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Title
Biomechanical evaluation of two plating configurations for fixation of a simple transverse caudal mandibular fracture model in cats.

Permalink
https://escholarship.org/uc/item/6mn7364z

Journal
American journal of veterinary research, 78(6)

ISSN
0002-9645

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Publication Date
2017-06-01

DOI
10.2460/ajvr.78.6.702

Peer reviewed

Biomechanical evaluation of two plating configurations for fixation of a simple transverse caudal mandibular fracture model in cats

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OBJECTIVE
To evaluate biomechanical properties of intact feline mandibles, compared with those for mandibles with an experimentally created osteotomy that was stabilized with 1 of 2 internal fixation configurations.

SAMPLE
20 mandibles from 10 adult feline cadavers.

PROCEDURES
An incomplete block study design was used to assign the mandibles of each cadaver to 2 of 3 groups (locking plate with locking screws [locking construct], locking plate with nonlocking screws [nonlocking construct], or intact). Within each cadaver, mandibles were randomly assigned to the assigned treatments. For mandibles assigned to the locking and nonlocking constructs, a simple transverse osteotomy was created caudal to the mandibular first molar tooth after plate application. All mandibles were loaded in cantilever bending in a single-load-to-failure test while simultaneously recording load and actuator displacement. Mode of failure (bone or plate failure) was recorded, and radiographic evidence of tooth root and mandibular canal damage was evaluated. Mechanical properties were compared among the 3 groups.

RESULTS
Stiffness, bending moments, and most post-yield energies for mandibles with the locking and nonlocking constructs were significantly lower than those for intact mandibles. Peak bending moment and stiffness for mandibles with the locking construct were significantly greater than those for mandibles with the nonlocking construct. Mode of failure and frequency of screw damage to tooth roots and the mandibular canal did not differ between the locking and nonlocking constructs.

CONCLUSIONS AND CLINICAL RELEVANCE
Results indicated that both fixation constructs were mechanically inferior to intact mandibles. The locking construct was mechanically stronger than the nonlocking construct. (*Am J Vet Res* 2017;78:702–711)

Mandibular fractures occur commonly in cats, representing 11.4% to 16% of all fractures.[1–3] Among mandibular fractures and related injuries, 73.3% involve separation of the symphysis, 16% involve fracture of the mandibular body, 6.7% involve fracture of the condyloid process, and 4% involve fracture of the condylar process.[3] Apart from acute bleeding subsequent to trauma, mandibular body fractures typically result in malocclusion, signs of pain and discomfort, and pronounced loss of function.

Repair options for fractures of the caudal portion of the mandible are limited. Maxillomandibular fixation stabilizes the mandibles to the maxillas in a closed-mouth position with minimal overlapping of the canine teeth. The assumption is that this fixation method will anatomically align the caudal aspect of the mandibles to facilitate fracture healing. Fixation is achieved by various methods such as interdental bonding or muzzle coaptation.[4] However, prolonged fixation requires extraoral nutritional support, the risk of hyperthermia is increased subsequent to impaired panting, and aspiration and asphyxia can occur secondary to vomiting.[4–8] Also, interdental bonding is difficult to achieve in patients that lack adequate dentition to support bonding material.[4] Regardless of the method used, maxillomandibular fixation is not characterized by a quick return to normal function and may result in nonunion of the fracture.

Miniplate systems designed for maxillofacial fractures in human patients are an effective means for internal fixation of mandibular and maxillofacial fractures in dogs and cats.[9] Titanium miniplates have a modulus of elasticity and density similar to bone and enable osteointegration with the underlying bone.

ABBREVIATIONS
CSA	Cross-sectional area
PMMA	Polymethyl methacrylate

Those advantages make titanium miniplates an attractive alternative stabilization method for mandibular body fractures.[9]

The plate placement technique used for mandibular fracture fixation affects fracture stability and the risk for complications. In human patients, placement of a miniplate along the alveolar margin uses the tension-band principle to provide the interfragmentary stabilization necessary for bone healing. The miniplate is advantageously positioned to resist tensile forces induced by mastication while allowing compressive load transfer through the mandibular bone fragments.[9,10] Results of studies[11-13] of mandibular fracture fixation with miniplates in dogs, cats, and rabbits indicate that return to function is faster than with maxillomandibular fixation and excellent dental occlusion is achieved by direct opposition of bone fragments. In dogs, a single titanium locking reconstruction plate can be used to stabilize a critical-size defect with minimal damage to dental structures and the mandibular canal.[14] Moreover, the 2-plate method previously suggested is technically difficult to perform owing to the thinness of the bone of the coronoid process and the proximity of the mandibular first molar tooth.[15] To our knowledge, studies on the biomechanical properties of intact feline mandibles are lacking as are studies that compare the effects of locking versus nonlocking miniplate constructs for the fixation of mandibular fractures in cats. Therefore, the objectives of the study reported here were to evaluate the biomechanical properties of intact mandibles obtained from feline cadavers and compare them with the biomechanical properties of mandibles with an experimentally induced osteotomy at the junction of the body and ramus of the mandible that were plated with either a locking or nonlocking miniplate configuration.

Materials and Methods

Samples

Twenty clinically normal mandibles were obtained from 10 adult feline cadavers. Mandibles were excised, debrided of associated muscle and soft tissues, and separated at the mandibular symphysis to yield 2 mandibles per cadaver. Mandible length was measured from the most rostral aspect (ie, the mandibular first incisor tooth) to the caudal aspect of the condylar process. For each mandible, the dorsoventral (a) and mediolateral (b) diameters across the body immediately caudal to the mandibular molar tooth were measured for use in the formula for approximation of the area of an ellipse to calculate the CSA (ie, CSA = $\pi \cdot a/2 \cdot b/2$).

