Objective Assessment of Knot-Tying Proficiency With the Fundamentals of Arthroscopic Surgery Training Program Workstation and Knot Tester

Robert A. Pedowitz, M.D., Ph.D., Gregg T. Nicandri, M.D., Richard L. Angelo, M.D., Richard K. N. Ryu, M.D., and Anthony G. Gallagher, Ph.D., D.Sc.

Purpose: To assess a new method for biomechanical assessment of arthroscopic knots and to establish proficiency benchmarks using the Fundamentals of Arthroscopic Surgery Training (FAST) Program workstation and knot tester. **Methods:** The first study group included 20 faculty at an Arthroscopy Association of North America resident arthroscopy course (19.9 ± 8.25 years in practice). The second group comprised 30 experienced surgeons attending an Arthroscopy Association of North America fall course (17.1 ± 19.3 years in practice). The training group included 44 postgraduate year 4 or 5 orthopaedic residents in a randomized, prospective study of proficiency-based training, with 3 subgroups: group A, standard training (n = 14); group B, workstation practice (n = 14); and group C, proficiency-based progression using the knot tester (n = 16). Each subject tied 5 arthroscopic knots backed up by 3 reversed hitches on alternating posts. Knots were tied under video control around a metal mandrel through a cannula within an opaque dome (FAST workstation). Each suture loop was stressed statically at 15 lb for 15 seconds. A calibrated sizer measured loop expansion. Knot failure was defined as 3 mm of loop expansion or greater. **Results:** In the faculty group, 24% of knots "failed" under load. Performance was inconsistent: 12 faculty had all knots pass, whereas 2 had all knots fail. In the second group of practicing surgeons, 21% of the knots failed under load. Overall, 56 of 250 knots (22%) tied by experienced surgeons failed. For the postgraduate year 4 or 5 residents, the aggregate knot failure rate was 26% for the 220 knots tied. Group C residents had an 11% knot failure rate (half the overall faculty rate, *P* = .013). **Conclusions:** The FAST workstation and knot tester offer a simple and reproducible educational approach for enhancement of arthroscopic knot-tying skills. Our data suggest that there is significant room for improvement in the quality and consistency of these important arthroscopic skills, even for experienced arthroscopic surgeons. **Level of Evidence:** Level II, prospective comparative study.

Knot tying is an essential skill for proficiency in arthroscopic surgery.[1,2] Arthroscopic knot tying is difficult to teach and to assess objectively. At this time, most trainees are assessed by visual inspection of arthroscopic knots, either by direct view or by an arthroscopic image. Hanypsiak et al.[3] recently showed that even experienced practicing surgeons are relatively inconsistent when it comes to arthroscopic knot tying. Technical inconsistency could have a negative impact on surgical outcomes.

In the laboratory setting, arthroscopic knots (more accurately, the suture loops created after knot tying) are usually tested with expensive material testing devices that allow sophisticated variation of load magnitude, cyclic versus single pull, loop preload, and load application rate.[2,4-10] However, these devices are not practical for day-to-day education of residents and fellows or for continuing medical education of practicing surgeons. It would be advantageous to have a cost-effective and relatively simple-to-use tester for objective assessment of knot performance, as opposed to knot appearance.

In the teaching laboratory, knot-tying skills are generally developed using knot-tying boards under direct visualization with the trainee's eyes looking directly at the hands, suture, and associated surgical

From the University of California (R.A.P.), Los Angeles, California; University of Rochester School of Medicine and Dentistry (G.T.N.), Rochester, New York; Evergreen Orthopaedic Clinic (R.L.A.), Seattle, Washington; The Ryu Hurvitz Orthopedic Clinic (R.K.N.R.), Santa Barbara, California, U.S.A.; and University College Cork (A.G.G.), Cork, Ireland.

The authors report the following potential conflict of interest or source of funding: R.A.P. receives support from Virtamed. R.L.A. receives support from DePuy Mitek. R.K.N.R. receives support from MedBridge, Mitek, and Rotation Medical.

Received December 2, 2014; accepted June 17, 2015.

