher injury rates to the nerve root and vertebral artery.[49] In porcine models, additional stability has been demonstrated with bicortical fixation in the anterior vertebral bodies[50]; however, this hasn't been demonstrated in human models.

It should be noted that no high-quality studies definitively demonstrate superiority for bicortical fixation in the setting of osteoporosis. Several studies have not found benefit in the utilization of bicortical fixation. Lehmann et al. compare unicortical to bicortical fixation with anterior vertebral body screws and fail to demonstrate any immediate differences in stiffness.[60] While initial stiffness was equivalent, it should be noted that these authors did not complete repetitive testing or load to failure tests. Papagelous et al. examined unicortical vs bicortical lateral mass fixation and failed to demonstrate any significant improvement in rigidity with bicortical fixation, but did show an advantage of lateral connectors in improving rigidity.[59]

Screw Size and Trajectory

Appropriate screw length and trajectory selection is critical as pullout strength is directly related to screw length and to a larger degree, screw diameter.[52] As such, depending on the degree of osteoporosis, the surgeon may consider larger

Table 1. A List of the Included Studies in the Analysis, as Well as Proposed Construct in the Setting of Osteoporosis.

Authors	Year	Study Design	Number of Participants	Proposed Construct	Osteoporotic Advantage (Actual/ Theoretical)	Main Findings
Eck et al[12]	2007	Cadaveric case series	15	Bicortical C1 lateral mass fixation	Theoretical	Authors examined mean pullout strength of unicortical C1 lateral mass screw 588N (212-1234N) compared to bicortical 807N (163-1460N) experimentally in non-osteoporotic vertebrae, demonstrating significant benefit for bicortical fixation
Heller et al[17]	1996	Cadaveric case series	12	Bicortical subaxial lateral mass fixation	Theoretical	Various screw designs, vertebral level, and quality of bone were examined as risk factors for mechanical failure. Greatest pullout resistance was seen with bicortical fixation, cortical bone screws, and 3.5 mm cancellous bone screws
Hostin et al[18]	2008	Cadaveric case series	57	Posterior cervical pedicle screw	Theoretical	Authors compare various screw techniques for revision after lateral mass screw pullout including Magerl trajectory, Roy-Camille and pedicle screws. Pedicle screws had the greatest pullout strength (566N) compared to Magerl (382N) or Roy-Camille (351N). 20% of pedicle screws had a breech. Osteoporosis is not explicitly mentioned
Lee et al[19]	2012	Retrospective case series	50	Posterior cervical pedicle screws	Theoretical	Authors examine safety of subaxial pedicle screw placement using key slot technique and demonstrate 90.3% success rate with no neurovascular complications after initial learning curve. Patients involved in the review were not necessarily osteoporotic
Cornefjord, Alemany & Olerud[20]	2005	Retrospective case series	19	1 Posterior cervical pedicle screw 2 Load sharing with anterior and posterior fixation	Theoretical	Authors retrospectively review patients with ankylosing spondylitis related fractures undergoing subaxial pedicle screw fixation and review complication rates. One patient had a pedicle screw-related weakness which resolved after removal of hardware. One screw perforated the pedicle and 2 pedicles could not be probed. While the patients were presumed to have some degree of osteoporosis due to ankylosing spondylitis, no mention of bone quality is made
Mattei et al[21]	2015	Case study	1	1 Avoid caspar pin distraction 2 Bicortical vertebral body screws 3 Staged anterior and posterior fixation for load sharing 4 Posterior cervical pedicle screws	Theoretical	Authors describe a case of a patient with metabolic bone disease (Hajdu–Cheney syndrome), cervical myelopathy with kyphotic deformity. A C6 corpectomy with multilevel discectomies was followed by halo-traction, staged anterior bone grafting, and posterior pedicle screw fixation C2-T3

(continued)

Table 1. (continued)