Study design

An incomplete block study design was used to minimize the effect of individual cat differences on the desired study outcomes and enhance comparisons among the experimental groups. The study had 3 experimental groups or treatments: locking plate and locking screws (locking construct), locking plate and nonlocking screws (nonlocking construct), and intact mandible. Two of the 3 treatments were assigned to each cat. Within a cat, 1 of the 2 assigned treatments was randomly selected for 1 mandible and the other treatment was assigned to the contralateral mandible. That treatment allocation resulted in the locking construct being compared with the nonlocking construct for 4 cats, the locking construct being compared with an intact mandible in 3 cats, and the nonlocking construct being compared with an intact mandible in the remaining 3 cats. The biomechanical properties of the mandibles within each group were then evaluated.

Fixation method

For each mandible assigned to the locking and nonlocking constructs, the plate and screws were applied by a board-certified veterinary dentist (BA) experienced with the placement of internal fixation to the mandible to best engage the thick cortical bone and avoid or minimize iatrogenic damage to the tooth roots and neurovascular structures located within the mandibular canal immediately ventral to the roots of the molar and premolar teeth.[13,15-18] The ideal location for application of the plate to the mandible **(Figure 1)** was determined by subjective visual assessment of each mandible and its associated radiograph.

The same type of 2-mm, 6-hole titanium intermediate locking miniplate[a] (thickness, 1.3 mm; width, 5.1 mm; hole spacing, 6.5 mm; and distance between central holes, 12.0 mm) was used for both locking and nonlocking constructs. Six 2-mm bi-
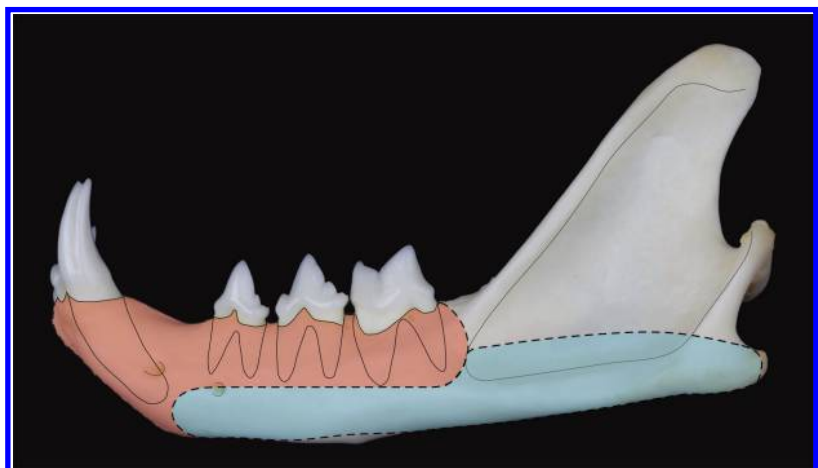

Figure 1—Illustration of the lateral aspect of an intact feline mandible that depicts the ideal (blue) and nonideal (red) regions for miniplate application. The ideal region overlies bone capable of supporting internal fixation. Although the nonideal region has bone that is capable of supporting screws, the risk of penetrating mandibular tooth roots is high. The bone of the masseteric fossa and coronoid process is too thin for adequate screw anchorage.
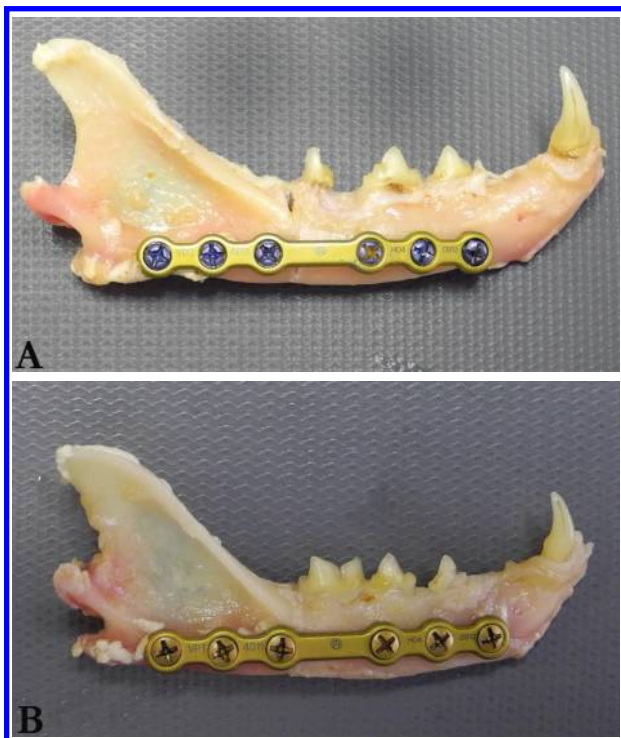
Figure 2—Photographs of the lateral aspect of 2 feline mandibles with an experimentally created simple transverse osteotomy within the mandibular body immediately caudal to the mandibular first molar tooth root that was stabilized by use of either a locking plate and locking screws (locking construct; A) or locking plate with nonlocking screws (nonlocking construct; B). Notice that the plates were secured to the lateral surface of the mandible near its ventral margin in the region that was depicted as ideal for plate application in Figure 1.

Figure 3—Lateral radiographic images of the mandibles of an adult feline cadaver that were assigned to the intact group (A) and a plate-mandible fixation construct with creation of a simple transverse osteotomy immediately caudal to the mandibular molar tooth root (B) prior to mechanical testing.

Figure 4—Lateral radiographic image of the rostral portion of an intact adult feline mandible. Brackets depict the areas measured to determine the tooth root length (white) and root-ventral border length (black) for the mesial root of the mandibular first molar tooth.

cortical locking screws[b] (length, 8 mm) were used to secure the miniplate to the mandibles assigned to the locking construct, whereas six 2-mm bicortical cortex screws[c] (length, 8 mm) were used to secure the miniplate to the mandibles assigned to the nonlocking construct. Each plate was contoured to provide appropriate contact with the lateral surface of the mandible before being secured with the appropriate screw type **(Figure 2)**. The screws were inserted into the bone with a torque-limiting screwdriver set to the least amount of torque (mean, 3.0 Nm; range, 2.4 to 3.4 Nm) necessary for each mandible.

