Knot Security- How is it Affected by Suture Technique, Material, Size, and Number of Throws?

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Purpose: To measure knot security in relation to different surgical knotting techniques, suture materials, suture sizes, and number of throws commonly used in oral and maxillofacial surgery.

Materials and Methods: Three surgical tying techniques were tested: square, surgeon's, and sliding knots. Suture materials included chromic gut, nylon, silk, and Vicryl (polyglycolic acid). Suture diameter sizes 3-0, 4-0, and 5-0 were tested. Ten trials were undertaken for each combination of material, size, and technique using 2, 3, 4, 5, and 6 throws (ties). Suture materials were presoaked in 0.9% saline solution for 15 minutes to simulate the environment of the oral cavity. A standard knot-tying force for each throw was applied to each combination. Knot security satisfaction was set from pilot experimental trials at less than 1.8-mm slippage from the center of the knot while testing. The dichotomous outcome of knot slippage (stable or unstable) was analyzed using logistic regression analysis and odds ratios with Tukey-adjusted 95% confidence intervals.

Results: Knot security depended on suture technique, material, and number of throws but did not depend on suture size. In general, 4 throws were required for surgeon's and square knots, whereas 5 throws were required for sliding knots. After 5 throws, tying an additional throw did not contribute to knot security. Surgeon's knots were stronger than square knots and sliding knots ($P < .0001$ and $P < .0001$). Square knots were stronger than sliding knots ($P = .01$). Vicryl had the greatest knot security, followed by chromic gut, nylon, and silk.

Conclusion: This study showed that knot security depends on suture material, tying technique, and number of throws, but is independent of suture size. Surgeon's knot security was greater than that for square and sliding knots when using sutures commonly used in the oral cavity. Vicryl had the greatest knot security and silk had the least. For surgeon's and square knots, at least 4 throws were generally indicated to achieve knot security; for sliding knots, at least 5 throws were generally indicated. Knot security did not increase after 5 throws and 2 throws are never indicated.

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Knot security, defined as the ability of a knot to resist slippage and breakage as load is applied, is a critical factor in maintaining the integrity of a tied suture,[1] because the knot is always the weakest link in a surgical seal.[2,3] Knot failure can result in a wound reopening, thus affecting the success of the surgical result. Although

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knot security is established as an important factor in suturing, it has been poorly studied in the literature, especially in relation to tying techniques, materials, and sizes commonly used in the oral cavity. Many surgeons use a commonly accepted anecdotal number of ties (throws) that varies among surgeons and training programs, but is not based on complete scientific data.[4] It has been stated that tying with too few throws can result in knot failure, whereas using more knots than required offers no mechanical advantage and represents more foreign bodies in the wound that damage host defenses and resistance to infection.[2] Therefore, it is important to have a working knowledge of the minimum number of throws for knotting.

Previous studies have investigated knot security based on suture techniques and properties, with varying results. Certain studies have found that sliding knots do not perform as well as square or surgeon's knots, whereas others have found sliding knots to be equally or more effective than surgeon's knots.[1,5,6] In addition, some studies have found no difference in knot security based on suture material, whereas others have determined that suture material does indeed affect knot security.[7,8] Some studies have concluded there is no difference in knot security between square and surgeon's knots, although surgeon's knots require an additional cross at the base.[5,9]

A review of the literature indicates that the study of knot security and its relation to surgical techniques and suture materials has been performed mostly in general, obstetric, orthopedic, and veterinary surgery. A scarcity of research is noted in oral and maxillofacial surgery.

Oral and maxillofacial surgery has unique properties compared with other specialties, including a wet environment and smaller suture materials and sizes. Therefore, it is necessary to undertake a study to establish guidelines to evaluate knot security in oral and maxillofacial surgery, rather than relying on results gleaned from research more relevant to other fields. This study was designed to compare knot security among different knotting techniques, suture materials, and suture sizes that are commonly used in oral and maxillofacial surgery.

The purpose of this study was to compare knot security of sutures based on their material, size, and tying technique. Based on previous literature in other specialties, the authors hypothesized that knot security would depend on suture technique, but would not depend on suture material or size. The specific aims of this study were to create performance tables outlining the proportion of secure knots for each combination of suture material, size, and tying technique commonly used in the oral cavity and to compare which variables have an effect on knot security and which variables do not.

Materials and Methods

ETHICAL CONSIDERATIONS

The study was not subject to the University of Connecticut Health Center (Farmington, CT) institutional review board because no live subjects were being studied.