Authors	Year	Study Design	Number of Participants	Proposed Construct	Osteoporotic Advantage (Actual/ Theoretical)	Main Findings
Su et al[13]	2014	Cadaveric	15	C2 pedicle	Theoretical	Construct stiffness between C2 pars, pedicle and hybrid systems are compared, demonstrating 92% improved pullout strength for pedicle over pars fixation. This is not tested in osteoporosis specifically
Wu et al[22]	2015	Cadaveric case series	60	Anterior cervical transpedicular screw fixation	Actual	Healthy and osteoporotic vertebrae are compared with regard to fixation using anterior pedicle screw placement compared with standard vertebral body screws with improved peak PullOut Force (PPF) and fatigue resistance favoring ATPS fixation
Koller et al[23]	2008	Cadaveric cohort	45	Anterior cervical transpedicular screw fixation	Theoretical	Authors examine feasibility of ATPS fixation and demonstrate 21% critical breech during screw placement. No correlation was seen between screw length, bone mineral density, or level on pullout strength between ATPS vs vertebral body screws. Bone mineral density of the cadaveric vertebrae was not assessed
Veeravagu et al[24]	2012	Case study	1	1 Anterior and posterior fixation for load sharing 2 Augment with post-operative halo	Theoretical	Authors describe a case of an osteoporotic patients with dialysis associated destructive spondyloarthropathy (DSA) who underwent cervical fusion followed by hardware complication. C5 and 6 corpectomies, mesh cage and plate reconstruction were followed by posterior stabilization C4-T1. At follow-up posterior hardware failure was observed so the construct was extended to C2-T5 and augmented with post-operative halo
Waschke et al[25]	2013	Case series	9	Augmentation of anterior vertebral body screws with PMMA	Theoretical	A retrospective case series of 9 patients is presented including both tumor (6) and osteoporotic (3) fractures. One or 2 level corpectomy was performed with plate and screw, augmented with vertebroplasty. At 10 months (range 4-18 months), no loosening of screws was detected although one cage subsided
Oppenlander et al[26]	2014	Case study	1	1 Augmentation of anterior vertebral body screws with PMMA 2 Augment with post-operative halo	Theoretical	Authors describe a single case of a 75-year-old female with cervical myelopathy, and C3/4 instability, who underwent C3-7 ACDF with PMMA augmentation through screw pilot holes, and post-operative halo. The patient achieved solid fusion without subsidence at 6 months. The patient's bone mineral density was not recorded

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Table 1. (continued)

Authors	Year	Study Design	Number of Participants	Proposed Construct	Osteoporotic Advantage (Actual/ Theoretical)	Main Findings
Pitzen et al[27]	2006	Cadaveric case series	6	1 Augmentation of anterior vertebral body screws with PMMA 2 Anterior cervical vertebral body rescue screws	Actual	PMMA augmented compared to non-augmented vertebral body screw fixation at C4-7 are compared. Results favored augmentation (102.6 N/cm), compared to non-augmented (67.1 N/cm) fixation. Cadaveric bone quality was not assessed directly.
Chen et al[28]	2014	Cadaveric case series	12	Augmentation of anterior vertebral body screws with PMMA	Actual	Osteoporotic and non-osteoporotic cadaveric vertebrae were treated with vertebral body screws with and without augmentation. PMMA augmentation showed significantly greated peak pullout force in osteoporotic vertebrae
Lehmann et al[60]	2004	Cadaveric case series	14	Unicortical vs bicortical anterior vertebral body screws	Theoretical	Authors utilized fresh frozen cadavers, inducing injury at C4/5 and then repairing with anterior plate utilizing either unicortical or bicortical fixation, checking immediate stability in flexion/extension demonstrating no difference between groups. Repetitive testing was not performed. Bone mineral density was not demonstrated prior to the experiment
Terreaux et al[29]	2015	Case study	2	Augmentation of C2 odontoid screw with PMMA	Theoretical	Authors present two elderly, osteoporotic patients with unstable odontoid fractures for which anterior odontoid screw fixation was performed with balloon kyphoplasty above and below fracture site. Leakage from the fracture site was noted but asymptomatic. The patients bone mineral density was not recorded
Kohlhof et al[30]	2013	Retrospective case series	24	Augmentation of C2 odontoid screw with PMMA	Theoretical	Authors retrospectively reviewed elderly patients with type 2 fractures of the odontoid undergoing anterior screw fixation with PMMA augmentation at the anterior-inferior body of C2. Of 24 patients, early loss of reduction seen in 3 patients, 2 patients had early post-operative death, 2 had slight dorsal malunion, and one pseudarthrosis
Schwarz et al[31]	2018	Retrospective case series	24	Augmentation of C2 odontoid screw with PMMA	Actual	Authors provide a retrospective cohort comparing elderly patients with C2 fracture treated with odontoid screw fixation with or without PMMA augmentation. Fusion rates were higher in the PMMA augmentation group without statistical significance. While all patients were elderly, bone quality was not assessed directly

