In Vitro and In Situ Characterization of Arthroscopic Loop Security and Knot Security of Braided Polyblend Sutures: A Biomechanical Study

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Abstract

We conducted a study to evaluate biomechanical performance during destructive testing of several different suture materials in various arthroscopic knot configurations under both in vitro and in situ conditions. Surgeons of different levels of experience tied the knots.

Three different arthroscopic knots (static surgeon's, Weston, Tennessee slider) with 3 reverse half-hitches on alternating posts were tested using Fiberwire, ForceFiber, Orthocord, and Ultrabraid suture materials under both in vitro and in situ (blood plasma at 37°C) conditions. Three surgeons of different experience levels tied the knots on a post 30 mm in circumference. A single load-to-failure test was performed.

There were no significant in vitro–in situ differences for Ultrabraid in the different knot configurations or with the different experience levels. Surgeon B (intermediate experience) showed no significant differences between test conditions for any knot configuration or suture material. With Tennessee slider knots, surgeon C (least experience) showed significantly lower clinical failure load under both test conditions and had a higher percentage of complete knot slippage. Surgeon B had no knot slippage with use of Fiberwire.

Both the aqueous environment and the surgeon's familiarity with certain knots have an effect on knot security.

Open-surgery knot tying is easily learned and performed, but knot tying during arthroscopic procedures can be both challenging and frustrating. According to Burkhart and colleagues,[1,2] knot security is defined as the effectiveness of the knot in resisting slippage when load is applied, whereas loop security is the effectiveness in maintaining a tight suture loop while a knot is being tied. Arthroscopic knots commonly begin with an initial slipknot locked in place with a series of half-hitches. During arthroscopic surgery, the surgeon usually must tie an arthroscopic knot to obtain secure tissue fixation, an essential component of soft-tissue repair. A secure knot provides optimal tissue apposition for healing, which will ultimately improve functional outcome. For a knot to be effective, it must have both knot security and loop security. Knot security depends on knot configuration, the coefficient of friction, ductility, handling properties, solubility and diameter of suture material, internal interference, slack between throws, and surgeon experience. Tissue fluid and tissue reaction to suture material may affect knot and loop security.

The ideal knot would be easy to tie and reproducible and would not slip or stretch before tissue is healed. The ideal suture material should provide adequate strength to hold soft tissue in an anatomically correct position until healing can occur. It should also be easily and efficiently manipulated by arthroscopic means when tissues are being secured with knots and secure suture loops. Studies have been conducted to evaluate the security of knots tied with arthroscopic techniques, knot configurations, and suture materials, and these investigations have often evaluated knot performance under single load-to-failure (LTF) test scenarios and cyclic loading in vitro (dry environment) in a room-temperature environment.[2-10] To our knowledge, few if any attempts have been made to simulate in situ conditions at body temperature when testing knot security. The fluid environment and the temperature could potentially affect the effectiveness of knots, as knot security depends on friction, internal interference, and slack between throws.[1]

We conducted a study to evaluate biomechanical performance (knot security, loop security) during destructive testing of several different suture materials with various arthroscopic knot configurations. The study was performed under in vitro (dry environment) and in situ (wet environment) conditions by surgeons with different levels of experience.

Authors' Disclosure Statement: DePuy-Mitek, Smith & Nephew, and Stryker provided the suture materials used in this study. The authors report no actual or potential conflict of interest in relation to this article.

Materials and Methods

This investigation was conducted at the Orthopaedic Research Institute at Via Christi Health in Wichita, Kansas. The study compared 4 different suture materials tied with 3 different commonly used arthroscopic knots by 3 surgeons with different levels of experience. The 4 types of braided polyblend polyethylene sutures were Fiberwire (Arthrex, Naples, Florida), ForceFiber (Stryker, San Jose, California), Orthocord (DePuy-Mitek, Warsaw, Indiana), and Ultrabraid (Smith & Nephew, Memphis, Tennessee). Each suture material was tied with 3 arthroscopic knots—static surgeon's knot, Weston knot,[11] Tennessee slider[12]—and a series of 3 reversing half-hitches on alternating posts (RHAPs) (**Figure 1**). These knots were chosen based on studies showing they have a higher maximum force to failure when combined with 3 RHAPs.[1,2,5,9,13-17]