For each mandible assigned to the locking and nonlocking constructs, after the plate and screws were applied, a standardized transverse mandibular osteotomy was created caudal to the mandibular molar tooth to mimic a fracture of the caudal aspect of the mandible in a manner that ensured 3 screws were present on each side of the fracture line. The osteotomy was created after placement of the internal fixation to avoid any osteotomy-induced changes to the mandibular dimensions such as a decrease in the mandible length subsequent to inadvertent reduction of the osteotomy gap. The osteotomy was cre-
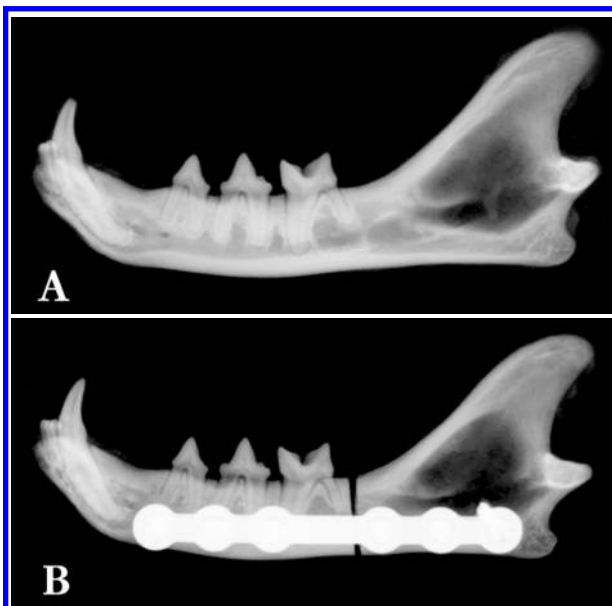
ated by use of a 0.5-mm-thick oscillating tool saw and a 0.2-mm-thick hand saw with care to avoid damaging the treatment constructs. Thus, the osteotomy gap (0.5 mm) was standardized for all plated mandibles.

Radiography

Digital radiography[d,e] (imaging parameters, 7.2 mAs and 40 kV with a focus-image distance of 1.10 m) was used to acquire a lateral radiographic image of each mandible before **(Figure 3)** and after mechanical testing and after implant removal. Post-failure radiographs were obtained after the plates and screws were removed so evaluators would be unaware of (blinded to) the plate-mandible construct group to which each mandible was assigned. The radiographs were evaluated for evidence of

tooth root or mandibular canal abnormalities indicative of iatrogenic damage caused by the fixation construct.[19-21] Iatrogenic damage to tooth roots or the mandibular canal by screws was quantified by counting the number of screw holes that were superimposed over a tooth root[20] or the mandibular canal, a method that has high sensitivity (low false-negative rate) and low specificity (high false-positive rate).

Radiographic assessment of the mandibular root length (ie, root length) was recorded as the length of the mesial tooth root of the mandibular first molar tooth from the alveolar border to the root apex. The distance between the mesial tooth root apex of the mandibular first molar tooth and the ventral mandibular border (ie, root-ventral border length) was also recorded **(Figure 4)**.

Mechanical testing

Intact and plated mandibles were loaded in cantilever bending by use of a servohydraulic testing system[f] **(Figure 5)**. The caudodorsal aspect of the mandibular ramus that contains the insertion sites for the muscles of mastication was embedded in PMMA[g] to provide a rigid site of attachment to the testing system. The incisor and canine teeth were also embedded in PMMA to evenly distribute force onto the rostral portion of the mandible. The mandibles were oriented with the symphysis perpendicular to the loading surface of the PMMA blocks and with the canine teeth and coronoid process centered in their respective blocks, allowing for mechanical loading to be applied in a physiologic manner. The PMMA was allowed to cure for a minimum of 20 minutes before testing to maximize PMMA strength. Bending moment arm was determined by measuring the distance between the rostral aspect of the PMMA block containing the ramus and the caudal aspect of the PMMA block containing the canine and incisor teeth.

Custom loading fixtures were used to accommodate angular deformation of the mandibles during loading to failure. Intact mandibles and plate-mandible constructs were loaded in a single-load-to-failure test under constant displacement control (1 mm/s) while simultaneously recording load and actuator axial displacement at 120 Hz and obtaining video[h] at 30 Hz. Tests were automatically stopped at 50% peak load after a peak was detected.

Mode of failure

The mode of failure (ie, bone fracture, plate bending, or screw failure) was recorded immediately following failure testing. Photographs were obtained both before and after testing to document the mode of failure for each mandible, and video recordings were examined for further verification.

Data analysis

Bending moment–angular displacement data were calculated and plotted for each test. Bending
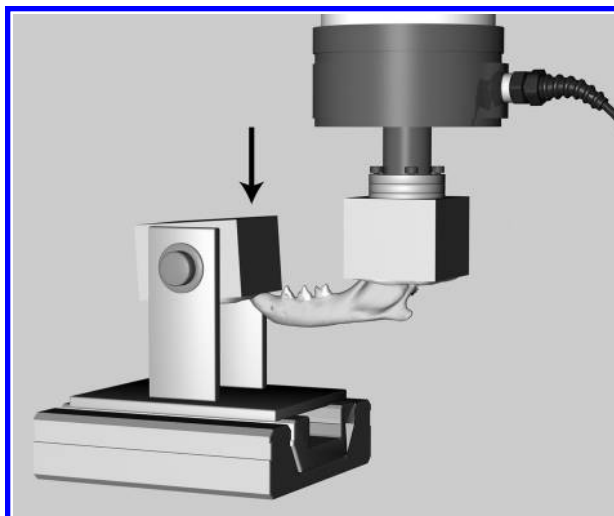

