Effect of the length of the superficial plate on bending stiffness, bending strength and strain distribution in stacked 2.0–2.7 veterinary cuttable plate constructs

An in vitro study

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Keywords
Veterinary cuttable plate, stacked plates, four-point bending, axial loading, strain gauge

Summary

Objectives: Use of stacked veterinary cuttable plates (VCP) increases the construct stiffness, but it also increases the stress protection and concentrates the stress at the extremities of the implants. We hypothesized that by shortening the superficial plate, it would not reduce the stiffness of the construct, but that it would reduce the stress concentration at the plate ends.

Methods: A 3 mm fracture gap model was created with copolymer acetal rods, stacked 2.0–2.7 VCP and 2.7 screws. The constructs consisted of an 11-hole VCP bottom plate and a 5-, 7-, 9- or 11-hole VCP superficial plate. Five of each construct were randomly tested for failure in four-point bending and axial loading. Stiffness, load at yield, and area under the curve until contact (AUC) were measured. Strains were recorded during elastic deformation for each configuration.

Results: During both testing methods, stiffness, load at yield and AUC progressively decreased when decreasing the length of the superficial plate. No statistically significant differences were obtained for load at yield in four-point bending and AUC in axial loading. The strain within the implant over the gap increased as the length of the superficial plate decreased.

Clinical significance: Shortening the superficial plate reduces the stiffness and strength of the construct, and decreases stress concentration at the implants ends. As the cross section of the implant covering the gap remained constant, friction between the plates may play a role in the mechanical properties of stacked VCP.

Introduction

Veterinary cuttable plates (VCP) are commonly used for fracture repair or arthrodesis in small dogs and cats (1–5). They are manufactured as a 300 mm long, 50-hole implant. Two sizes of VCP exist: a 1.5/2.0 mm and a 2.0/2.7 mm. These are differentiated by their thickness and the diameter of the screw hole in the plate. The 2.0/2.7 VCP and the 1.5/2.0 VCP are 1.5 mm and 1 mm thick, respectively (6, 7). The mechanical properties of VCP have been previously studied (2). Because of the increased number of holes and their reduced thickness, their stiffness and strength are often decreased when compared to implants utilizing similar screw sizes, and it has been recommended that a single VCP not be used when the bone column cannot be reconstructed: in this situation, a stiffer construct is required (2, 3, 8). Two VCP may be stacked to increase the stiffness, strength and fatigue life of the construct when compared to using a single plate (2, 9, 10).

Stacking two VCP of the same length may result in a bulky construct and may cause soft tissue morbidity. In our hospital, it is current practice to shorten by 1 or 2 holes the distal extremity of the superficial plate when using stacked plates. The use of a superficial plate shorter than the bottom plate has been described (3).
Use of an implant that is too rigid causes stress shielding or stress protection of the bridged bone and stress concentration at the metal to bone interface at the ends of the construct (8, 11). Clinical consequences are osteopenia, delayed healing, screw pull-out and implant related fractures (8, 12–14).

Bone surrogates have been preferred for use in in vitro studies as they reduce the typically high variability inherent with the use of cadaveric bones (15–25). Even though they do not reproduce the irregular shape, the anisotropy or the non-homogeneity of the bone, they have proven adequate for studying the mechanical properties of orthopaedic implants (16).

Axial loading, three-point bending, four-point bending and the cantilever test have been utilized to evaluate the properties of orthopaedic implants (26). In many long bones, physiologic load produces bending (27). Axial loading is of interest since it represents the main load on the long bones during physiologic weight bearing (15). For this reason, axial loading is commonly used to characterize strength, stiffness or fatigue of the implants (9, 10, 17, 19, 20, 25). Four-point bending produces a homogenous bending moment throughout the area between the inner actuators and is commonly used for in vitro implant testing (28, 29).