Address correspondence to Robert A. Pedowitz, M.D., Ph.D., 4043 Irving Pl, Ste 304, Culver City, CA 90232, U.S.A. E-mail: robertpedowitz@gmail.com

0749-8063/141016/$36.00

http://dx.doi.org/10.1016/j.arthro.2015.06.021

instruments. However, in the clinical setting, arthroscopic knots and backup hitches are created outside of the body, delivered through an arthroscopic cannula, and then tensioned within the joint, with visualization provided by a 2-dimensional video screen. This combination requires an integrated chain of complex psychomotor skills that are performed in 3-dimensional space with mostly binocular cues.[11] Such skills are best acquired and rehearsed in a gradual and systematic fashion.[12,13]

The Fundamentals of Arthroscopic Surgery Training (FAST) Program is a collaborative initiative of the Arthroscopy Association of North America (AANA), the American Academy of Orthopaedic Surgeons, and the American Board of Orthopaedic Surgery. The FAST Program offers a basic arthroscopic motor skills curriculum with associated teaching modules to facilitate core training in orthopaedic surgery. It is logical to achieve a baseline level of technical proficiency, if possible, before operating on patients.[14]

The FAST Program curriculum was developed after task deconstruction of basic arthroscopic skills (available, with open access, at http://www.aana.org/FASTProgram/FASTProgramSurgicalSkillsContent.aspx). The FAST workstation (Sawbones, Vashon Island, WA) was custom designed for training of these skills. The system allows for initial practice under direct visualization, then advances to triangulation through simulated portals under direct visual control, and finally moves to skill rehearsal through simulated portals using a video camera, with the direct surgeon view eliminated. The purposes of this study were to assess the FAST knot tester and to establish benchmarks for knot-tying proficiency using this system. Our hypothesis was that the FAST knot tester would facilitate objective, accurate, and immediate mechanical assessment of knot performance.

Methods

For all groups in this study, 5 consecutive knots were created by each subject on the FAST workstation using No. 2 FiberWire (Arthrex, Naples, FL) under dry, room-temperature conditions through a 7-mm plastic cannula. Each subject created an arthroscopic knot of his or her choice, backed up by 3 reversed half-hitches on alternating posts. Each suture was labeled, well away from the knot and suture loop, for later identification. The 5 knots were gently placed within a labeled plastic bag for each subject and set aside for subsequent analysis using the FAST knot tester.

Faculty Reference Group (n = 20)

The first group (faculty) was composed of 20 experienced surgeons teaching at a dedicated AANA resident arthroscopy skills course at the Orthopedic Learning Center (Rosemont, IL). This expert group reported clinical practice experience of 19.9 ± 8.25 years and performed 381 ± 150 arthroscopies per year.

Resident Comparison Groups (n = 44)

Orthopaedic surgery residents (postgraduate years 4 and 5) participated in a randomized, prospective study of proficiency-based training at the Orthopedic Learning Center (the AANA Copernicus Study, described in detail in a separate publication[15] that did not include specific information about knot-tying performance, benchmarks, and associated methodology). Residents were divided into 3 subgroups. Group A included 14 residents who were instructed on knot-tying skills using standard educational methodology during a regular AANA resident arthroscopy course. Standard educational methodology included didactic instruction, faculty demonstration, practice with rope, and progression to knot tying using suture around a metal hook and then through an arthroscopic cannula, all under direct visualization. When group A participants felt ready for testing, each resident used the FAST workstation and USB camera system to create 5 arthroscopic knots in sequence without interval feedback.

Group B included 14 residents who received similar didactic instruction to group A, but they were also allowed to practice knot-tying skills using the FAST workstation/USB camera system until they were ready to create 5 knots for later testing. Group C comprised 16 residents who received the same didactic instruction and practiced with the workstation/USB camera setup. However, group C residents were allowed to use the FAST knot tester after each knot was tied, providing immediate performance feedback during the practice phase, until they were ready to create 5 test knots. Practice time before knot testing was not a controlled variable for the resident study groups.

Surgeon Reference Group (n = 30)

Thirty surgeons volunteered to create 5 knots using the FAST workstation and USB camera setup at the 2013 AANA fall course. For the purposes of setting the benchmark for resident proficiency (as described later), we only used the faculty from the Copernicus course as the reference group. We were surprised at the high knot failure rate among the Copernicus faculty, so we pursued an additional cohort of practicing surgeons (whether faculty or non-faculty surgeons) from the AANA fall course. We thought that this would, at a minimum, represent arthroscopic surgeons in practice, and we believed that observations of 50 practicing surgeons would enhance overall confidence in the observations. The knots were tested later with no feedback provided to the surgeon during knot creation. All participants were in clinical practice for at least 1 year (maximum, 40 years). The group had an average

Fig 1. Fundamentals of Arthroscopic Surgery Training (FAST) base station with knot-tying mandrel and lucent dome for skills rehearsal under direct visualization.