We evaluated performer variability with the help of 3 investigator-surgeons who differed in their level of experience tying arthroscopic knots. This experience was defined on the basis of total number of arthroscopies performed—one of the most important factors predicting basic arthroscopic skills. Our surgeon A was a sports medicine fellowship–trained surgeon with 10 years of experience and a significant number of arthroscopies performed annually (350); surgeon B was a sports medicine fellowship–trained surgeon with 3 years of experience and an annual arthroscopy volume of more than 250 procedures; and surgeon C was a third-year orthopedic resident with about 100 arthroscopies performed.

All knots were tied on a standardized post 30 mm in circumference, which provided a consistent starting circumference for each knot and replicated the suture loop created during arthroscopic rotator cuff repair. All knots were tied using standard arthroscopic techniques, with a standard knot pusher and a modified arthroscopic cannula, in a dry environment (**Figure 2**). Servohydraulic materials testing system instruments (model 810; MTS Systems, Eden Prairie, Minnesota) were used to test the knot security and loop security of each combination of knots and suture types. Two round hooks (diameter, 3.9 mm) were attached to the actuator and the load cell (**Figure 3**). Loops were preloaded to 6 N to avoid potential errors caused by slack in the loops or by stretching of suture materials and to provide a well-defined starting point for data recording.

LTF testing was performed for both in vitro and in situ conditions using 10 samples of each su-

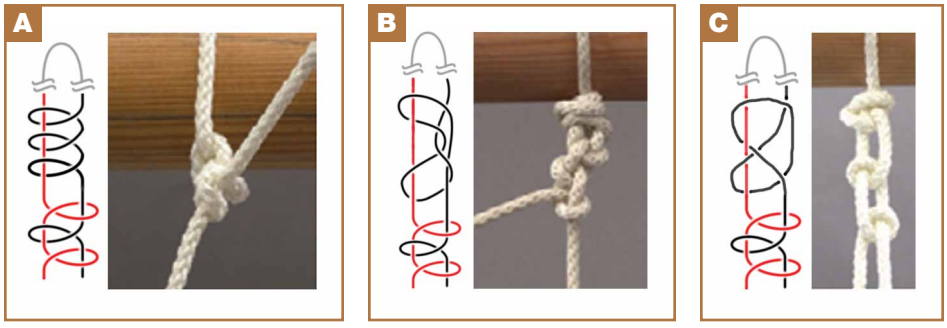

Figure 1. Sliding knot configurations evaluated: (A) static surgeon's knot with 3 reversing half-hitches on alternating posts (RHAPs), (B) Weston knot with 3 RHAPs, (C) Tennessee slider knot with 3 RHAPs.

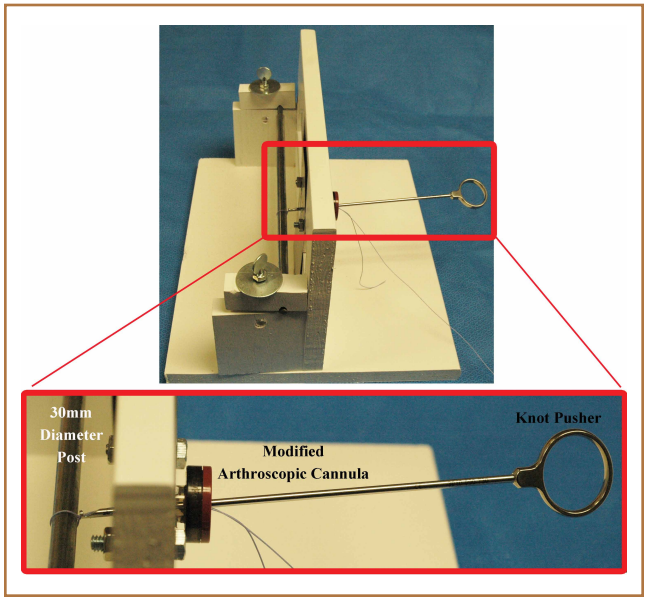

Figure 2. Tying apparatus.