STUDY DESIGN AND SAMPLE

To address the research question, the authors designed and implemented a cross-sectional study. The sample was composed of surgical knots tied using a mechanical knotting machine (described below).

STUDY VARIABLES

The set of predictor variables was composed of suture material, suture thickness (size), tying technique, and number of throws. The first variable, suture materials, included 4 types of suture material: chromic gut (absorbable), Vicryl (absorbable), silk (nonabsorbable), and nylon (nonabsorbable). The second variable, suture thickness, included 3 suture sizes: USP-designated 3-0, 4-0, and 5-0. The third variable, tying technique, included 3 types of knotting techniques: sliding knot, square knot, and surgeon's knot (Figs 1-3).[10,11] The sliding knot technique was derived from the method outlined by Trimbos et al,[10] in which the 2 sides of the suture are not crossed for each throw and forces are not distributed evenly. The square and surgeon's knot methods were derived from the method outlined by Brown,[11] in which the 2 sides of the suture are crossed. The base (first throw) of a surgeon's knot is crossed twice, whereas the base of a square knot is tied once. The final variable, number of throws, included 2, 3, 4, 5, and 6 throws. The materials, sizes, and techniques tested were chosen because they are commonly used to achieve wound closure in the oral cavity.

OUTCOME VARIABLE

The primary outcome variable was knot slippage. It was defined as a binary variable, stable ($\leq$1.8 mm of slippage) or unstable (>1.8 mm of slippage). Slippage was measured by the change in end-to-end length of the suture after applying a standard force and adjusting for intrinsic laxity (described below).

TESTING MODEL

All measurements were taken with calipers to increase precision. Before the trials were conducted, a testing apparatus was designed that allowed a hemostat to be secured to one side with a force gauge secured to the other (Figs 4, 5). Ten attending oral and maxillofacial surgeons and residents affiliated with the University of Connecticut were asked to

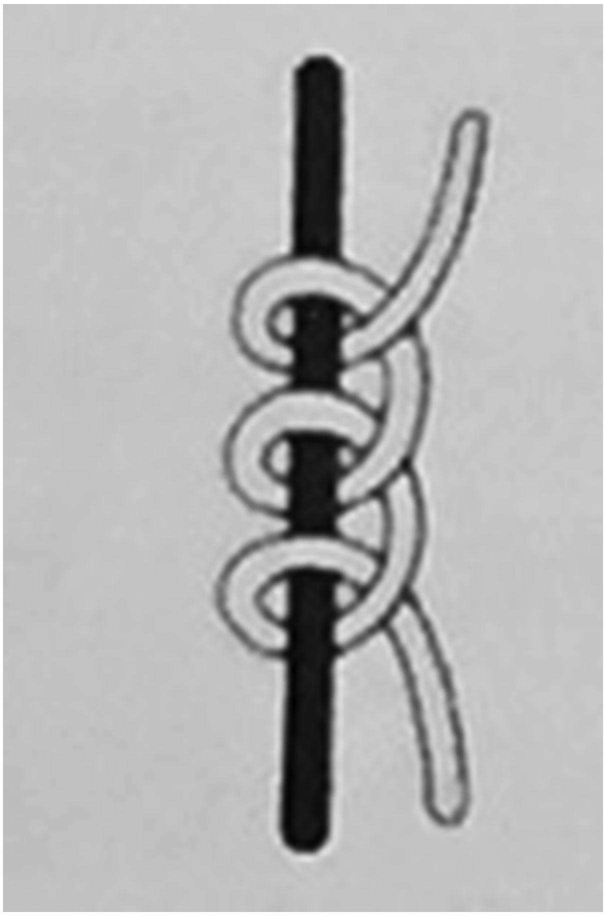

FIGURE 1. Sliding knot.[10]

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pull the force gauge with the amount of estimated force they use when tying off a suture. The average force of 1 lb (4.44 N), was recorded and used as the force to tie off each throw. Combinations of suture material, size, and technique that broke before 1 lb of force could be applied were tied off with their maximum possible tying force.