Fig 2. Fundamentals of Arthroscopic Surgery Training (FAST) workstation with opaque dome and light-emitting diode penlight. An inexpensive USB camera is directed at the knot-tying mandrel, and the image is displayed on a laptop computer. This arrangement simulates arthroscopic visualization.

practice experience of 17.1 ± 19.3 years (mean ± SD). Ten surgeons self-reported as course faculty, 12 self-reported as attendees, and 8 surgeons did not indicate whether they were faculty or attendees.

Study Participants

Each subject was verbally informed about the purpose of the study, and all volunteers were assigned a unique identification number. All test knots were labeled using subject identification numbers (subject names excluded). The study protocol was reviewed by the Western Institutional Review Board (Puyallup, WA) and deemed exempt.

FAST Workstation

The FAST workstation is composed of a base unit, which accommodates various snap-in teaching modules that complement the FAST Program curriculum. The base station can be used for basic skills practice under direct visualization without the need for triangulation. Two snap-in dome units allow for skills rehearsal either under direct visualization with the lucent dome (Fig 1) or with video imaging using the opaque dome (Fig 2). Both domes have multiple, identically positioned access holes that mimic portal positions and geometries of knee and shoulder arthroscopy.

The FAST workstation has a horizontally positioned, smooth, stainless steel knot-tying mandrel for practice with suture (Fig 1). The circumference of the knot-tying mandrel matches the first marked position on the conical loop sizer of the FAST knot tester (Fig 3). The loop sizer is calibrated in 1-mm increments to measure up to 5 mm of expansion relative to the knot-tying mandrel. On the basis of prior literature,[3,16] 3 mm of loop expansion or more was deemed to indicate knot failure. This is considered an amount of suture loop elongation that might be associated with biological healing failure at the tendon-bone interface after rotator cuff repair.[16,17]

Visualization Protocol

To mimic clinical conditions, the FAST workstation was designed for use with an inexpensive USB camera mounted on a stand (Fig 2). For this study, a

Fig 3. Conical loop sizer of Fundamentals of Arthroscopic Surgery Training (FAST) knot tester. The first mark indicates zero loop expansion, and each subsequent mark reflects 1 mm of additional loop expansion compared with the knot-tying mandrel.

Fig 4. Fundamentals of Arthroscopic Surgery Training (FAST) knot tester. The suture loop is positioned on the 2 tines, and the handle allows for controlled application of 15 lb of longitudinal load.

high-resolution Point 2 View camera (IPEVO, Sunnyvale, CA) was mounted on its base station and connected to a laptop computer, which provided the image on the video monitor (Fig 2). The camera was directed at the knot-tying mandrel through a hole in the opaque workstation dome, which forced subjects to look at the image on the laptop screen during knot tying. The camera was set at 2× screen magnification using the IPEVO software. Illumination within the dome was augmented using a disposable light-emitting diode penlight (PLED23A; Energizer, St Louis, MO), although we found that ambient room light was generally sufficient because of the high sensitivity of the USB camera.

FAST Knot Tester

The FAST knot tester is composed of a rigid base with an integrated spring for application of linear tension to a suture loop (Fig 4). The tester was designed to apply 15 lb of tension (60 N) based on published theoretical modeling of relevant clinical forces because direct in vivo measurements of postoperative suture tension are not available. Burkhart et al.[18] estimated that 60 N would be the maximal force per suture that might be created by muscle contraction after a balanced suture anchor repair of a medium-sized rotator cuff tear. Peak loads would potentially be greater with an unbalanced repair or with an abrupt event, such as a postoperative fall. High-strength No. 2 sutures are relatively stiff, and the material can withstand loads greater than 300 N before rupture.[4,8] Therefore the 60-N load of the FAST knot tester was selected to assess knot performance as opposed to suture performance.