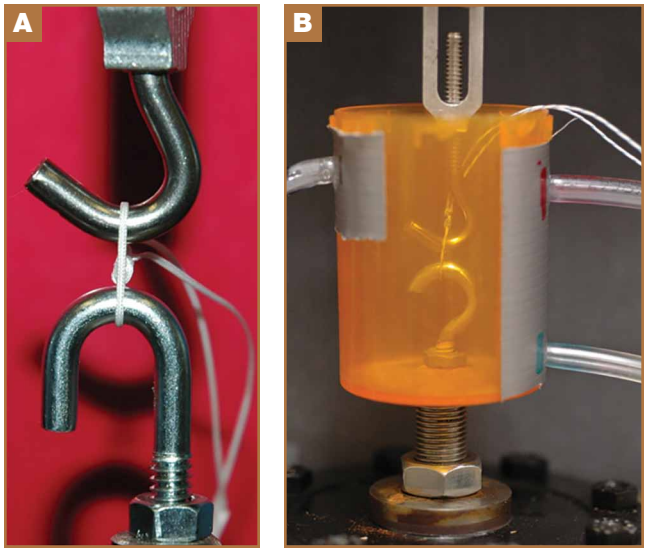

Figure 3. Experimental setup: (A) in vitro and (B) in situ.

ture–knot configuration for each mechanical testing. Each type of testing was conducted for a total of 240 suture–knot combinations per investigator. For the in vitro condition, each suture loop was initiated with 5 preconditioning loading cycles, from 6 N to 30 N at 1 Hz. The load was then applied continuously at a crosshead speed of 1 mm/s until "clinical failure" (3 mm crosshead displacement). We used this criterion for clinical failure, as studies have indicated that 3 mm is the point at which tissue apposition is lost.[15,18-21] After the crosshead reached the 3-mm displacement, the loads (under load control) were held for 5 minutes at maximum load, and then load was applied continuously at a crosshead speed of 1 mm/s until complete structure failure. Load and displacement data were collected at a frequency of 20 Hz.

There was a significant difference between in vitro and in situ conditions with respect to both knot configuration and surgeon experience level, except when Ultrabraid suture material was used.

For the in situ condition, the same test parameters were used, except that each combination of the suture loop was preloaded to 6 N and soaked in physiologic solution bath (human blood plasma) at 37°C (body temperature) for 24 hours before testing in an effort to simulate the aqueous medium in vivo after surgery. The in situ tests were performed under physiologic solution maintained at 37°C to approximate postoperative physical conditions.

Statistical Analysis

Means and standard deviations of the knot security and loop security achieved by the surgeons (different experience levels) were calculated for each test configuration and each test condition. These values were used to determine the statistical relevance of the difference in arthroscopic loop security and knot security in each configuration. One-way analysis of variance (ANOVA) performed with SPSS Version 19.0 software (SPSS, Chicago, Illinois) with the least significant difference (LSD) multiple comparisons post hoc analysis was used to determine if any observed differences between the types of braided polyblend sutures, the types of sliding knots, the test conditions (in vitro, in situ), and the levels of surgeon experience were significant for each knot configuration. The level of significance of differences was set at $P < .001$.

Results

Figure 4 shows the mean maximum clinical failure load (3 mm of displacement) of different arthroscopic knot configurations for different braided polyblend sutures by surgeons of different levels of experience. In the comparison of biomechanical performance (knot and loop security) under in vitro and in situ conditions, no significant difference was detected when Ultrabraid suture material was used, regardless of surgeon experience, for all knot configurations. For surgeon B, there was no significant difference between in vitro and in situ conditions for any knot configurations or suture materials. When Orthocord suture material was used, Weston knots tied by surgeon A, and static surgeon's knots by surgeons A and C, resulted in a significant difference between the in vitro and in situ conditions. When ForceFiber suture material was used, only Weston knots and Tennessee slider knots by surgeon A had a significant difference between in vitro and in situ conditions. Weston knots by surgeon A exhibited a significant difference between in vitro and in situ conditions, except when Ultrabraid suture material was used.