Our objective was to describe the mechanical consequences of shortening the superficial plate in stacked VCP constructs. Our null hypotheses were that in a fracture gap model, shortening the superficial plate would not affect the stiffness nor the strength of the construct during axial loading or four-point bending as long as the superficial plate is secured by a minimum of two screws on each side of the fracture gap. We also hypothesized that shortening the superficial plate would decrease the stiffness of the ends of the implants and thus would reduce the stress concentration at the implant ends by providing a more progressive transition of strain along the implant. To test these two hypotheses, stiffness and strength were measured using acetal rods and VCP. Strain was measured at six sites and compared between constructs during elastic deformation.

Materials and methods

A fracture gap model was created utilizing 13 mm diameter acetal rods. The rods were processed in a high precision machining system to obtain similar 85 mm long rods with five pre-drilled 2.0 mm screw holes (Fig. 1). The centre of the first screw hole was located 4.5 mm away from the end of the rod to ensure a consistent 3 mm gap after the plates were mounted. A 3 mm fracture gap model was created by assembling two identical rods with one 11-hole 2.0/2.7 VCP centred on the gap with one open screw hole. A 5-, 7-, 9- or 11-hole 2.0/2.7 VCP was used as the superficial plate resulting in 11/5, 11/7, 11/9 and 11/11 constructs (Fig. 2). All constructs were assembled with ten 2.7 mm screws following AO principles resulting in a consistent 3 mm fracture gap. All screws were tightened to 1.5 Nm torque.

Mechanical testing

The study was divided into two phases: 1) mechanical testing to failure and 2) strain measurement during cyclic elastic deformation. Each phase was performed in four-point bending and in axial loading in a materials testing system equipped with a 50 kN load cell. Custom jigs were manufactured for each testing method to allow free motion of the tested constructs except in the direction in which the load was applied. Data were recorded by a dedicated computer at 120 Hz using data acquisition software. The speed of the crosshead was set at a constant displacement rate of 10 mm/min for all tests.

Mechanical testing to failure

For all tests, complete mechanical failure was defined as the time when the two rods

Fig. 1 Acetron GP rod after machining: A concavity was milled into the extremity opposite to the fracture site to accommodate the ball bearing of the compression jig, and the last 35 mm of the cylindrical rods were flattened in order to maintain orientation and ensure stability during four-point bending. A) View from the side, B) from the top and C) oblique showing the rounded cavity at the extremity of the rod (arrow).

Fig. 2 Complete construct: view from the side of an 11-hole Veterinary Cuttable plate (VCP) stacked with a similar 11-hole VCP (fully stacked configuration).
on either side of the fracture gap came into contact, resulting in a complete closure of the fracture gap (Fig. 3).

The tests were performed in a randomized order. Five constructs of each plate configuration were tested in each method. Implants and rods were discarded after each test.

For four-point bending testing, an aluminium jig was designed. An aiming device was used to ensure the fracture gap was centred between the actuators of the jig. The distance between the internal loading and support rollers was 102 mm; the distance between the external loading supports was 165 mm (Fig. 4). The bending moment was calculated as the load multiplied by the difference in distance between the actuators (63 mm) divided by four (Appendix 1 - Available online at www.vcot-online.com).

For axial loading testing, the constructs were mounted between two metallic balls to allow freedom of rotation during compression (Fig. 5).

Strain measurement

Six basic constructs (two rods, ten screws and only one bottom plate) were equipped with six 120 ohms monoaxial strain gauges (fully encapsulated, self-temperature-compensated and pre-wired) as described in Figures 6 and 7. These points were of...
interest because they were the point of suspected weakness of the construct (gauge 1); at the level adjacent to the screws, where the contact between the plate and the rod is expected to be maximum (gauges 2, 3 and 4); where the plate construct ends representing the region stress concentration (gauge 5); and remote from the implants to evaluate a section of the surrogate that is not covered (gauge 6). Strain data were amplified by a dedicated amplifier set in a ¼ Wheatstone bridge configuration and recorded by a computer at 120 Hz using data acquisition software. Each equipped basic construct was tested with each superficial plate size (5, 7, 9 and 11 holes) in four-point bending and axial loading, with the same jigs as previously described. The screws were carefully removed, replaced and tightened to 1.5 Nm as required to change the superficial plates between measurements. For the tests performed during axial loading, strains were recorded at a constant load of 130 N during six consecutive cycles of loading performed in the range of elastic deformation. During four-point bending testing, strains were recorded at a constant load of 3.78 Nm during six consecutive cycles of loading performed in the range of elastic deformation. Data acquired during testing to failure were used to determine these loads. The order of measurement was randomized.