Figure 5—Illustration of the servohydraulic testing system used for biomechanical testing of 20 mandibles obtained from 10 adult feline cadavers that were assigned to 1 of 3 treatment groups (locking plate with locking screws [locking construct; n = 7], locking plate with nonlocking screws [nonlocking construct; 7], or intact [6]). Mandibles assigned to the locking and nonlocking constructs had a simple transverse osteotomy experimentally created immediately caudal to the mandibular molar tooth after plate application. The caudodorsal portion of the mandibular ramus was embedded in PMMA to provide a rigid site of attachment to the testing system. The incisor and canine teeth were also embedded in PMMA to evenly distribute force onto the rostral portion of the mandible. The mandible was oriented in the testing system with the symphysis perpendicular to the loading surface of the PMMA blocks and the canine teeth and coronoid process centered within their respective PMMA blocks, which allowed a mechanical load to be applied in a physiologic manner. Load (arrow) applied to the rostral portion of the mandible caused cantilever bending about the mandibular coronoid process and condylar process in a direction parallel to the mandibular symphysis.

moments were calculated by multiplying the specimen bending moment arm by applied force for each data collection point as follows: bending moment (N•mm) = applied force (N) X bending moment arm (mm). Angular displacement (Θ) was calculated by use of the arctangent of the ratio between vertical displacement and bending moment arm for each data collection point as follows: Θ = arctan (vertical displacement [mm]/bending moment arm [mm]).

Two deviations from linearity (yield points) were consistently observed before peak loads were obtained on bending moment versus angular displacement plots. First and second yield points were determined by detecting the deviation from linearity by use of a running least squares mean regression line with 0.35% and 1.5%, respectively, angle offset criteria. Construct stiffness was determined before the first yield point, between the first and second yield points, and between the second yield point and peak load by calculating the slope of the middle third of the recorded data between the respective points. Mandible failure was determined as a drop to 50% of the attained peak load. Bending moments and angular displacements were the respective values calculat-

ed at each of the determined yield, peak, and failure points. Energies were calculated as the areas under the bending moment–angular deformation curve between the respective yield, peak, and failure points and the immediately previous point or zero (for the first yield point).

Statistical analysis

The effect of group (locking construct, nonlocking construct, or intact mandible) on mandibular mechanical properties was assessed with an ANOVA that accounted for the repeated measures within a cadaver on the ranked data. A nonparametric analysis[i] was used because the residuals from an ANOVA of the raw data were not normally distributed (ie, Shapiro-Wilk W test, $P < 0.05$) for all variables. Pairwise differences between groups were assessed with least squares means. A Student t test[j] was used to assess differences in the number of instances of screw damage to tooth roots and the mandibular canal between the locking and nonlocking constructs. After the relevant data were confirmed to have normal distributions (Shapiro-Wilk W test, $P > 0.05$), the mandible root length and root-ventral border length were respectively compared with CSA, body weight, and mandible length by use of Pearson correlation.[j] Values of $P < 0.05$ were considered significant for all analyses.

Results

Samples

Of the 20 mandibles evaluated, 7 were assigned to the locking construct, 7 were assigned to the nonlocking construct, and 6 were left intact. The mean ± SD length, CSA, and bending moment arm for all 20 mandibles were 65.3 ± 3.7 mm, 49.9 ± 14.3 mm², and 33.2 ± 2.4 mm, respectively, and those variables did not differ significantly among groups **(Table 1)**.

Table 1—Median (range) for biomechanical test variables for 20 mandibles obtained from 10 adult feline cadavers that were assigned to 1 of 3 treatment groups (locking plate with locking screws [locking construct; n = 7], locking plate with nonlocking screws [nonlocking construct; 7], or intact [6]).