Surgeon C's Tennessee slider knots with all polyblend sutures showed significantly lower loads at clinical failure compared with all the other knot configurations and with knots tied by the other 2 surgeons under both in vitro and in situ conditions. Overall, knots tied by surgeon B had higher clinical failure load than knots tied by the other 2 surgeons.

Figure 5 shows the mean ultimate failure load (complete structural failure) of different arthroscopic knot configurations for different braided polyblend sutures by surgeons of different levels of experience. Knots tied with Orthocord suture material had the overall lower ultimate failure load compared with other suture materials, whereas knots tied with Ultrabraid suture material had the overall highest ultimate failure load. However, the ultimate failure loads for all the knots tied using any suture material, regardless of surgeon experience, were more than 61 N, which is the estimated minimum required ultimate load per suture during a maximum muscle contraction.[1]

Figure 6 shows the percentage of knot slipping at constant clinical failure load. Orthocord and Fiberwire suture materials had the lowest incidence of knot slippage. Surgeon C had complete knot slippage at constant clinical failure load using ForceFiber with the Weston knot and Ultrabraid with the Tennessee slider knot. When using Ultrabraid or ForceFiber, surgeons A and C had at least 2 knots slip for all knot configurations.

Discussion

Optimization of knot security for any given knot configuration, suture material, and surgeon experience level during arthroscopic knot tying is crucial.[1-10] Our study results showed that, under single LTF test scenarios, there was a significant difference between in vitro and in situ conditions with respect to both knot configuration and surgeon experience level, except when Ultrabraid suture material was used. Arthroscopic sliding knots are lockable or nonlockable.[7,12] With lockable sliding knots, slippage may be prevented by tensioning the wrapping limb, which distorts the post in the distal part of the knot, resulting in a kink in the post, thereby increasing the internal interference that increases the resistance of the knot from backing off. With nonlockable sliding knots, slippage