Data evaluation

Load displacement curves were obtained for each test. The elastic portion of every curve was determined and a linear regression equation was fitted using commercially available software. The stiffness of the construct was retrieved from the angular coefficient of this curve. The yield point was defined as the point of intersection between the load displacement curve and a two percent offset line. The moment or load at the yield point was obtained graphically and represented the energy the construct could store before the two rods came into contact with each other; this was also known as ‘work to failure’.

Strain gauge data were acquired from the six cycles. Data from the two initial cycles were discarded. The average strain was calculated for each test as the average of the recording for the four remaining cycles. In order to provide a standardized point for comparison and to illustrate the magnitude of the changes, the expected strain during four-point bending at the location where the strain gauges were placed was calculated for a similar rod with no fracture and no implant applied (Appendix 2 - Available online at www.vcot-online.com). Calculation was based on the assumption that acetal behaves as a linear material according to Hooke’s law whereby stress and strain are linearly related throughout the elastic phase and the 13 mm diameter acetal rod was homogenous. Material property data were provided by the published standards.

Statistical analyses

For the mechanical tests to failure, the different configurations were compared for stiffness, load at yield, and work to failure with an analysis of variance for a completely randomized design. Strain data were analyzed with an analysis of variance blocking on constructs (randomized block design), as each basic construct was utilized in the four configurations. A Shapiro Wilk test and examination of the residuals after running the models determined whether the data met the assumptions of normality. A log transformation of the parameters was performed if required. If the overall f test was significant for the main effect of configuration, a post hoc Tukey test was applied. All statistical analyses were performed with commercially available software. The level for significance was set at $\alpha = 0.05$.

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Appendix 2 - Available at: www.matweb.com

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h MEPTS-9000S Multichannel Universal Signal Conditioning Amplifier: Techkor Instrumentation, Middletown, PA, USA

i Microsoft Office Excel 2003: Microsoft Corp., Redmond, WA, USA

k 2007 SAS OnlineDoc® 9.2: SAS Institute Inc., Cary, NC, USA
Table 1 Descriptive statistics of the measurements recorded during testing to failure in four-point bending. Data are presented as a mean ± standard deviation for each configuration (11-hole VCP stacked with a 5-, 7-, 9- or 11-hole VCP). Within each row of the table, mean values that share the same superscript lower case letter are significantly different (a to d).

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<td>1.468 ± 0.019cd</td>
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<td>Moment at yield</td>
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<td>point (Nm)</td>
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<td>6.05 ± 0.685</td>
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<tr>
<td>Work to failure</td>
<td>926 ± 69.3abc</td>
<td>943 ± 78.5cd</td>
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<tr>
<td>(Jm)</td>
<td>1172 ± 120.7bd</td>
<td>1098 ± 40.7ac</td>
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Fig. 8 Measured stiffness, moment at yield and (energy) stored by the construct before contact of the two rods (work to failure) for each configuration during four-point bending testing. Results are represented as a percentage of the value obtained with the fully stacked construct (11-hole Veterinary Cuttable Plate [VCP] stack with a similar 11-hole VCP). Significant differences between values and the measurement obtained for the fully stacked construct are represented for stiffness (a) and work to failure (b). No statistically significant differences were obtained for moment at yield.

Results

All the constructs tested in failure failed by plastic deformation of the two VCP at the level of the open screw hole (Fig. 3).

Tests to failure in four-point bending

The results are presented in Table 1 and are summarized in the following paragraph. The stiffness of the constructs, the moment at yield point, and the energy stored by the constructs decreased as the superficial plate was shortened (Fig. 8).

A significant decrease in stiffness was obtained when the superficial plate was reduced from 11 to seven holes (p < 0.001), or from 11 to five holes (p < 0.001). This represented a 4.1% and an 8.1% decrease in stiffness, respectively. A significant decrease in stiffness was obtained when the superficial plate was reduced from 9 to five holes (p < 0.001).