Intrinsic laxity, a property unique to each suture material and size, was defined as the change in end-to-end distance when applying a given force to an untied suture. Before each trial, intrinsic laxity was

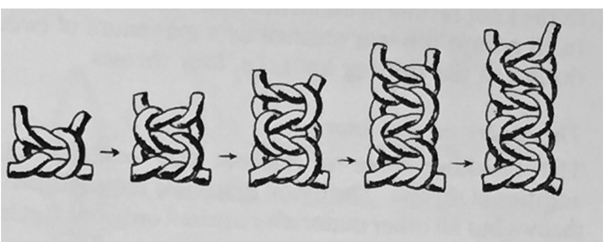

FIGURE 2. Square knot.[11]

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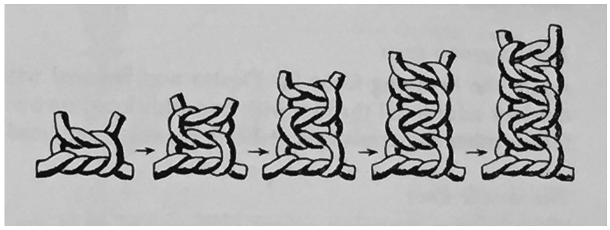

FIGURE 3. Surgeon's knot.[11]

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determined for each combination of suture material and size by taking the average of 10 trials using the testing apparatus. Each suture was placed in 0.9% saline solution at 37°C for 15 minutes before testing to simulate the oral environment. The testing apparatus was used with a 3-mm tail between hemostats. Sutures were pulled with the maximum applicable force (limit, 2 lb; 8.9 N; Fig 6). Sutures were not reused.

The suture preparation for the knot slippage trials was the same as for the intrinsic laxity trials. When the suture was taken out of the saline, the knot was tied on a sponge soaked in saline fluid to prevent drying. The suture was clamped to the hemostats in the same manner as for the intrinsic laxity test and a 3-mm tail was left on each side of the knot, for a total end-to-end length of 6 mm (Fig 5). Knots were pulled at the maximum applicable force (limit, 2 lb; 8.89 N). Ten trials were conducted for each combination of material, size, tying technique, and number of throws, for 1,800 trials. Sutures were not reused. Knot slippage was measured by a change in end-to-end length of the suture while subtracting out intrinsic laxity.

DATA ANALYSIS

For each combination of these 4 variables, the proportion of secure knots was summarized and reported. To better understand their association with knot security, logistic regression was used to regress the dichotomous outcome of knot slippage (stable vs unstable) against knotting technique, suture material, material size, and number of throws as predictor variables. All experiments with 2 throws failed and were not included in the model. If a predictor was significant ($P < .05$) in the model, then pairwise comparisons were made using the Tukey procedure to control the experiment-wise type I error rate. Odds ratios and Tukey-adjusted 95% confidence intervals for these pairwise comparisons were calculated from the model, controlling for other factors. All statistical analyses were performed using SAS 9.4 (SAS Institute, Cary, NC) and a 2-sided α level of significance of 0.05 was used for all tests.

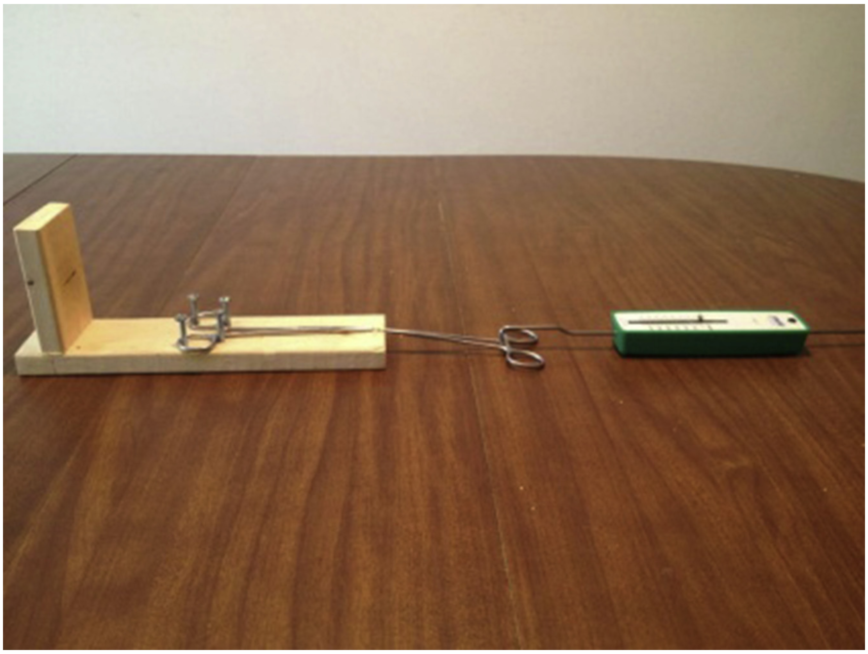

FIGURE 4. Testing apparatus with hemostat secured to one side and the other hemostat secured to a force gauge. The suture is clipped between the 2 hemostats.