Variable	Group			P value*		
	Locking construct	Nonlocking construct	Intact	Locking construct vs intact	Nonlocking construct vs intact	Locking construct vs nonlocking construct
Prior to first yield						
Stiffness (N•mm/degree)	301.9 (219.9–788.9)	443.9 (152.9–765.1)	1,113.0 (542.3–1,672.7)	0.002	0.002	0.952
First yield						
Angle (°)	0.3 (0.1–2.0)	0.2 (0.2–1.2)	0.4 (0.1–0.8)	0.463	0.290	0.728
Bending moment (N•mm)	219 (128–611)	173 (135–312)	447 (170–1,085)	0.039	0.012	0.572
Displacement (mm)	0.2 (0.0–1.3)	0.1 (0.1–0.7)	0.2 (0.1–0.5)	0.416	0.330	0.862
Load (N)	6 (4–17)	6 (4–9)	15 (5–33)	0.027	0.011	0.677
Energy (N•mm•degree)	41 (14–796)	31 (19–237)	142 (11–464)	0.230	0.187	0.893
Prior to second yield						
Stiffness (N•mm/degree)	183.8 (71.8–509.7)	106.7 (75.8–224.5)	659.7 (511.1–1,018.4)	< 0.001	< 0.001	0.175
Second yield						
Angle (°)	1.9 (0.5–7.7)	2.3 (1.0–4.0)	2.5 (0.8–8.4)	0.534	0.940	0.469
Bending moment (N•mm)	468 (282–1,171)	421 (352–541)	1,771 (634–4,316)	0.002	< 0.001	0.377
Displacement (mm)	1.1 (0.3–4.8)	1.3 (0.6–2.3)	1.4 (0.42–4.7)	0.591	0.995	0.581
Load (N)	14 (9–33)	12 (11–19)	52 (20–135)	0.001	< 0.001	0.327
Energy (N•mm•degree)	444 (94–4,907)	571 (261–1,008)	2,766 (290–19,022)	0.089	0.194	0.645
Prior to peak						
Stiffness (N•mm/degree)	85.7 (42.1–105.2)	42.8 (22.1–88.7)	181.1 (42.6–423.5)	0.056	< 0.001	0.037
Peak						
Angle (°)	11.4 (5.9–23.1)	9.7 (6.3–23.1)	15.6 (10.8–18.1)	0.098	0.098	1.000
Bending moment (N•mm)	1,216 (886–2,161)	806 (595–1,094)	4,051 (1,096–6,205)	0.006	< 0.001	0.022
Displacement (mm)	6.2 (3.4–15.4)	5.7 (3.4–15.4)	8.9 (5.6–11.8)	0.209	0.156	0.857
Load (N)	38 (28–60)	24 (18–38)	122 (58–188)	0.001	< 0.001	0.021
Energy (N•mm•degree)	7,579 (3,616–26,965)	5,476 (2,522–17,258)	44,438 (20,184–64,976)	0.001	< 0.001	0.219
Failure						
Angle (°)	13.1 (6.8–32.3)	13.9 (9.2–28.8)	17.7 (13.4–30.6)	0.214	0.401	0.660
Bending moment (N•mm)	170 (37–886)	299 (79–405)	1,849 (358–3,783)	0.001	0.001	1.000
Displacement (mm)	7.5 (3.9–22.1)	8.8 (5.0–19.8)	10.5 (6.9–21.3)	0.263	0.338	0.860
Load (N)	4 (–10–25)	8 (–10–25)	59 (10–118)	< 0.001	0.002	0.616
Energy (N•mm•degree)	3,261 (226–20,413)	1,969 (981–5,477)	6,937 (2,247–55,660)	0.089	0.052	0.774
Bending arm (mm)	34.0 (31.0–36.0)	33.0 (28.0–36.0)	32.5 (29.0–36.0)	0.830	0.902	0.921
Mandible length (mm)	64.0 (61.0–74.0)	65.0 (63.0–74.0)	63.5 (61.0–68.0)	0.542	0.217	0.502
Body weight (kg)	3.8 (3.0–4.1)	2.6 (1.9–3.7)	3.5 (1.9–4.1)	0.700	0.346	0.198
CSA (mm²)	49.7 (31.6–79.8)	47.4 (38.4–80.0)	42.4 (32.7–66.4)	0.565	0.350	0.682

An incomplete block design was used to assign the mandibles of each cadaver to 2 of the 3 groups. Within each cadaver, mandibles were randomly assigned to the assigned treatments. For mandibles assigned to the locking and nonlocking constructs, a simple transverse osteotomy was created caudal to the mandibular first molar tooth after plate application. All mandibles were loaded in cantilever bending in a single-load-to-failure test while simultaneously recording load and actuator displacement.

*Values of $P < 0.05$ were considered significant.

Body weight was available for 6 of the 10 cadavers, and the median body weight was 3.4 kg (range, 1.9 to 4.1 kg). Body weight was not significantly correlated with mandible length ($r = -0.539$; $P = 0.07$); however, there was a strong positive correlation between mandible length and CSA ($r = 0.827$; $P = 0.001$).

Mechanical variables

The only significant differences observed between the locking and nonlocking constructs involved variables associated with peak load (Table 1). Importantly, the locking construct was 1.5 times as strong and twice as stiff at peak loading, compared with the nonlocking construct **(Figure 6)**. Intact mandibles were significantly stiffer and stronger throughout cantilever bending than were the mandibles assigned to the locking and nonlocking constructs. Mandibles assigned to the locking and nonlocking constructs had first-yield stiffness and strength that were ≤ 49% and ≤ 40%, respectively, that for intact mandibles; second-yield stiffness and strength that were < 28% and < 24%, respectively, that for intact mandibles; and strength and energy at peak loading that were < 31% and < 24%, respectively, that for intact mandibles. The mean failure load for the mandibles assigned to the locking and nonlocking constructs was < 9% and < 16%, respectively, that for intact mandibles. Displacement values for mandibles in the locking and nonlocking constructs at all yield, peak, and failure points did not differ significantly from those for intact mandibles.
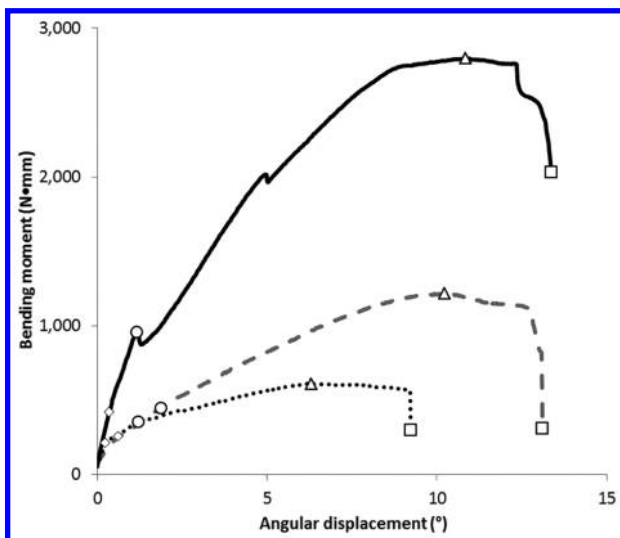

Figure 6—Representative bending moment–angular displacement curves that depict first yield (diamonds), second yield (circles), peak (triangles), and failure (squares) points for adult feline mandibles that were assigned to the locking construct (dashed line), nonlocking construct (dotted line), and intact (solid line) groups described in Figure 5. The peak bending moment (> 2,000 N•mm) for the intact group was not included in the statistical analysis because it was not consistent among all tests; however, the first and second yield points were consistent among all tests and were included in the statistical analysis. *See* Figure 5 for remainder of key.