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Table 1. (continued)

Authors	Year	Study Design	Number of Participants	Proposed Construct	Osteoporotic Advantage (Actual/Theoretical)	Main Findings
Waschke et al[32]	2015	Cadaveric series	18	Augmentation of C2 odontoid screw with PMMA	Actual	Cadaveric, osteoporotic type 2 odontoid fractures were induced and then fixed using a cannulated lag screw with perforations in the proximal screw shank for PMMA augmentation at the anterior-inferior body of C2. PMMA augmented screws had a 2.4x higher maximum force to failure and 2.7x higher energy to failure, 1.76x higher stiffness compared to non-augmented fixation
Tonosu et al[33]	2013	Case study	1	Variable pitch headless screw for anterior odontoid fixation	Theoretical	Authors present a single case of a patient with osteopenic odontoid fracture that was treated with an Acutrak 4/5 screw which had a good clinical result for at least 3 years. Authors propose the variable pitch may improve compression to improve union
Vale, Oliver & Cahill[34]	1999	Retrospective case series	24	Rigid occipitocervical plating with keel fixation in the occiput	Theoretical	Authors present a retrospective review of 24 patients undergoing T plating across the occipital keel with rigid occipitocervical fixation. This is compared to older techniques of non-rigid fixation. There is no mention of bone mineral density
Liu et al[35]	2016	Mathematical modelling	NA	Inclusion of C1 lateral mass with OC2 fusions	Theoretical	Authors present a non-linear finite element model (FEM) comparing Occipital plate with C2 pedicle screw with or without a C1 lateral mass screw. Addition of the C1 fixation reduced C0-2 motion by 3%, 35.4%, 29.2%, 56.9% in flexion, extension, lateral bending, and rotation
Song, Kim, & Choi[36]	2011	Retrospective case series	21	Utilization of PEEK cages with anterior plating	Theoretical	Authors present 21 osteoporotic patients undergoing 3 level ACDF using PEEK cages. 5 patients had cage subsidence and screw loosening occurred in 3 patients
Epstein[37]	2008	Retrospective case series	35	Posterior cervical wiring around spinous processes	Theoretical	Authors present 35 elderly patients undergoing cervical decompression for myelopathy and a fusion technique utilizing wires around the spinous processes with iliac crest graft. Fusion occurred in 100% of patients at 2 years. Bone mineral density is not reported

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Table 1. (continued)