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Results

Data were collected for each trial by measuring how much slippage occurred. Knot security was achieved if the end-to-end change was less than a predetermined length of 1.8 mm of slippage. This number was determined by pretest trials before actual data collection. A table was built to visualize the proportion of secure knots for each combination of suture material, size, technique, and number of throws (Table 1). Using 90% security as a threshold, it is evident that in general at least 4 throws are suggested for different

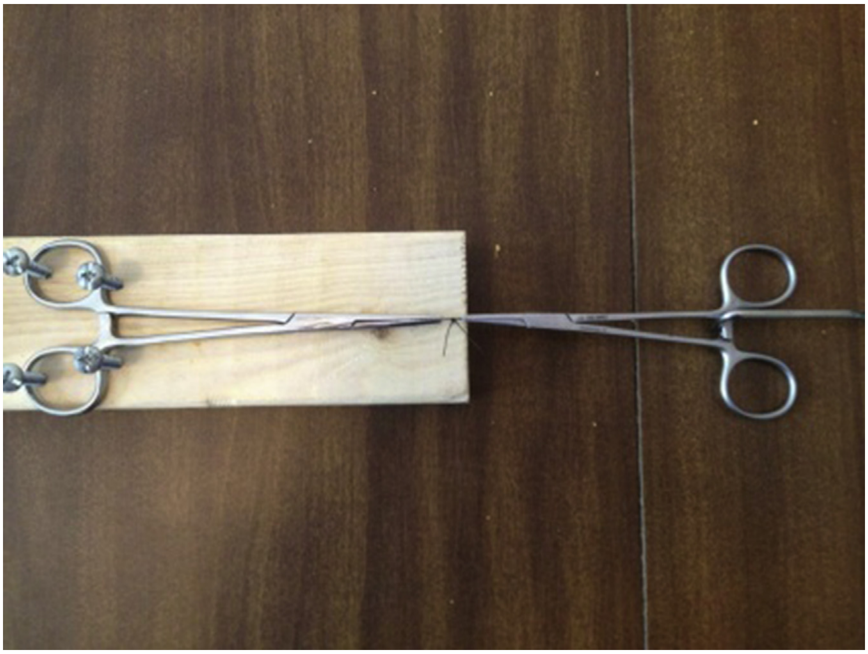

FIGURE 5. Overhead view of hemostats clipped to the 2 sides of the suture, with the testing apparatus on the left and the force gauge on the right.

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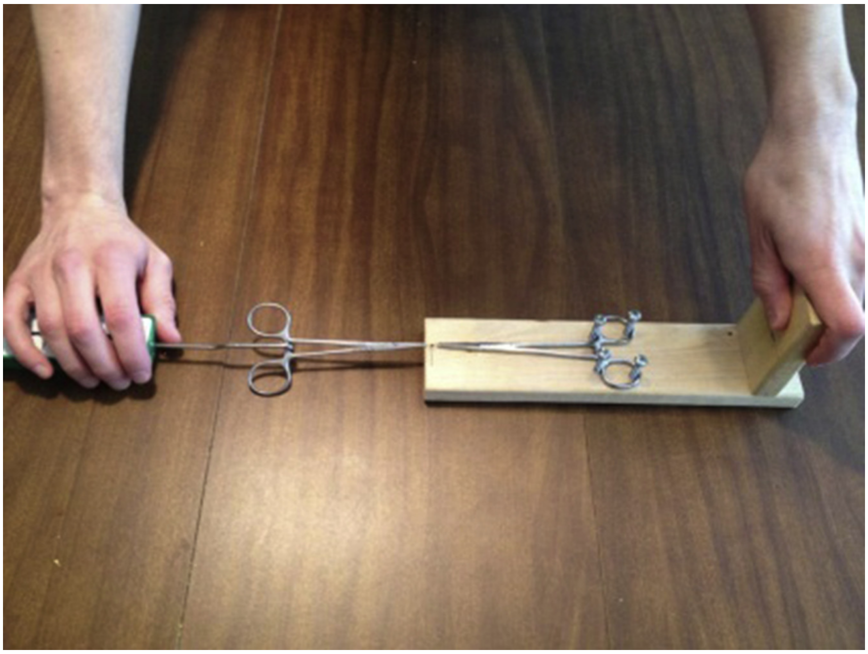

FIGURE 6. Operator pulling force gauge with the right hand while stabilizing the testing apparatus with the left hand.