After a knot is created on the workstation, the loop is gently slipped off the knot-tying mandrel and transferred to the conical loop sizer, which gives a baseline measurement of the suture loop. The loop is then transferred to the 2 tines of the knot tester. One of the tines is solidly attached to the rigid base. Tension is applied by an actuator handle connected by a calibrated spring to the other tine. A force gauge allows the user to apply 15 lb of axial tension to the suture loop. We chose 15 seconds of steady force application because pilot studies indicated that significant additional loop expansion did not occur beyond this time point (in fact, most of the loop expansion was observed within a few seconds of force application). After 15 seconds of static load, the actuator handle is released, and the suture loop is removed from the tines and transferred back to the conical loop sizer. The calibrated markings are used to assess final loop size compared with initial loop size. A loop created with a perfect knot would therefore have zero baseline difference from the knot-tying mandrel and zero expansion after load application.

Reproducibility of Load Application

A digital force scale with a maximum load capacity of 30 lb (HS-30; CCI Scale Company, Clovis, CA) was used to measure the consistency of load application created by the FAST knot tester. Two sets of 10 measures each were acquired by independent observers. One observer applied 15 lb of load with the actuator handle for 15 seconds while looking at the force scale of the FAST knot tester. The other observer recorded axial load using the digital force scale after 15 seconds. The force scale was connected by a rigid metal link to the suture tine of the knot tester. The digital force scale was rezeroed after each pull of the actuator handle. The roles of the 2 observers were reversed during the second set of measurements. By use of this protocol, mean force application measured by the digital force scale was 15.03 lb, with an SD of 0.05 lb (expressed as the SD for 2 independent sets of 10 measures).

Statistical Analysis

Logistic regression analysis was used to compare relative differences between knot-tying performance of the 3 resident trainee groups and faculty knot-tying performance. Statistical significance was considered at $P < .05$.

Results

Performance data from the AANA Copernicus Study participants and from the AANA fall course subjects are presented in Table 1 and Table 2, respectively. This information is stratified according to the number of knots that failed (defined as ≥3 mm of loop expansion) after application of 15 lb of static load for 15 seconds. Of the 20 Copernicus course faculty, 12 had 0 knots fail. Four faculty had 2 knot failures, 2 faculty had 3 knot failures, and 2 faculty had all 5 of their knots fail on the FAST knot tester. Overall, 24% of the faculty knots

Table 1. Knot Tying at Arthroscopy Association of North America Residents' Copernicus Course

	Faculty (n = 20)	Group A Residents (n = 14)	Group B Residents (n = 14)	Group C Residents (n = 16)
Years in practice, mean ± SD (range)	19.9 ± 8.3 (4-32)			
Knot performance, n				
0 of 5 failed	12	3	3	11
1 of 5 failed	0	3	5	2
2 of 5 failed	4	7	2	2
3 of 5 failed	2	0	1	1
4 of 5 failed	0	1	1	0
5 of 5 failed	2	0	2	0
No. of knots that failed	24 of 100 (24%)	21 of 70 (30%)	26 of 70 (35%)	9 of 80 (11%)

NOTE. Knot failure was defined as 3 mm of loop expansion or greater with application of 15 lb of load for 15 seconds.

were considered failures. Only 1 faculty surgeon tied 5 consecutive "perfect" knots (zero loop expansion compared with the knot-tying mandrel at baseline and zero loop expansion after 15 lb of load application).

A similarly high rate of knot failure was noted in the second group of experienced surgeons (Table 2). Overall, for these practicing surgeons, 21% of the knots were noted to be failures. Five of the 30 participants had 3 of 5 knot failures. Taking in aggregate all knots tied by faculty and practicing surgeons at the 2 courses, this study found that 56 of 250 knots (22%) were deemed failures by mechanical testing.

Overall, the knot failure rate was 26% for the 220 knots that were tied by the orthopaedic surgery residents (Table 1). However, the group C residents, who were allowed to use the knot tester for feedback during the training experience, had an overall 11% knot failure rate, which was exactly one-half the knot rate of the Copernicus course faculty.

Data from the Copernicus course faculty were used to create a proficiency benchmark for "passing" resident performance. This passing benchmark was applied to the group C Copernicus course residents (proficiency-based progression group; full details were provided by Angelo et al.[15]). On the basis of the Copernicus faculty data, we defined a proficiency benchmark of less than or equal to 2 knot failures out of 5 knot attempts as a passing grade. When we apply these same thresholds to the surgeons in practice at the fall course (Table 2), with the bar set at less than or equal to 2 knot failures out of 5 attempts, 5 of the 30 surgeons (17%) missed the passing mark.