No significant differences were obtained between the four constructs for the moment at yield point of the constructs (p = 0.31).

A significant decrease in work to failure was obtained when the superficial plate was reduced from 11 to seven holes (p = 0.0013) or from 11 to five holes (p = 0.0005). This represented a 20% and a 21% decrease in work to failure, respectively.

No statistically significant difference was obtained when the superficial plate was reduced from 11 to nine holes for the stiffness (p = 0.45), the moment at yield point, and the work to failure (p = 0.18).

Tests to failure in axial loading

The results are presented in Table 2 and are summarized in the following paragraphs. The stiffness, the load at yield point, and the work to failure decreased as the superficial plate was shortened (Fig. 9).

A significant decrease in stiffness was obtained when the superficial plate was reduced from 11 to nine holes (p = 0.008), from 11 to seven holes (p < 0.001) and from 11 to five holes (p < 0.001). This represented a 14.5%, 24.4% and a 32.6% decrease in stiffness, respectively.

A significant decrease in load at yield point was obtained when the superficial plate was reduced from 11 to nine holes (p = 0.006), from 11 to seven holes (p < 0.001) and from 11 to five holes (p < 0.001). This represented a 5.2%, an 11.7% and a 16.0% decrease in load, respectively. No statistical difference in load at yield point was obtained when a 5-hole plate was used compared to a 7-hole plate (p = 0.16).

No significant difference in work to failure (p = 0.2596) was obtained when the superficial plate was shortened from 11 to nine, seven or five holes. However, work to failure decreased by 13%, 25% and 36% when the length of the superficial plate was decreased from 11 to nine, seven, and five holes, respectively.

Strain measurement

Due to different material properties, the results recorded on the plate at the fracture gap (Fig. 10) are presented separately from the results recorded on the rod by the five other strain gauges (Fig. 11 and 12).

Interpretation of the curves (Fig. 7, 8 and 9) revealed that four-point bending produced compression at the level of gauge 1, on the underside of the plate at the gap level, and tension on the rod (gages 3 to 6). At the level of gauge 2, either a low magnitude compression or tension was recorded, depending on the length of the superficial plate. During axial loading, compression was recorded at the level of gauges 1, 2, 5 and 6, and tension was recorded at the level of gauges 3 and 4.
**Strain at the gap (Fig. 10)**

During four-point bending, the strain significantly increased when the superficial plate was shortened (p = 0.0043). A statistically significant difference was obtained when the superficial plate was shortened from 11 to five holes (p = 0.0064) or from nine to five holes (p = 0.0124). This represented a 26.5% and a 19.5% increase in compression, respectively.

During axial loading, a similar result was obtained (p = 0.0002). A statistically significant difference was obtained when the superficial plate was shortened from 11 to seven holes (p = 0.0054), from 11 to five holes (p = 0.0001), or from nine to five holes (p = 0.0240). This represented a 387%, a 59.8% and a 25.6% increase in compression, respectively.

**Rod strain during four-point bending (Fig. 11)**

A low strain with a large variability was obtained for the data acquired at gauge 2. Because of this variability, the results of the statistical analysis are not presented.

A significant increase in tension on the rod at gauge 3 was obtained when the superficial plate was reduced from 11 to five holes (p = 0.0083) or from 11 to nine holes (p = 0.0090). This represented a 7.2% and a 7.6% decrease, respectively.

A significant decrease in tension on the rod at gauge 5 was obtained when the superficial plate was reduced from 11 to five holes (p = 0.0083) or from 11 to nine holes (p = 0.0090). This represented a 387% and a 372% increase, respectively.

A significant increase in tension on the rod at gauge 3 was obtained when the superficial plate was reduced from 11 to seven holes (p = 0.0001), and from 11 to five holes (p = 0.0001). This represented a 100.5% and a 213% increase, respectively.

No significant difference in strain was found for the strain at gauge 2 (p = 0.5026), or at gauge 6 (p = 0.0618) when the different constructs were compared.