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combinations of suture material and size using surgeon's and square knots, whereas at least 5 throws are suggested for sliding knots. However, the number of throws required to achieve knot security depends on the specific combination, as listed in Table 1. For example, a 3-0 chromic gut suture with a surgeon's knot requires 5 throws, whereas a 3-0 Vicryl suture with a surgeon's knot requires only 3 throws.

Based on the logistic regression model, it was determined that knot security depends on suture material, technique, and number of throws, whereas knot security is independent of suture size (Table 2). Using odds ratios developed from the regression model, it was determined that surgeon's knots are more secure than square knots and sliding knots and that square knots are more secure than sliding knots. Vicryl was found to be more secure than chromic gut, nylon, and silk. Chromic gut was found to be less secure than Vicryl and more secure than silk. There was no strong evidence that chromic gut differed from nylon in knot security. Nylon was found to be less secure than Vicryl. There was no strong evidence that nylon differed from chromic gut or silk in knot security. Silk was found to be less secure than Vicryl and chromic gut. There was no strong evidence that silk differed from nylon in knot security. Overall, when analyzing all combinations, Vicryl was the most secure material and silk was the least secure material. Three throws were found to be less secure than 4 throws, and 4 throws were found to be less secure than 5 throws. There was no strong evidence that tying 6 throws was more secure than 5 throws (Table 3). Because all combinations involving 2 throws failed, 2 throws are never suggested for any material, size, or technique.

Discussion

The purpose of this study was to investigate knot security in relation to different surgical knotting techniques, suture materials, and sizes commonly used in oral and maxillofacial surgery. Although multiple studies have conducted research on suture and knot properties in other specialties,[4,7,12] this study, to the authors' knowledge, is the first to focus on how number of throws affects knot security when using different techniques, suture materials, and sizes that are commonly used in oral and maxillofacial surgery. Furthermore, the present study is the first, to the authors' knowledge, to test knot security in a wet environment with the specific intention of simulating the oral cavity.

The authors hypothesized that, as in previous studies, knot security would depend on suture technique but would be independent of suture material or size. They also hypothesized that sliding knots would be the weakest technique. The specific aims of this study were to give clinicians a scientific basis to establish guidelines ensuring knot security for combinations of suture materials, sizes, and tying techniques commonly used in the oral cavity. Key findings in this study were that knot security depends

Table 1. PROPORTION OF SECURE KNOTS FOR EACH COMBINATION*

Material	Size	Technique	Throws, n: 2	3	4	5	6
Chromic gut	3-0	Sliding	0.00	0.00	0.60	0.90	0.90
		Square	0.00	0.00	0.50	0.90†	0.90†
		Surgeon's	0.00	0.00	0.40	1.00†	0.90†
	4-0	Sliding	0.00	0.10	0.60	0.90†	0.90†
		Square	0.00	0.10	0.70	0.70	0.90†
		Surgeon's	0.00	0.30	0.80	0.80	0.80
	5-0	Sliding	0.00	0.00	0.80	1.00†	1.00†
		Square	0.00	0.50	1.00†	1.00†	1.00†
		Surgeon's	0.00	0.70	1.00†	1.00†	1.00†
Nylon	3-0	Sliding	0.00	0.10	0.80	0.80	1.00†
		Square	0.00	0.00	1.00†	1.00†	1.00†
		Surgeon's	0.00	0.70	1.00†	1.00†	1.00†
	4-0	Sliding	0.00	0.00	0.60	1.00†	1.00†
		Square	0.00	0.20	0.90†	1.00†	1.00†
		Surgeon's	0.00	0.30	1.00†	1.00†	1.00†
	5-0	Sliding	0.00	0.00	0.30	1.00†	1.00†
		Square	0.00	0.00	0.60	1.00†	1.00†
		Surgeon's	0.00	0.00	1.00†	1.00†	1.00†
Vicryl	3-0	Sliding	0.00	0.30	0.50	0.90†	1.00†
		Square	0.00	0.00	0.70	1.00†	1.00†
		Surgeon's	0.00	1.00†	1.00†	1.00†	1.00†
	4-0	Sliding	0.00	0.30	0.80	1.00†	1.00†
		Square	0.00	0.20	0.70	1.00†	1.00†
		Surgeon's	0.00	0.80	1.00	1.00†	1.00†
	5-0	Sliding	0.00	0.30	0.60	1.00†	1.00†
		Square	0.00	0.30	1.00†	1.00†	1.00†
		Surgeon's	0.00	0.80	1.00†	1.00†	1.00†
Silk	3-0	Sliding	0.00	0.00	0.50	1.00†	1.00†
		Square	0.00	0.00	1.00†	1.00†	1.00†
		Surgeon's	0.00	0.50	1.00†	1.00†	1.00†
	4-0	Sliding	0.00	0.00	0.60	1.00†	1.00†
		Square	0.00	0.10	0.90†	0.90†	0.90†
		Surgeon's	0.00	0.70	1.00†	1.00†	1.00†
	5-0	Sliding	0.00	0.00	0.80	1.00†	1.00†
		Square	0.00	0.00	1.00†	1.00†	1.00†
		Surgeon's	0.00	0.20	1.00†	1.00†	1.00†

* Ten trials were conducted for each combination.
† Combinations that achieved at least 90% secure knots.