Mode of failure

Five of the 6 intact mandibles failed because of bone fracture that began at the caudal aspect of the first molar tooth near the alveolar border and was propagated to the base of the condylar process adjacent to the PMMA fixture **(Figure 7)**. The remaining intact mandible failed because of bone fracture that began at the dorsal aspect of the mandibular body and was propagated directly to the ventral border at the level of the angle of the mandible. Six of the 7 mandibles assigned to the locking construct and all 7 mandibles assigned to the nonlocking construct failed because of bone fracture. The remaining mandible assigned to the locking construct failed because of screw pullout. The fractures were similar for both the locking and nonlocking constructs. All fractures were incomplete fractures that occurred adjacent to the 3 screws in the caudal mandibular fragment and coursed from the osteotomy surface longitudinally toward the angular process. The bone plate also bent at the level of the osteotomy gap for 2 mandibles assigned to the locking construct and 1 mandible assigned to the nonlocking construct.

Tooth root and mandibular canal damage attributable to plating method

One tooth root in the locking construct and 4 tooth roots in the nonlocking construct were damaged by screw placement **(Figure 8)**; however, the mean number of screw-induced tooth root injuries per mandible for the locking construct (0.14 ± 0.38) did not differ significantly ($P = 0.226$) from that for the nonlocking construct (0.57 ± 0.79). There were 20 and 18 instances of screw approximation or superimposition on the mandibular canal for the locking and nonlocking constructs, respectively. The mean ± SD number of screw superimpositions on the mandibular canal per mandible for the locking construct (2.86 ± 0.38) did not differ significantly ($P = 0.273$) from that for the nonlocking construct (2.57 ± 0.53).

Root length and root-ventral border length

Body weight was not significantly ($P = 0.934$) correlated with root-ventral border length ($r = -0.027$); however, there was a significant ($P = 0.003$) positive correlation ($r = 0.763$) between body weight and root length. Mandible length was significantly correlated with root length ($r = 0.518$; $P = 0.019$) and root-ventral border length ($r = 0.670$; $P = 0.001$). Cross-sectional area was strongly correlated with root-ventral border length ($r = 0.887$; $P < 0.001$) and was also significantly ($P = 0.041$) correlated with root length ($r = 0.461$).

Discussion

The present study was the first to evaluate the biomechanical properties of intact mandibles and internal fixation constructs for a simulated fracture of the caudal aspect of the mandible (caudal mandibular frac-
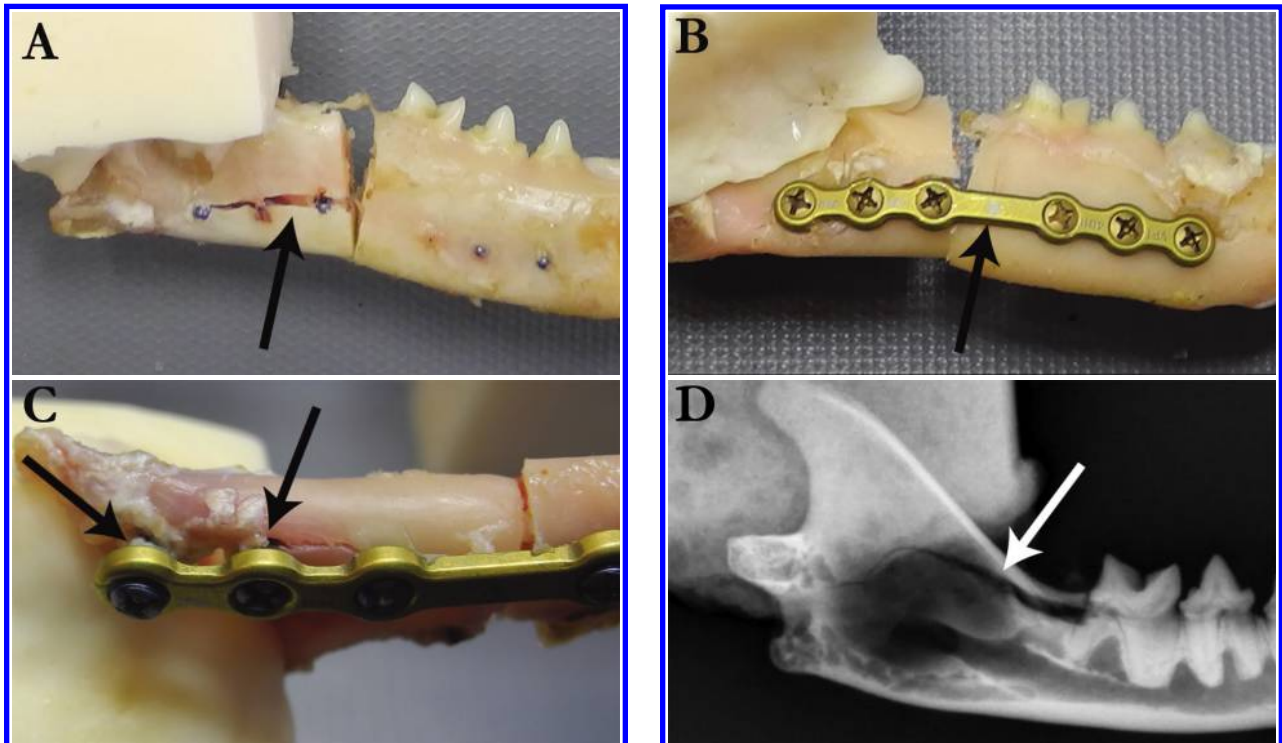
Figure 7—Representative photographs (A, B, and C) and lateral radiographic image (D) of adult feline mandibles assigned to the 3 treatment groups described in Figure 5 after biomechanical testing. A—Representative photograph of a plate-mandible construct that failed by the most common mode, incomplete bone fracture that began at the osteotomy and was propagated caudally adjacent to the screws in the caudal bone segment in a longitudinal direction toward the angular process (arrow). B—Photograph of a plate-mandibular construct that failed because of plate bending (arrow), which occurred for 2 mandibles assigned to the locking construct and 1 mandible assigned to the nonlocking construct. Notice the narrowing of the ventral aspect and widening of the dorsal aspect of the osteotomy gap for the mandibles in panels A and B. C—Photograph of the 1 mandible assigned to the locking construct that failed because of screw pullout (arrows) and incomplete bone fracture, which was not propagated to the osteotomy site. D—Lateral radiographic image of a mandible assigned to the intact group that failed because of an incomplete transverse fracture (arrow), which began at the alveolar margin caudal to the mandibular first molar tooth and was propagated toward the base of the condylar process adjacent to the PMMA fixture. ***See*** Figure 5 for remainder of key.
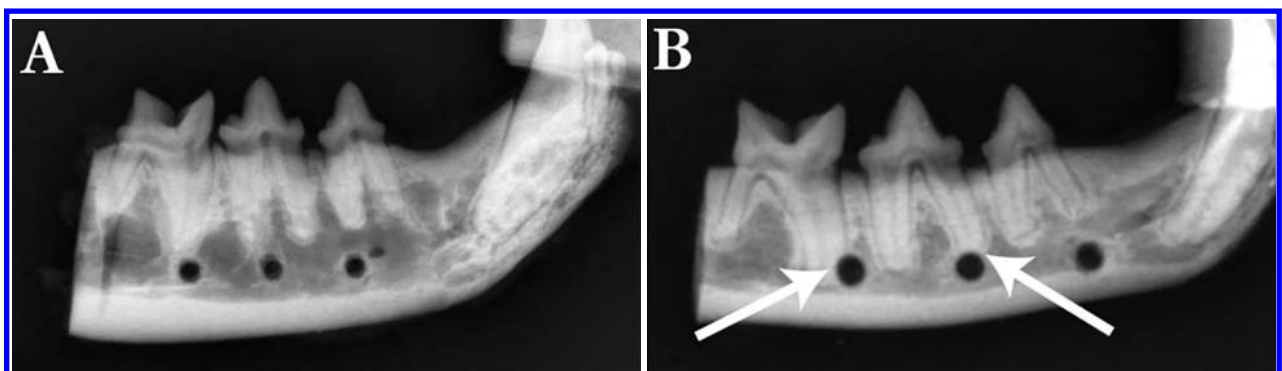