Authors	Year	Study Design	Number of Participants	Proposed Construct	Osteoporotic Advantage (Actual/ Theoretical)	Main Findings
Eleraky, Masferrer & Sonntag[38]	1998	Retrospective case series	36	1 Posterior transarticular screw fixation 2 Augmented with posterior C1-2 wiring 3 Augmented with post-operative halo	Theoretical	Authors present a retrospective case review of 36 patients with rheumatoid-related atlantoaxial instability undergoing C1/2 transarticular fixation with supplemental wiring, strut graft. Three patients also had a post-operative halo due to severe osteoporosis. Fusion rate was 92% at 2 years with stable fibrous union in 8%
Liu et al[39]	2020	Case study	1	Additional C2 spinous process screw fixation	Theoretical	Authors present a case of a 31-year-old male undergoing occipitocervical fusion for a congenital deformity with myelopathy. An occipital plate, C2 pedicle screws, and C3 lateral mass was supplemented with an additional screw in the spinous process of C2. The patient had good results with solid fusion at 2 post-operative years. His bone mineral density was not mentioned
Cho et al[40]	2017	Cadaveric	18	Subaxial translaminar fixation	Theoretical	Authors examine cadaveric cervical spine segments for feasibility in placing translaminar fixation in the cervical spine. Most levels permitted a single screw. At C3, only one specimen permitted 2 screws. At C4, 37% of lamina can tolerate 2 screws. At C5 58%, C6 89%, and C7 all specimens could tolerate dual laminar fixation. This study did not involve osteoporotic vertebrae
Ni et al[41]	2013	Retrospective case series	72	C1-2 posterior transarticular screw fixation augmented with C1 posterior arch hook	Theoretical	Authors retrospectively review 72 patients without documented osteoporosis undergoing C1/2 fusion using transarticular fixation with ancillary hook in the C1 arch. No hardware complications reported
Mizutani et al[42]	2019	Cadaveric series	9	Short posterior arch screw in C1	Theoretical	Authors use a cadaver model to compare pullout strength of a short posterior arch screw in C1 compared to unicortical harms screw, demonstrating improved pullout for posterior arch screw (1048.5 N) compared to harms technique (257.9 N). The cadaveric bone quality was not mentioned

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Table 1. (continued)

Authors	Year	Study Design	Number of Participants	Proposed Construct	Osteoporotic Advantage (Actual/Theoretical)	Main Findings
Nagoshi et al[43]	2014	Case study	1	Posterior arch screw at C1	Theoretical	Authors report a case of a 90-year-old male with odontoid fracture and C1/2 instability where C1 lateral mass and C2 pedicle were placed on the non-dominant side of the vertebral artery, and C1 posterior arch with C2 laminar screw were placed on the side of the dominant vertebral artery. Authors observed solid union of the fracture side without complication. The patients bone mineral density is not mentioned
Ebraheim et al[44]	2009	Cadaveric case series	10	Standard halo pin torque of 8 inch-pounds is safe in the osteoporotic calvarium	Theoretical	Authors examined 10 osteoporotic cadaveric calvarium. 8–12 in/lb of torque wasn't sufficient to penetrate the outer table in any specimens. At 16 ft/lb, the outer table was penetrated, only at the anterolateral table
Haher et al[47]	1999	Cadaveric case series	12	1. Bicortical fixation at the occipital keel	Theoretical	Authors compare 21 occipital fixation sites on 12 cadaveric calvaria. Bicortical fixation had pullout strength 50% greater than unicortical fixation with screws in the occipital protuberance providing the greatest strength. The cadaveric bone mineral density was not assessed
Park et al[48]	2001	Cadaveric case series	21	1. Bicortical lateral mass fixation	Theoretical	Authors placed unicortical and bicortical lateral mass fixation in non-osteoporotic subaxial lateral masses to examine rates of dangerous screw placement. Bicortical screws had a 5.8% risk of direct arterial injury and 17.4% incidence of nerve root injury. No unicortical screws placed the artery or nerve root at risk. Bone mineral density is not assessed
Chen[49]	1996	Porcine cadaveric model	9	1. Bicortical anterior vertebral body fixation	Theoretical	Authors examined unicortical vs bicortical anterior vertebral body screws in a porcine model without osteoporosis. Segments were exposed to flexion and extension before and after discectomy for analysis. Prior to cyclic loading unicortical and bicrotical screws had comparable stability. After cyclic loading bicortical fixation had greater time to failure

(continued)

Table 1. (continued)