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Table 2. LOGISTIC REGRESSION MODEL PREDICTING KNOT SECURITY*

Predictor Variable	Regression Coefficient: Estimate	Standard Error	P Value
Throws			<.0001†
3	−5.74	0.41	<.0001
4	−2.58	0.39	<.0001
5	−0.43	0.47	.36
6	ref		
Suture size			.06†
3-0	−0.52	0.22	.02
4-0	−0.35	0.22	.12
5-0	ref		
Material			<.0001†
Chromic gut	−0.78	0.25	.002
Nylon	−0.26	0.26	.31
Vicryl	0.75	0.27	.006
Silk	ref		
Technique			<.0001†
Sliding	−2.24	0.26	<.0001
Square	−1.62	0.25	<.0001
Surgeon's	ref		
Constant	5.93	0.48	<.0001

Abbreviation: ref, reference.
* The model included the predictors of number of throws, size, suture material, and knotting technique based on slippage data. All 2-throw data were excluded from the model. Listed are estimated logistic regression coefficients, from which the odds ratios (presented in Table 3) are derived.
† *P* value from type III analysis of overall effect for each predictor variable. Number of throws, material, and technique had a statistically significant effect on knot security ($P < .0001$ for all comparisons). The effect of size on knot security was not statistically significant ($P = .063$).

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on suture material, technique, and number of throws but is independent of suture size. In addition, it is not necessary to use more than 5 throws when suturing because knot security was not statistically increased between 5 and 6 throws. To the authors' knowledge, this is the first study to come to this conclusion using statistical analysis.

As in other studies, the authors found that 2 throws are never suggested for any combination of suture material, size, or technique.[4,5,7] Although the minimum number of throws depends on the suture combination presented in Table 1, in general, no fewer than 4 throws are ever suggested to achieve knot security (except for 3-0 Vicryl surgeon's knots). For every other combination of suture material, size, and technique, at least 4 throws are required to ensure knot security. In general, surgeon's and square knots require 4 throws, whereas sliding knots require 5 throws. It is not necessary to suture using more than 5 throws.

Because the present study found no difference in knot security based on suture size, clinicians should use suture sizes they are comfortable using and believe will achieve the best results given the clinical situation. The present study found that suture material, technique, and number of throws are of much greater importance than suture size to achieve knot security. Oftentimes in pre-doctoral and residency training programs, trainees are taught to use "3 throws for 3-0, 4

Table 3. ODDS RATIOS ESTIMATED FROM LOGISTIC REGRESSION MODEL

Predictor Variable	OR (95% CI)	*P* Value
Throws		
3 vs 4	0.042 (0.024-0.076)	<.0001
3 vs 5	0.005 (0.002-0.012)	<.0001
3 vs 6	0.003 (0.001-0.009)	<.0001
4 vs 5	0.12 (0.050-0.27)	<.0001
4 vs 6	0.076 (0.028-0.21)	<.0001
5 vs 6	0.65 (0.20-2.17)	.80
Material		
Chromic gut vs nylon	0.60 (0.31-1.13)	.16
Chromic gut vs Vicryl	0.22 (0.11-0.44)	<.0001
Chromic gut vs silk	0.46 (0.24-0.88)	.01
Nylon vs Vicryl	0.37 (0.18-0.73)	.001
Nylon vs silk	0.77 (0.40-1.49)	.74
Vicryl vs silk	2.11 (1.05-4.22)	.03
Technique		
Sliding vs square	0.54 (0.32-0.89)	.01
Sliding vs surgeon's	0.11 (0.058-0.19)	<.0001
Square vs surgeon's	0.20 (0.11-0.35)	<.0001

Note: Tukey-adjusted CI and *P* values are listed. Estimated ORs derived from the logistic regression model are measurements of effect to quantify the association between knot slippage (stable vs unstable) and a predictor variable, controlling for the other variables. When the OR is less than 1, then the indicated category of the predictor variable is associated with lower odds of being secure compared with the reference category. For instance, 3 throws was only 0.3% as secure as 6 throws (OR = 0.003; 95% CI, 0.001 to 0.009). If the OR is greater than 1, then the indicated category of the predictor variable is associated with higher odds of being secure compared with the reference category. For instance, Vicryl was approximately twice as secure as silk (OR = 2.11; 95% CI, 1.05 to 4.22).