The expected strain during four-point bending was calculated to be 2480 μm strains (tensile deformation) when a 3.78 Nm load was applied. Strains higher than the calculated expected strain were obtained on the rod at the implant ends during four-point bending. Strains lower than the expected strain were obtained on the rod on the section covered by the plate (strain gauges 2 and 3).

**Rod strain during axial loading (Fig. 12)**

A significant increase in tension on the rod at gauge 3 was obtained when the superficial plate was reduced from 11 to seven holes (p = 0.0301), and from 11 to five holes (p = 0.0001). This represented a 100.5% and a 213% increase, respectively. A significant increase in tension at gauge 3 was also obtained when the superficial plate was reduced from nine to five holes (p = 0.0005), and from seven to five holes (p = 0.0175).

A significant decrease in tension on the rod at gauge 5 was obtained when the superficial plate was reduced from 11 to nine holes (p = 0.0053), seven holes (p = 0.0044) or five holes (p = 0.0006). This represented a 68.0%, a 69.6% and an 81.9% decrease, respectively.

No significant difference in strain was found for the strain at gauge 2 (p = 0.5026), at gauge 4 (p = 0.0620), or at gauge 6 (p = 0.0547) when the different constructs were compared.

**Discussion**

The cross section of the implants over the fracture gap remained constant between the different constructs, and the two plates were secured by at least two screws on each side of the fracture. The first null hypothesis that shortening the superficial plate would not affect the stiffness or the strength of the construct during either four-point bending or axial loading was not verified in this study. Shortening the superficial plate caused a reduction in stiffness, moment at yield, and work to failure.

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**Table 2**

Descriptive statistics of the measurements recorded during testing to failure in axial loading.

Data are presented as a mean ± standard deviation. Within each row of the table, mean values that share the same superscript lower case letter are significantly different (a to d).

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<th>Partially stacked</th>
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<td>11 - 7</td>
</tr>
<tr>
<td>Stiffness (N/mm)</td>
<td>435 ± 34.2ab</td>
<td>481 ± 46.7c</td>
</tr>
<tr>
<td>Load at yield point (N)</td>
<td>155.6 ± 1.3ab</td>
<td>163.6 ± 4.0c</td>
</tr>
<tr>
<td>Work to failure (J)</td>
<td>0.1434 ± 0.0536</td>
<td>0.1674 ± 0.0402</td>
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**Fig. 9**

Measured stiffness, moment at yield and (energy stored) by the construct before contact of the two rods (work to failure) for each configuration during axial loading testing. Results are represented as a percentage of the value obtained with the fully stacked construct (11-hole Veterinary Cuttable plate [VCP] stacked with a similar 11-hole VCP). Significant differences between values and the measurement obtained for the fully stacked construct are represented for stiffness (a) and load at yield (b). No statistically significant differences were obtained for work to failure.
432 S. Bichot et al.: Properties of stacked veterinary cuttable plate constructs

We propose that the difference between two stacked plates and one plate of similar thickness is explained by the likelihood that stacked plates can slide over each other. The force that limits the gliding between the plates is friction between the two stainless steel surfaces. This would suggest that when the length of the superficial plate is increased, friction between the plates increases, resulting in a stiffer and stronger construct.

Rose and colleagues, studied the fatigue life of single, partially stacked and fully stacked VCP in a gap model during axial loading (9). They concluded there were no differences in stiffness between the fully stacked and the partially stacked constructs as long as the superficial plate was covering two screw holes on each fragment. In their model, the bottom plate was attached to the distal fragment with only two screws, so the friction between the two plates distally to the fracture gap remained similar in the fully stacked and the partially stacked constructs, even if the total length of the superficial plate was increased. Our results suggest that their recommendation to stack two holes on each side is based on their particular configuration of the implant relative to the fracture gap (two screws on the distal fragment) and not directly on the mechanical properties of the stacked plates.