Authors	Year	Study Design	Number of Participants	Proposed Construct	Osteoporotic Advantage (Actual/ Theoretical)	Main Findings
Conrad et al[50]	2005	Artificial bone model	9	1. Longer screws had greater pullout force	Theoretical	Authors utilize an artificial bone model to examine self-tapping vs self-drilling screws and screw geometry (length, diameter, pitch) on pullout strength. Each 1 mm of increased length corresponded to 16N of increased force for pullout. Pullout did not vary according to screw diameter or between self-drilling/ tapping screws. Osteoporotic bone was not modeled specifically
Lapsiwala et al[52]	2006	Cadaveric case series	8	1. Sublaminar wiring significantly strengthens transarticular fixation at C1/2 with no added benefit for C1 lateral mass/C2 pedicle constructs	Theoretical	Eight cadaveric spines were tested for fixation strategies with the dens intact, and after fracture. Transarticular and pedicle screw constructs were tested with and without cable augmentation. Cadaveric bone was not assessed directly for bone quality
Hartmann et al[53]	2017	Cadaveric case series	12	1. PMMA augmentation of anterior vertebral body screws reduces ROM after 2 level corpectomy	Theoretical	Twelve cadaveric spines without diagnosed osteoporosis were exposed to C4 and C5 corpectomy with anterior grafting and plating, with and without PMMA augmented screws. Augmented constructs had lower ROM, especially with cyclic loading (32% vs 78% non-augmented)
Mendelsohn et al[54]	2015	Case series	3	1. Bilateral C2 pedicle with additional C2 translaminar fixation	Theoretical	Authors present a case series of 3 individuals requiring posterior cervical fusion where crossed laminar screws in addition to pedicle screws were utilized for improved fixation at C2 without complication. The patients had either ankylosing spondylitis, rheumatoid arthritis, or osteoporotic deformity although bone mineral densities are not reported
Papagelous et al[59]	2003	Cadaveric case series	16	1. Unicortical vs bicortical lateral mass 2. Transverse connectors	Theoretical	Authors compare posterior cervical constructs in fresh frozen cadavers including unicortical vs bicortical lateral mass fixation, presence or absence of a C6 lateral mass, and presence or absence of transverse connectors. No Benefit was seen for bicortical lateral masses, however transverse stabilizers reduced the number of lateral mass screws needed to resist physiologic load to failure with repeated testing. Osteoporosis was not mentioned directly

Table 2. Common Principles from Extracted Studies to Improve Biomechanical Support of Cervical Constructs.

Strategy	Examples
Bicortical fixation	1 Posterior bicortical: Occiput,[47] C1, subaxial[12,13,17,49,50] 2 Anterior bicortical: Vertebral body[21,49]
Screw selection (size and trajectory)	1 Larger screws/rescue screws[27,50,51] 2 Cervical pedicle screws Anterior[22,23] Posterior C2 pedicle[13] Posterior subaxial[13,17-21] 3 Transarticular fixation with augmented wiring/hooks[35,38,41]
Screw augmentation with PMMA	1 Anterior vertebral body screws[25-28,53] 2 Odontoid screws[29-32]
Load sharing	Anterior and posterior fixation[20,21,24] PEEK interbody fusion[36]
Ancillary fixation	1 Transarticular screws at C1/2[35,38,41] 2 Posterior arch screw in C1[43,44] 3 Translaminar fixation in subaxial or C2[40] 4 C2 spinous process screw 40 or wiring[38] 5 Bilateral C2 pedicle with C2 translaminar fixation[55]
Post-operative strategies	Collar or halo[24,38]

(4.0 mm or 4.5 mm compared to standard 3.5 mm) screws[27] within the cervical spine. While multiple studies have examined pullout strength in relation to screw size/diameter in the thoracolumbar spine, minimal work has been done to investigate this in the human cervical spine. Further, the importance of screw length in fixation was demonstrated in an artificial bone model by Conrad et al. where each additional 1 mm in length was associated with an additional 16N of pullout force.[51]

In terms of trajectory, cervical pedicle screws have been utilized throughout the cervical spine with increased pullout strength. At the level of C2, pedicle fixation has been shown to have twice the pullout over pars fixation.[13] In the subaxial spine, pedicle screws have been utilized from an anterior[2-28] or posterior approach.[13,18-21] While they place the vertebral artery and nerve root at increased risk, cervical pedicle screws allow for improved biomechanical strength.[52] The pullout strength of cervical pedicle fixation is roughly 3.5x that of lateral mass fixation.[59] Additionally, transarticular screw fixation while in isolation have increased failure in flexion, augmentation with cables produces a construct with similar rigidity to traditional harms techniques at the C1/2 level.[53]

While there is additional risk with the placement of pedicle screws at C2 and in the subaxial spine, there does appear to be consistent biomechaical data suggesting improved pullout strength.