Abbreviations: CI, confidence interval; OR, odds ratio.

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throws for 4-0, and 5 throws for 5-0." The authors did not find this adage to hold true when tested using scientific analysis.

The present study confirmed the findings of Riboh et al[1] and van Rijssel et al[5] who found that surgeon's knots and square knots are stronger than sliding knots. However, the authors tested suture materials and sizes commonly used in the oral cavity. This makes sense because square and surgeon's knots are created by crossing each throw, as opposed to sliding knots.[13] This results in an asymmetrically distributed force in sliding knots, thus predisposing to breakage. That is not to say that sliding knots are completely contraindicated in every situation, because the fact that they do not need to be crossed makes them easier and faster to tie.[6] Some clinicians might choose to tie additional sliding knots rather than the more time-intensive undertaking of tying fewer square or surgeon's knots.

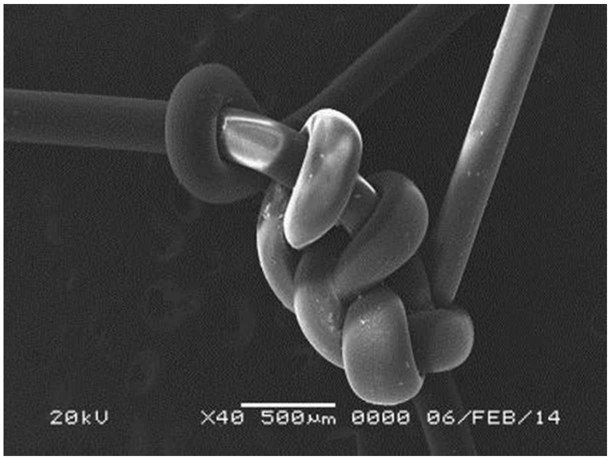

FIGURE 7. Scanning electron microscopic image of sliding knot.

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Van Rijssel et al[5] and Muffly et al[9] reported that square and surgeon's knots had statistically similar knot security. The authors found that surgeon's knots had greater knot security than square knots, which makes sense because surgeon's knots are crossed twice at the base, whereas square knots are crossed only once.

The present study found that knot security depends on suture material, with the strongest being Vicryl followed by chromic gut, nylon, and silk. Certain studies have shown that knot security depends on suture material, whereas other studies have concluded that knot security is independent of suture material. For example, Marturello et al[8] found that braided sutures have greater tensile strength than monofilament sutures. In contrast, Muffly et al[7] found that knot security does not depend on suture material. The present study concluded that knot security depends on material, although the authors did not specifically compare braided and monofilament sutures. As in the present study, Muffly et al[7] soaked sutures in 0.9% saline, whereas Marturello et al[8] soaked sutures in donor plasma. Saline might have an effect on suture material that donor plasma does not, such as washing away the coating, thus standardizing the results in the in vitro environment. This question should be investigated further.

It has been noted that knotting force is a critical factor in obtaining knot security.[2] It has been found that applying 10% of knot-breaking strength while tying off a suture will likely result in slippage, whereas applying 80% of knot-breaking strength ensures minimal slippage. The present study used 1 lb of force in tying off each knot, which was determined by taking the average of 10 oral surgeons and residents. Most tested suture combinations had a maximum breaking force of less than 2 lb, putting the tying force of each

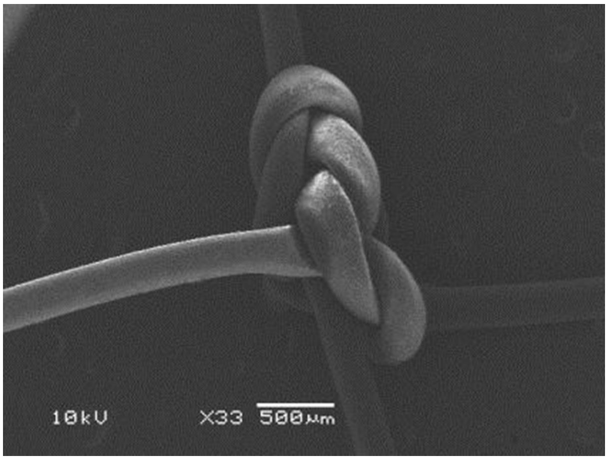

FIGURE 8. Scanning electron microscopic image of square knot (top-down view).