Our second hypothesis was that shortening the superficial plate would reduce the stress concentration at the implant ends by more evenly distributing the strain along the implant-bone interface. This hypothesis was verified both during four-point bending and axial loading. The bending of the constructs submitted to axial loading should have created a degree of tensile stress on the convex side of the structure (26). Our data showed that this predicted tensile stress was partially compensated for by the axial compression during axial loading, mainly at the first screw hole (gauge 2) and at the end of the plate (gauges 5 and 6). This finding highlights an important difference between the two methods of testing used in this study.

During four-point bending, the highest strains in the rods were measured at the ends of the implants. As we cannot assume our constructs behave as a structure made with a linear material as defined by Hooke’s
law, stress cannot be calculated from strain. However, even if the relationship is not established, stress in the rod would be expected to increase as strain does. Thus, the results we reported showed stress concentration in the bone surrogate at the ends of the implants (8, 31).

As a load of 130 N is thought to represent the axial force applied on the thoracic limb of a 10 kg dog when trotting, the load used in our study in axial loading is clinically relevant (32). Stress protection of bone undergoing healing after internal fracture fixation is thought to be caused by the excessive stiffness of the implants, particularly in static loading at the ends of implants (33). Our study showed the presence of the implants could reduce the strain on the portions of the rods spanning during axial loading at a physiologic load. Our results also showed that the use of a fully stacked 11/9 construct, or a partially stacked superficial plate influenced the stiffness, the construct using three screws on each side of the fracture model. The strain recorded on the rods and the 11-hole construct, reduced the strain in the surrogate between the second and the fourth screw holes at a level lower or similar to that which would be recorded in an intact surrogate in four-point bending. When the magnitude of the stress protection is severe enough, osteopenia develops or gain in strength of the healing bone is slowed down (11, 13, 14). To our knowledge, the knowledge necessary to avoid osteopenia is not known.

We noticed little strain protection in our study during four-point bending testing with the shorter superficial plates. The magnitude of the moment was determined by the testing to failure and the clinical significance of the magnitude utilized during four-point bending is not known.

A decrease in stiffness by 10% and 15% was noted when the shortest superficial plate was used during four-point bending and during axial loading, respectively. Based on the study by Fruchter and Holmberg using two screws on each side of the fracture model, the stiffness of two stacked 2.0–2.7 VCP was about twice the stiffness of a single 2.0–2.7 VCP (2). Thus, even if its stiffness represented 67 to 90% of the stiffness of the fully stacked construct as measured in our study, the construct using the shortest superficial plate should still have a greater stiffness than a single VCP. The advantage of a short stacked plate over the single plate has been shown for stiffness and fatigue life by Rose and colleagues (9).

Limitations in clinical application of the results of this study are due to the use of a model. The strain recorded on the rods and the plate would have been different due to different material and geometrical properties of the bone, including the different coefficient of friction (0.25 dry versus steel for the Acetron GP® compared to 0.42 for bone versus steel) and the different stiffness (34). On the other hand, the bending stiffness of the rods (0.37 MPa*m²) is consistent with the bending stiffness reported for cat femurs (0.19 MPa*m²), and the compressive strength of the rods (103 MPa) is similar to the one reported for cat femurs (110.6 MPa) (35).

As reported by other investigators, another limitation is the high incremental friction between the screws and the substitute (8). Even if the screw holes were tapped before screw insertion, this resistance may have limited the compression of the plates against each other or against the bone surrogate.

This study showed that the length of the superficial plate influences the stiffness, the strength, and the stress concentration on the bone substitute surface close to the end of the implants in stacked VCP constructs. Use of a partially stacked construct may be considered to be an option between a single VCP and a fully stacked construct when looking for intermediate stiffness or to decrease stress concentration at implant ends. The results of our study indicate that a reduction of stiffness of more than 10% will occur if the superficial plate is reduced by more than 1 hole at each end. If, however, decreasing stress concentration at the ends of the implants is the goal, a short superficial plate attached by two screws on each side of the fracture may be used.

Acknowledgements
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Conflict of interest
Except in-kind donation of the implants, none of the authors of this paper has a financial or personal relationship with other people or organizations that could inappropriately influence or bias the content of the paper.

References