Figure 8—Representative lateral radiographic images of the rostral portion of 2 adult feline mandibles, each of which was assigned to either the locking or nonlocking construct described in Figure 5, after biomechanical testing and removal of the implants in which radiographic evidence of screw involvement with tooth roots was not (A) and was (B) present. Superimposition of screw holes with the roots (arrows; B) of the last premolar and first molar teeth was suggestive of screw involvement with those tooth roots. ***See*** Figure 5 for remainder of key.

ture) in cats. Results provided evidence-based information regarding which internal fixation construct (locking or nonlocking) best mimicked the biomechanical properties intrinsic to intact mandibles. Reconstructed mandibles were significantly weaker at yield, peak, and failure loads than intact mandibles regardless of construct (locking or nonlocking). The locking construct had significantly greater stiffness and withstood a stronger load at peak loading than the nonlocking construct. Additionally, radiographic evidence suggested that the space ventral to the mandibular first molar tooth was positively associated with mandibular length and CSA. Therefore, tooth root and mandibular canal damage by screws is an important consideration when internal

fixation is used for stabilization of caudal mandibular fractures in cats.

In the present study, locking constructs were mechanically stiffer and stronger than nonlocking constructs. Stiffness prior to peak loading for locking constructs was significantly greater than that for nonlocking constructs. Peak bending moment for locking constructs was also significantly greater than that for nonlocking constructs, most likely because the locking and nonlocking constructs were dependent on different fixation principles.[22-24] The fixed angle between the screws and the plate intrinsic to the locking construct allows for symmetrical loading of the lateral and medial cortices of the mandible, which resulted in improved biomechanical properties for mandibles assigned to the locking construct relative to those assigned to the nonlocking construct.[22,24]

For the mandibles of the present study, loading was applied to the canine and incisor teeth, which is not typical placement of major loading during mastication. Bending moment was compared among mandibles because it accounted for the bending moment arm of the load and the distance between the rostral and caudal PMMA blocks and provided a maximum limit to the amount of torque that the plate-mandible construct could resist before failure. In carnivores, most of the biting force is typically placed at the mandibular first molar and maxillary fourth premolar teeth.[25] Therefore, constructs in which those teeth were loaded in a physiologic manner may have been able to withstand a greater load than that observed in this study because the force would be applied with a shorter bending moment arm to the defect. This concept is consistent with models that predict, in cats, bite forces on the carnassial teeth (92.9 to 152.6 N) are greater than those on canine teeth (56 to 98 N).[26]

Ideally, physiologic bite force would be used to measure whether reconstructed mandibles can provide sufficient support for return to function. Unfortunately, scientific literature regarding in vivo bite forces in cats is lacking. Bite force models indicate that the maximum possible bite force at the canine teeth of cats ranges from 56.0 to 73.3 N.[26,27] Those values are consistent with the median load at failure (59 N) for intact mandibles in the present study. However, domestic cats would rarely be in situations that require maximum bite force because commercial cat food is considerably more amiable to mastication than what would be found in an undomesticated habitat.[28] The median peak loads withstood by the locking (38 N) and nonlocking (24 N) constructs of the present study were significantly less than the maximum bite force recorded for cats; however, in vitro testing of the constructs required stripping of all supporting soft tissues and removal of stabilization provided by the contralateral mandible through the mandibular symphysis. The findings of the present study were consistent with those of 2 case-series reports[11,12] in which use of miniplates for internal fixation of mandibular fractures in cats resulted in successful return to function for all cases.