Relative to the Copernicus course faculty, groups A and B were more likely to have their knots fail, but these differences were not statistically significant (P = .384 for group A *v* faculty and P = .07 for group B *v* faculty by logistic regression analysis). In contrast, residents in group C were more than twice as likely to have their knots pass in comparison with the faculty reference group (odds ratio, 2.84), and this difference was statistically significant (P = .013). Logistic regression analysis was also used to compare the relative differences between the 3 trainee subgroups, using standard training (group A) as the reference. There was no statistical difference between groups A and B (odds ratio, 0.725; P = .372). In contrast, group C residents were almost 4 times as likely to have their knots pass as group A (odds ratio, 3.857; P = .002).

If we apply a proficiency threshold of no more than 2 knot failures out of 5 trials (as described earlier), 6 of the 44 orthopaedic residents (14%) fell below the passing bar. Of note, 15 of 16 group C residents (94%) exceeded the passing threshold; this was the best performance for any subgroup in this study.

Table 2. Knot Tying at 32nd Arthroscopy Association of North America Fall Course

	Faculty (n = 10)	Surgeon Attendees (n = 12)	Faculty or Attendee Not Defined (n = 8)	Total for All Participants (n = 30)
Year in practice, mean ± SD (range)	20.5 ± 7.6 (3-30)	14.6 ± 12.4 (1-40)	19.0 ± 9.3 (9-32)	17.1 ± 19.3 (1-40)
Knot performance, n				
0 of 5 failed	5	3	4	12
1 of 5 failed	3	3	3	9
2 of 5 failed	1	3	0	4
3 of 5 failed	1	3	1	5
4 of 5 failed	0	0	0	0
5 of 5 failed	0	0	0	0
No. of knots that failed	8 of 50 (16%)	18 of 60 (30%)	6 of 40 (15%)	32 of 150 (21%)

NOTE. Knot failure was defined as 3 mm of loop expansion or greater with application of 15 lb of load for 15 seconds.

Discussion

The FAST workstation and FAST knot tester facilitated direct, objective measurements of arthroscopic knot-tying performance. Overall, 22% of knots tied by practicing surgeons "failed" using this testing protocol. A proficiency-based progression training protocol resulted in improved resident knot-tying skills (11% knot failure rate) compared with standard training methodology.

The FAST Program provides core education for orthopaedic surgery residents, fellows, and practicing surgeons who wish to develop and enhance their arthroscopic motor skills. The FAST Program is intended to create and enhance robust psychomotor skills, right from the outset of training. It is relatively difficult to correct bad surgical habits once they are firmly established.[12,13] Training of many surgical skills can be performed outside of the operating room in an efficient and cost-effective manner that maximizes educational quality and eliminates patient morbidity. There has been a significant shift toward structured simulation training, including recent simulation mandates by the American Board of Orthopaedic Surgery and the Orthopaedic Residency Review Committee of the Accreditation Council for Graduate Medical Education.[19-21] The FAST Program was designed to satisfy these educational mandates for arthroscopic surgery with a cost-effective, practical, modular system.

In the traditional approach to training, operative skills were acquired in an apprentice model of training that meant that learning was serendipitous. Resident experience was affected by when residents were on duty, which patients and procedures they encountered, and who was supervising and mentoring them. It also relied on learning by repeated practice.[22] The proficiency-based progression approach to training, afforded by technologies such as FAST, encourages a "deliberate practice" approach.[13,23] This means that the trainee receives objective metric-based feedback on his or her performance proximate to the measured task, thus augmenting the learning experience for him or her. Seeing knots slip when pulled is a very impactful learning experience, even for very experienced surgeons.

For decades, orthopaedic educators have been using knot-tying boards with rope and suture to train arthroscopic knot tying. In most cases, proficiency assessment has been based on subjective, visual observation of the knot-tying process and the visual appearance of the surgical knot.[24-34] However, what is most important, in terms of surgical outcome, is knot performance as opposed to knot appearance. A "pretty" knot has no clinical value if it does not hold under physiological loads.

Before this study, biomechanical assessment of sutures and knots has generally been restricted to analyses with sophisticated material testing devices (from MTS Systems [Eden Prairie, MN], Instron [Norwood, MA], and so on). These devices are quite expensive, and they are impractical for day-to-day training applications. However, they do have advantages for complex load-application paradigms, including cyclic load protocols. Nonetheless, we thought that it would be advantageous to create a very simple and inexpensive knot tester that could be used on the educational front lines. The FAST knot tester was not designed to be a sophisticated bioengineering research tool.