Screw Augmentation

PMMA augmentation has been described in the setting of anterior vertebral body screws[25-32] and odontoid fixation of the elderly.[29-31] Augmentation may occur prior to screw placement (cement-first technique) by injecting PMMA through a tapped screw hole or after screw placement (in situ technique) whereby cement is injected through a cannulated and fenestrated screw design.[54] In a cadaveric model of an osteoporotic cervical spine, augmented screw fixation demonstrated significantly reduced motion at corpectomy sites.[54] The available data on human participants for this technique is limited to small case series.[25-28] Further, augmentation of anterior odontoid fixation in the elderly is described with PMMA at the anterior-inferior body of C2 to help reduce backout on a fully threaded screw.[29-31]

Based on the current literature no definitive argument can be made to support PMMA augmentation; however, it has been employed in multiple circumstances by surgeons in an attempt to salvage anterior screw fixation.

Ancillary Fixation

Additional anchor points have been described to achieve occipitocervical fusion in the setting of osteoporosis. Mendelsohn et al. describe bilateral C2 pedicle fixation augmented with bilateral C2 translaminar screws to obtain circumferential anchorage around the ring of C2.[55] An auxiliary anchor around the C1/2 complex has been described with a screw in the spinous process of C2 by Liu et al.,[39] short screws in the posterior arch of C1[42,43] or hooks over the ring of C1[41] and supplemental wiring.[37] There are however no available biomechanical studies to validate these fixation points.

Load Sharing

Load sharing has been described via the use of anterior and supplementary posterior fixation to distribute the stress at the bone-implant interface[20,21,24] though this carries its own concerns for morbidity in elderly patients.[20] Cornefjord et al.[20] describe load sharing techniques in the setting of fractures related to ankylosing spondylitis. They report on 19 patients with ankylosing spondylitis related extension fractures that received long anterior plating with posterior fixation using cervical pedicle screws. The concept of load sharing has also been described in the setting of interbody cages with polyethyletherketone (PEEK) cages having an elastic modulus that more closely resembles that of human bone when compared to metal cages.[36] Although this technique has been described by multiple surgeons in case reports, and small series, iomechanical studies have yet to validate this front and back approach in the osteoporotic cervical spine.

Post-Operative Strategies

Post-operatively the patients construct may be augmented externally with a collar or halo device.[24,38] Largely the literature available on post-operative adjuncts for this difficult patient population is limited to small case series and case reports. The perioperative morbidity and mortality rates associated with halo devices in the elderly are extremely high and irrespective of injury severity scores and should be utilized as a last resort.[56] Nonetheless, in salvage situations they have been employed to augment internal fixation to help achieve union in the literature.[24,38] Veeravagu et al.[24] report on a 44-year-old patient with renal osteodystrophy and osteoporotic cervical fracture where they employed anterior and posterior constructs for load sharing followed by post-operative halo. Eleraky et al.[38] describe a series of 36 patients with rheumatological atlantoaxial instability where patients received C1/2 transarticular fixation, with 3 patients having severe osteoporosis which were managed in post-operative halo devices. Oppenlander et al[26] describe a case of a 75-year-old female with osteoporosis and degenerative cervical myelopathy which was treated with multilevel anterior decompression, and augmented with post-operative halo. No evidence to date has demonstrated higher fusion rates or reported on the increased halo-related complications associated with its use. Nonetheless, in extreme salvage situations it remains a viable option post-operatively.