Because of the complex material composition of the plate-mandible constructs and custom PMMA fixtures used in the present study, the bending moment–angular displacement curves derived from the data contained multiple yield points before peak loading was achieved, which is not typical for mechanical testing of homogeneous materials. Given that the curves for all failure tests had consistent shapes, data from the first and second yield points were used for pairwise comparisons between groups. During biomechanical testing, the intact mandibles had a tendency to yield at the PMMA-bone interface first, which was consistent with the first yield point. The second yield point for intact mandibles coincided with yielding of cortical bone prior to failure of the mandible. For locking and nonlocking constructs, the first yield point coincided with closure of the narrow osteotomy gap. The second yield point was consistent with yielding of the cortical bone longitudinal to the screw line in the caudal fracture fragment observed in the majority (13/14) of plate-mandible constructs. The slight variation in the mode of failure for the plate-mandible constructs can be explained by the torsional moment generated by the medial location of the mandibular body (incisor teeth) to the PMMA-embedded mandibular ramus, which was not controlled or measured in this study because it was only a minor vector of the applied load.

The mode of failure for the locking and nonlocking constructs of the present study indicated that there was a predilection for the mandible to fail before the plate or the plate-bone interface. In human patients with mandibular fractures, miniplates similar to those used in this study are occasionally installed in pairs with monocortical screws to avoid dental and neurovascular trauma.[29-32] The monocortical configuration of miniplates used in human patients most commonly fails at the plate-bone interface because only a single cortex is subjected to forces from the plate.[33] In dogs, like cats, miniplate systems are installed with screws long enough to engage both cortices of the mandible, which allows distribution of the forces from the plate over a greater amount of bone and provides greater resistance against torsional force between the plate and mandible.[9] Bicortical installation of screws increases the amount of force that can be applied to the construct before failure, and failure of the construct occurs most frequently within whichever part (plate or mandible) is weakest, a phenomenon that was apparent in both the present study that involved feline mandibles and another study[15] that involved canine mandibles.

Internal fixation of mandibular fractures in cats is possible by selection of the correct miniplate and screws and use of the proper technique.[9] Results of the present study indicated that there was a fairly safe region along the ventrolateral surface of the feline mandible that provides a suitable area to secure a

titanium miniplate. Unlike dogs, in which the width of the mandibular region suitable for miniplate application (ie, root-ventral border length) is significantly correlated with body weight,[34] the root-ventral border length was not significantly correlated with the body weight of the feline cadavers used in this study. Instead, in cats, the width of the mandibular region suitable for miniplate application was best correlated with the CSA of the mandible immediately caudal to the mandibular first molar tooth and was correlated to a lesser degree with the overall length of the mandible. The anatomic location of tooth roots and the mandibular canal is an important consideration when considering miniplate application to feline mandibles. In the present study, all mandibles assigned to the locking and nonlocking constructs had radiographic evidence of mandibular canal damage and some of those mandibles also had evidence of tooth root damage, although the incidence of tooth root damage was much less than the incidence of mandibular canal damage. The extent of radiographically evident dental trauma observed for the feline mandibles of the present study might overestimate the extent of true dental trauma induced by screw placement owing to radiographic parallax. Radiography has been reported to be a good tool to assess signs of screw damage to dental root structure, but the true extent of the damage can only be reliably ascertained histologically.[20,21] Screw-induced dental trauma is associated with infection or inflammation and can result in fixation failure and tooth loss[9,19,35]; therefore, it is imperative to minimize screw-root involvement during application of miniplates to the mandible. In human patients, titanium miniscrews can cause damage to the inferior alveolar nerve, which in most cases results in transient paresthesia or dysesthesia.[33,36] Given that, in cats, mandible body fractures are frequently the result of automobile trauma,[3] damage to the neurovascular bundle within the mandibular canal is highly likely. Therefore, presurgical planning involving dental radiography and CT can facilitate visualization of the fracture and anatomic configuration (ie, location of tooth roots and mandibular canal) of the mandible to help surgeons determine the optimal location for internal fixation placement.

Results of the present study indicated that stabilization of a simple transverse osteotomy of the caudal portion of the mandible in cats by use of a locking plate with locking screw (locking) construct was stronger at peak loading than stabilization with a locking plate and nonlocking screw (nonlocking) construct; however, both fixation constructs were weaker than intact mandibles. The incidence of radiographic evidence of dental trauma caused by screw involvement with tooth roots or the mandibular canal did not differ significantly between mandibles assigned to the locking and nonlocking constructs. There was a strong positive correlation between the CSA of the mandible and distance from the mesial mandibular molar tooth root to the ventral border of the mandible, which can be used during presurgical planning to minimize dental trauma. On the basis of those findings, we recommend that dental radiography and CT be used during presurgical planning to assist with selection of an appropriately sized miniplate for internal fixation of mandibular fractures in cats and that a locking configuration be used in preference to a nonlocking configuration owing to its superior biomechanical properties.

Acknowledgments

Footnotes

a. VPT4011.06, DePuy Orthopaedics Inc, West Chester, Pa.
b. VST202.008, DePuy Orthopaedics Inc, West Chester, Pa.
c. VST201.008, DePuy Orthopaedics Inc, West Chester, Pa.
d. Mark III, Sound-Eklin DR, Carlsbad, Calif.
e. Generator: HF100/30þ, MinXray Inc, Northbrook, Ill.
f. MTS Systems Corp, Eden Prairie, Minn.
g. Coe Tray Plastic, GC America Inc, Alsip, Ill.
h. Handycam DCR-SR47, Sony, Minato, Tokyo, Japan.
i. SAS version 9.4, SAS Institute Inc, Cary, NC.
j. Excel, Microsoft, Redmond, Wash.

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