It should be emphasized that the level of load application (15 lb) for the FAST knot tester was specifically selected for testing of high-strength No. 2 sutures used commonly during many arthroscopic procedures. The knot tester could be adapted with different spring loads to assess the performance of other suture materials. Objective proficiency benchmarks could be established for various sutures under specific performance conditions. This strategy is relevant to training and objective assessment of surgical knot tying across the medical spectrum because knot tying is a pervasive technical skill requirement for most procedural specialties. The FAST approach to measurement and quality assurance, by achieving performance benchmarks before training progression, fits well with the recommendations of the Institute of Medicine report on graduate medical education.[35] The Institute of Medicine proposed that medical education should move away from training that is process driven (i.e., time in training, number of procedures completed, duration of rotation) to an "outcome"-driven enterprise.[36] This means that trainees would be required to demonstrate a benchmark performance level.[12]

We were quite surprised by the high incidence of knot failures in this study for course faculty and surgeons in practice. After our data collection, Hanypsiak et al.[3] published similar observations in their study of 73 expert orthopaedic arthroscopists who tied 365 individual knots with No. 2 FiberWire suture. In their study, surgeons created knots under direct visualization, without magnification or video control, and the knots were tested using a sophisticated electromechanical dynamic testing system. The authors observed significant variations between surgeons and between knot configurations. Perhaps even more important, they concluded that "considerable variation and inconsistencies in knot strength exist between arthroscopic knots of the same type tied by the same surgeon."[3] Individual subject performance inconsistency was also noted in our study for knots created by experts under video control through arthroscopic cannulas. The observations of Hanypsiak et al. and the findings of our study are extremely important because technical consistency is a hallmark of surgical proficiency and patient safety.

We used the performance data for our expert faculty surgeons to create objective proficiency benchmarks that could be applied to resident and fellow training. Proficiency benchmarks must be reasonable and achievable. It would not make sense to set benchmarks that are unachievable for a high percentage of competent, experienced surgeons. Given the relatively high incidence of knot failure for our experienced surgeons, we defined a proficiency benchmark of no more than 2 of 5 knot failures to achieve a passing score for residents. Of course, surgeons should strive for technical perfection, with 0 knot failures, and we observed that level of high performance for some of our expert subjects. However, our data suggest that many arthroscopic surgeons (even experienced and expert surgeons) have substantial opportunities for improvement. Such opportunities are facilitated by direct, objective, and immediate performance feedback.

On the basis of the Copernicus faculty data, we defined a proficiency benchmark (a passing grade) of less than or equal to 2 knot failures out of 5 knot attempts. If the threshold had been set to no more than 1 failure in 5 attempts, 8 of our own Copernicus faculty (40%) would have fallen below the passing bar (Table 1). We thought it was important to avoid unrealistic or unachievable proficiency benchmarks for the residents, so we selected the more lenient proficiency standard of no more than 2 knot failures out of 5 knot attempts. For the surgeons in practice at the fall course (Table 2), if the threshold was set at less than or equal to 1 knot failure in 5 attempts, 9 of 30 surgeons in practice (30%) would not have passed. These data further support the use of the more lenient proficiency standard for training purposes.

Overall, the knot failure rate was 26% for the 220 knots that were tied by the orthopaedic surgery residents (Table 1). Surprisingly, this failure rate was not dramatically different than the overall failure rate for our faculty and surgeons in practice. However, the group C residents (who were allowed to use the knot tester for feedback during the training experience) had an overall 11% knot failure rate, which was significantly better than the Copernicus course faculty ($P = .02$). We were impressed by the strong performance of group C, the proficiency-based progression subgroup (Table 1). These residents could assess their performance based on direct proximate feedback, make adjustments in knot-tying technique, and then see for themselves whether their performance had improved. This approach appears to have resulted in substantial enhancement of this group's performance.

On the basis of our observations and the recent findings of Hanypsiak et al.,[3] we believe that it would be very challenging to objectively assess knot performance using video review of arthroscopic procedures. Some overt suture failures are easily observed. For example, it is visually obvious when sutures break or become entangled or when there is an overly loose suture loop that does not indent soft tissue. However, our findings suggest that some "visually acceptable" knots may fail under relevant mechanical loads even in the hands of very experienced surgeons.

Limitations

One of the limitations of this study was that we did not afford opportunities for self-directed performance feedback to our faculty surgeons or to the practicing surgeons at the AANA fall course. This study did not involve a homogeneous population of faculty and practicing surgeons, with prior clinical experience ranging from 1 to 40 years of practice.