Additionally, medical optimization of bone quality is recommended[57] including calcium, vitamin D, bisphosphonates, and/or PTH analogues with results favoring the use of teriparatide to improve bone mineral density.[57,58]

Discussion

With an ever-aging population, osteoporosis is becoming more prevalent and cervical spine fixation in this setting poses a challenge for spinal surgeons. This is the first study to systematically review the literature for construct options available to improve biomechanical strength of a cervical construct. Ultimately there is insufficient evidence to discuss the efficacy of one construct over another for patients with osteoporosis. Nonetheless, we found that the primary themes qualitatively emerging from the literature to produce a rigid construct included bicortical fixation, larger screws with pedicle fixation, PMMA augmention, with front and back constructs utilizing ancillary fixation around the occipitocervical junction, and supplemented with post-operative collar or halo. Multiple studies included did not reference osteoporosis or bone mineral density directly; however, utilized well-known models for osteoporosis such as cadaveric bone models so results are presumed to be relevant in the setting of poor bone quality. Multiple case reports and small series while not mentioning osteoporosis directly, investigated elderly patients with fragility fracture patterns, rheumatoid arthritis, ankylosing spondylitis, or other conditions frequently known to be osteoporotic. Therefore, while the majority of the studies included in this review do not demonstrate direct benefit for one particular construct in the setting of osteoporosis, this review offers nonetheless the construct options described for these complex salvage-type of surgical scenarios.

We performed an in-depth search of multiple databases which were screened in duplicate and PRISMA guidelines were followed throughout review process. As each surgical case is unique in the indication for surgery, surgical procedure, local anatomy, and particular bone quality, it is challenging assessing construct efficacy and fixation strategies and we often rely on expert opinion and personal experience to advice each case. Here, we have compiled the relevant literature and fixation strategies that a surgeon may consult and use are part of their armamentarium when tackling these challenging cases.

Overall, quality of evidence is low with the majority of reports involving case studies with expert opinion, cadaveric/biomechanical studies or retrospective case series on feasibility of various construct choices. There is a paucity of literature specifically examining osteoporosis and available constructs. The authors assumption in this case, that a construct which demonstrates superiority in normal bone is likely to show benefit in osteoporotic bone, may not always be the case. Furthermore, given the overall lack of evidence, and conflicting results of various biomechanical studies on topics such as unicortical vs bicortical fixation, the surgeon must use discretion when selecting their construct.

While many constructs were highlighted during the generation of this review, not all are practical. For example, fixation in the cervical pedicle from an anterior approach places the vertebral artery and nerve root at risk with a high miss rate[24] and we believe most spine surgeons would not utilize this fixation strategy. Many intuitive strategies however are proposed and feasible, including long posterior cervical constructs, posterior cervical pedicle screws, using larger rescue screws in the lateral mass, anterior and posterior fixation and augmenting a construct with a halo or post-operative collar.

Failure to achieve normal sagittal alignment in the thoracolumbar spine is a well-known risk factor for pseudarthrosis, hardware failure, and junctional disease.[45,46] As such, this is also a likely factor that contributes to failure of cervical constructs, although our search failed to capture articles related to this. Therefore, we believe that where feasible, the surgeon should attempt to restore normal sagittal alignment to reduce the strain at the proximal and distal end of the construct.

Conclusion

We have presented a systematic review of all relevant and currently available evidence on construct augmentation in the cervical spine. We identified and highlighted 6 strategies to help achieve fixation in the osteoprotoic cervical spine. These include bicortical fixation, appropriate screw selection (size and trajectory), augmentation of screws, load sharing, consideration of ancillary fixation around the occipitocervical junction, and supplementing the construct with post-operative collar or halo. Given the ever-increasing population age, high rates of osteoproosis in this population and significant global cervical spine pathology burden, further investigation is indicated into this difficult to manage patient cohort. Currently, there is a paucity of direct evidence to recommend one particular construct over another. Each construct should be considered carefully by the surgeon given the limited evidence to support their use, along with the added risk of each strategy.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

Publication Statement

This work has not, in whole or in part, been previously published or presented elsewhere.

ORCID iDs

Colby Oitment https://orcid.org/0000-0003-1351-9410
Thorsten Jentzsch https://orcid.org/0000-0002-6133-3314

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