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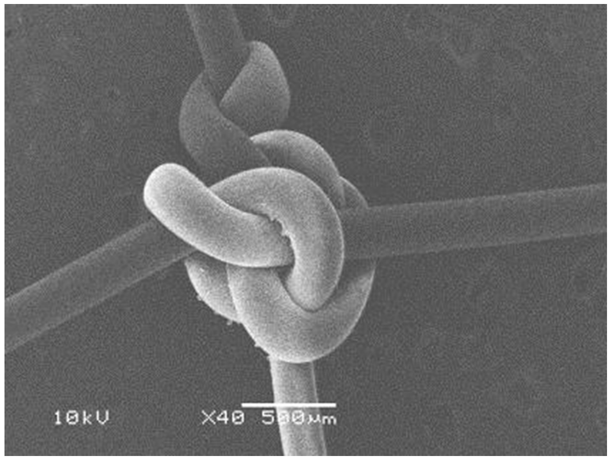

FIGURE 9. Scanning electron microscopic image of surgeon's knot (top-down view).

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knot generally above 50% of the maximum knot-breaking strength. By tying off most sutures with at least 50% of knot-breaking strength, the authors could be conservative when collecting their results. Had they used less force in tying off knots, their results might have overstated the number of knots needed to achieve knot security.

Many studies have tested the maximum load to breakage for different suture combinations.[1,12] Others have defined knot security as a knot that breaks rather than slips when tested to failure.[14] The authors judged it would be more clinically relevant to test each variable by pulling with the same force and then observing whether knot slippage occurred. This is because surgeons in clinical practice generally tie a suture at a given force so that it will stay secure as opposed to pulling until the knot breaks. Had the authors tested to knot breakage, they likely would have found that more throws are necessary than the present findings suggested, adding unnecessary surgery time.

Studies have shown that results differ when testing suture knots in a dry versus wet environment and that testing in a wet environment might be more realistic.[15] The present study used this principle by soaking sutures in 0.9% saline, helping to replicate the environment of the oral cavity with the potential advantage of an improved testing environment. Testing in a wet environment might have strengthened or weakened the various suture materials, thus affecting the results.

A scanning electron microscope was used to visualize different knotting techniques in detail. This helped to confirm that the knots were being tied in the proper manner, because it is nearly impossible to visualize the suturing technique with the naked eye (Figs 7-9).

Although the present study provides a useful baseline for clinicians, there is still much more work to be performed in this area. Depending on the procedure, oral and maxillofacial surgeons might use different suture materials, sizes, or techniques than those tested in this study. Furthermore, oral and maxillofacial surgeons also suture outside the mucosa, so dry tests with smaller sutures would help to expand on the results. It would be worthwhile to investigate suture properties using animal models so that various techniques, such as continuous and interrupted, can be compared. In addition, a major issue in knot security is slippage versus failure. Although knot security is desirable, it is still better to know if a suture will completely break or merely slip. The present study did not track this important characteristic, unlike other studies.[1] Monitoring knot failure would have been of critical importance had the authors also tested continuous sutures, because knot failure in this situation results in failure of multiple areas of wound closure.

The present study found that some previous findings in surgical studies could be extrapolated to sutures commonly used in oral and maxillofacial surgery. This is a clinically relevant conclusion and oral and maxillofacial surgeons who have used studies from other surgical specialties to determine tying strategy now have evidence-based research and support specific to their field.

Currently, the literature on knot security in other areas of surgery seems to be stronger than the literature on knot security in oral and maxillofacial surgery. The present study was clinically useful in providing oral and maxillofacial surgeons with clinical guidelines regarding the ideal number of throws to achieve knot security for different combinations of suture

material, size, and technique to prevent potential knot slippage (too few knots) or wasted surgery time and increased infection potential (too many knots). The present study showed that knot security depends on the number of throws. Clinicians should never use 2 throws and should generally use a minimum of 4 throws, whereas using more than 5 throws is redundant and does not add any additional knot security. The present study also found that surgeon's knots are stronger than square knots, which are stronger than sliding knots, and that Vicryl is the most secure material, followed by chromic gut, nylon, and silk. In addition, knot security is independent of suture size. In the future, the authors would like to test a wider range of suture combinations to reach a broader audience of clinicians. They also would like to pursue animal studies to study the in vivo effects of different combinations of suture material, size, and technique on knot security.

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