We did not assess transfer of motor skills to the clinical situation, nor did we examine same-subject test/retest consistency. Maximum practice time before knot testing was not a controlled variable. This study was not designed to compare performance differences according to knot type because we wanted each subject to select his or her own base knot based on personal preference and experience. Previous research has looked at biomechanical performance variation as a function of knot type, and it was not our purpose to examine this question. During the study design phase, we recognized and discussed the implications of variation in the base knot of each study participant. We wanted each subject, particularly the faculty and experienced surgeons, to pick the base knot that he or she would be most comfortable tying. We did not want to impose a particular knot choice because we were concerned that individual performance could be adversely affected by asking subjects to tie knots with which they were unaccustomed, thereby introducing greater data variability. This study was not designed to cross-correlate knot performance with knot "appearance." These are important study limitations and represent opportunities for further work.

Conclusions

The FAST workstation and knot tester offer a simple and reproducible educational approach for enhancement of arthroscopic knot-tying skills. Load displacement of the suture loop is a direct reflection of mechanical performance of the surgical knot. There is significant room for improvement in the quality and consistency of these important arthroscopic skills, even for experienced arthroscopic surgeons.

References

1. Mishra DK, Cannon WD Jr, Lucas DJ, Belzer JP. Elongation of arthroscopically tied knots. *Am J Sports Med* 1997;25:113-117.

2. Swan KG Jr, Baldini T, McCarty EC. Arthroscopic suture material and knot type: An updated biomechanical analysis. *Am J Sports Med* 2009;37:1578-1585.
3. Hanypsiak BT, DeLong JM, Simmons L, Lowe W, Burkhart S. Knot strength varies widely among expert arthroscopists. *Am J Sports Med* 2014;42:1978-1984.
4. Abbi G, Espinoza L, Odell T, Mahar A, Pedowitz R. Evaluation of 5 knots and 2 suture materials for arthroscopic rotator cuff repair: Very strong sutures can still slip. *Arthroscopy* 2006;22:38-43.
5. Baums MH, Sachs C, Kostuj T, Schmidt-Horlohé K, Schultz W, Klinger HM. Mechanical testing of different knot types using high-performance suture material. *Knee Surg Sports Traumatol Arthrosc* in press, available online 13 October, 2013. doi:10.1007/s00167-013-2711-9.
6. Ilahi OA, Younas SA, Alexander J, Noble PC. Cyclic testing of arthroscopic knot security. *Arthroscopy* 2004;20:62-68.
7. Ilahi OA, Younas SA, Ho DM, Noble PC. Security of knots tied with Ethibond, Fiberwire, Orthocord, or Ultrabraid. *Am J Sports Med* 2008;36:2407-2414.
8. Mahar AT, Moezzi DM, Serra-Hsu F, Pedowitz RA. Comparison and performance characteristics of 3 different knots when tied with 2 suture materials used for shoulder arthroscopy. *Arthroscopy* 2006;22:614.e1-614.e2.
9. Riboh JC, Heckman DS, Glisson RR, Moorman CT III. Shortcuts in arthroscopic knot tying: Do they affect knot and loop security? *Am J Sports Med* 2012;40:1572-1577.
10. Shah MR, Strauss EJ, Kaplan K, Jazrawi L, Rosen J. Initial loop and knot security of arthroscopic knots using high-strength sutures. *Arthroscopy* 2007;23:884-888.
11. Gallagher AG, Ritter EM, Lederman AB, McClusky DA III, Smith CD. Video-assisted surgery represents more than a loss of three-dimensional vision. *Am J Surg* 2005;189:76-80.
12. Gallagher AG, Ritter EM, Champion H, et al. Virtual reality simulation for the operating room: Proficiency-based training as a paradigm shift in surgical skills training. *Ann Surg* 2005;241:364-372.
13. Gallagher AG, O'Sullivan GC. *Fundamentals of surgical simulation; principles & practices*. London: Springer Verlag, 2011.
14. Department of Health. A framework for technology enhanced learning. Available at http://www.dh.gov.uk/en/Publicationsandstatistics/Publications/PublicationsPolicyAndGuidance/DH_130924. Published 2011.
15. Angelo RA, Ryu RKN, Pedowitz RA, et al. A proficiency-based progression training curriculum coupled with a model simulator results in the acquisition of a superior arthroscopic Bankart skill set. *Arthroscopy*. In press.
16. Chan KC, Burkhart SS, Thiagarajan P, Goh JC. Optimization of stacked half-hitch knots for arthroscopic surgery. *Arthroscopy* 2001;17:752-759.
17. Lo IK, Burkhart SS, Chan KC, Athanasiou K. Arthroscopic knots: Determining the optimal balance of loop security and knot security. *Arthroscopy* 2004;20:489-502.
18. Burkhart SS, Wirth MA, Simonich M, Salem D, Lanctot D, Athanasiou K. Knot security in simple sliding knots and its relationship to rotator cuff repair: How secure must the knot be? *Arthroscopy* 2000;16:202-207.
19. Karam MD, Pedowitz RA, Natividad H, Murray J, Marsh JL. Current and future use of surgical skills training laboratories in orthopaedic resident education: A national survey. *J Bone Joint Surg Am* 2013;95:e4.
20. Pedowitz RA, Marsh JL. Motor skills training in orthopaedic surgery: A paradigm shift toward a simulation-based educational curriculum. *J Am Acad Orthop Surg* 2012;20:407-409.
21. Thomas GW, Johns BD, Marsh JL, Anderson DD. A review of the role of simulation in developing and accessing orthopaedic surgical skills. *Iowa Orthop J* 2014;34:181-189.
22. Cuschieri A. Whither minimal access surgery: Tribulations and expectations. *Am J Surg* 1995;169:9-19.
23. Krampe RT, Ericsson KA. Maintaining excellence: Deliberate practice and elite performance in young and older pianists. *J Exp Psychol Gen* 1996;125:331-359.
24. Cheung JJ, Rojas D, Weber B, Kapralos B, Carnahan H, Dubrowski A. Evaluation of tensiometric assessment as a measure of skill degradation. *Stud Health Technol Inform* 2012;173:97-101.
25. Ching SS, Mok CW, Koh YX, Tan SM, Tan YK. Assessment of surgical trainees' quality of knot-tying. *J Surg Educ* 2013;70:48-54.
26. Horeman T, Blikkendaal MD, Feng D, et al. Visual force feedback improves knot-tying security. *J Surg Educ* 2014;71:133-141.
27. Huang E, Chern H, O'Sullivan P, et al. A better way to teach knot tying: A randomized controlled trial comparing the kinesthetic and traditional methods. *Am J Surg* 2014;208:690-694.
28. Hu Y, Tiemann D, Michael Brunt L. Video self-assessment of basic suturing and knot tying skills by novice trainees. *J Surg Educ* 2013;70:279-283.
29. Mashaud LB, Arain NA, Hogg DC, Scott DJ. Development, validation, and implementation of a cost-effective intermediate-level proficiency-based knot-tying and suturing curriculum for surgery residents. *J Surg Educ* 2013;70:193-199.
30. Rodrigues SP, Horeman T, Sam P, Dankelman J, van den Dobbelsteen JJ, Jansen FW. Influence of visual force feedback on tissue handling in minimally invasive surgery. *Br J Surg* 2014;101:1766-1773.
31. van Empel PJ, Verdam MG, Huirne JA, Bonjer HJ, Meijerink WJ, Scheele F. Open knot-tying skills: Resident skills assessed. *J Obstet Gynaecol Res* 2013;39:1030-1036.
32. van Leeuwen N, Trimbos JB. Strength of sliding knots in multifilament resorbable suture materials. *Gynecol Surg* 2012;9:433-437.
33. Wong IH, Denkers MR, Urquhart NA, Farrokhyar F. Systematic instruction of arthroscopic knot tying with the ArK Trainer: An objective evaluation tool. *Knee Surg Sports Traumatol Arthrosc* 2015;23:912-918.
34. Wong IH, Denkers M, Urquhart N, Farrokhyar F. Construct validity testing of the Arthroscopic Knot Trainer (ArK). *Knee Surg Sports Traumatol Arthrosc* 2015;23:906-911.
35. Committee on the Governance and Financing of Graduate Medical Education, Board on Health Care Services, Institute of Medicine, Eden J, Berwick D, Wilensky G, eds. *Graduate medical education that meets the nation's health needs*. Washington, DC: National Academies Press, 2014.
36. Asch DA, Weinstein DF. Innovation in medical education. *N Engl J Med* 2014;371:794-795.