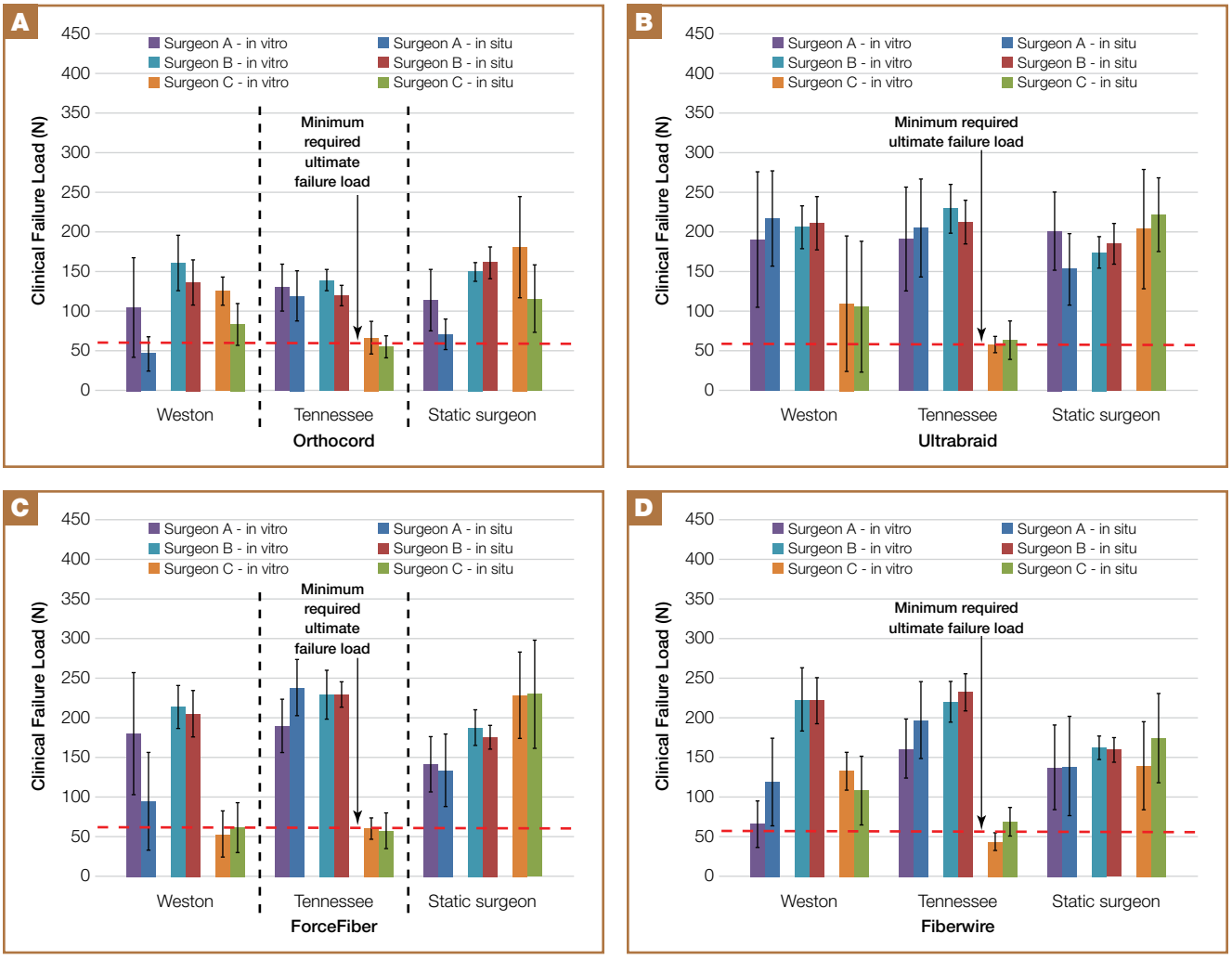

Figure 4. Mean maximum clinical failure load (3-mm displacement) of sliding knots with 3 reversing half-hitches on alternating posts for 4 different braided polyblend sutures: (A) Orthocord (DePuy-Mitek, Warsaw, Indiana), (B) Ultrabraid (Smith & Nephew, Memphis, Tennessee), (C) ForceFiber (Stryker, San Jose, California), and (D) Fiberwire (Arthrex, Naples, Florida). Surgeon A, sports medicine fellowship–trained and 10 years of clinical experience; surgeon B, sports medicine fellowship–trained and 3 years of clinical experience; surgeon C, third-year orthopedic resident.

may be prevented by the tight grip of the wrappings around the initial post.[7] The static surgeon's knot and the Tennessee slider knot are nonlockable, whereas the Weston knot is a distal lockable sliding knot. Compared with nonlockable sliding knots, lockable sliding knots cause less suture loop enlargement. In 1976, Tera and Aberg[22] studied the strength of knotted thread for 12 different types of suture knots combined with 11 types of suture material. They conducted their study 1 week after suture material was inserted into the subcutaneous tissue of rabbits. Their results show a greater propensity for certain suture materials to slip when tested in an aqueous environment. In 1998, Babetty and colleagues[23] used Wistar rats to compare the in vivo strength, knot efficiency, and knot security of 4 types of sliding knots and to assess tissue reaction as a result of knot configuration, knot volume, and suture size. They found that 4/0 knots lost more strength than 2/0 knots did, and they concluded that the tissue response to all the knots, except 2/0 nylon, was similar. They indicated that the inflammatory sheath volume varied with knot volume, suture size, and knot configuration. Our results agree with observations that exposure to an aqueous environment alters the force to clinical failure of comparable suture and knot configurations.

In addition, our findings indicate that surgeon familiarity with certain knots has a major effect on knot security. The difference in our 3 surgeons' levels of familiarity with certain knots was somewhat minimized by the knot tying they practiced before submitting knots for testing. The findings contrast with those of Milia and colleagues,[24] who conducted a biomechanical study to determine the effect of experience level on knot security. They compared an experienced arthroscopic shoulder surgeon with a junior-level orthopedic resident surgeon and concluded that experience did not affect knot security. However, the knots in their study were tied by hand, not through an arthroscopic cannula with instruments.

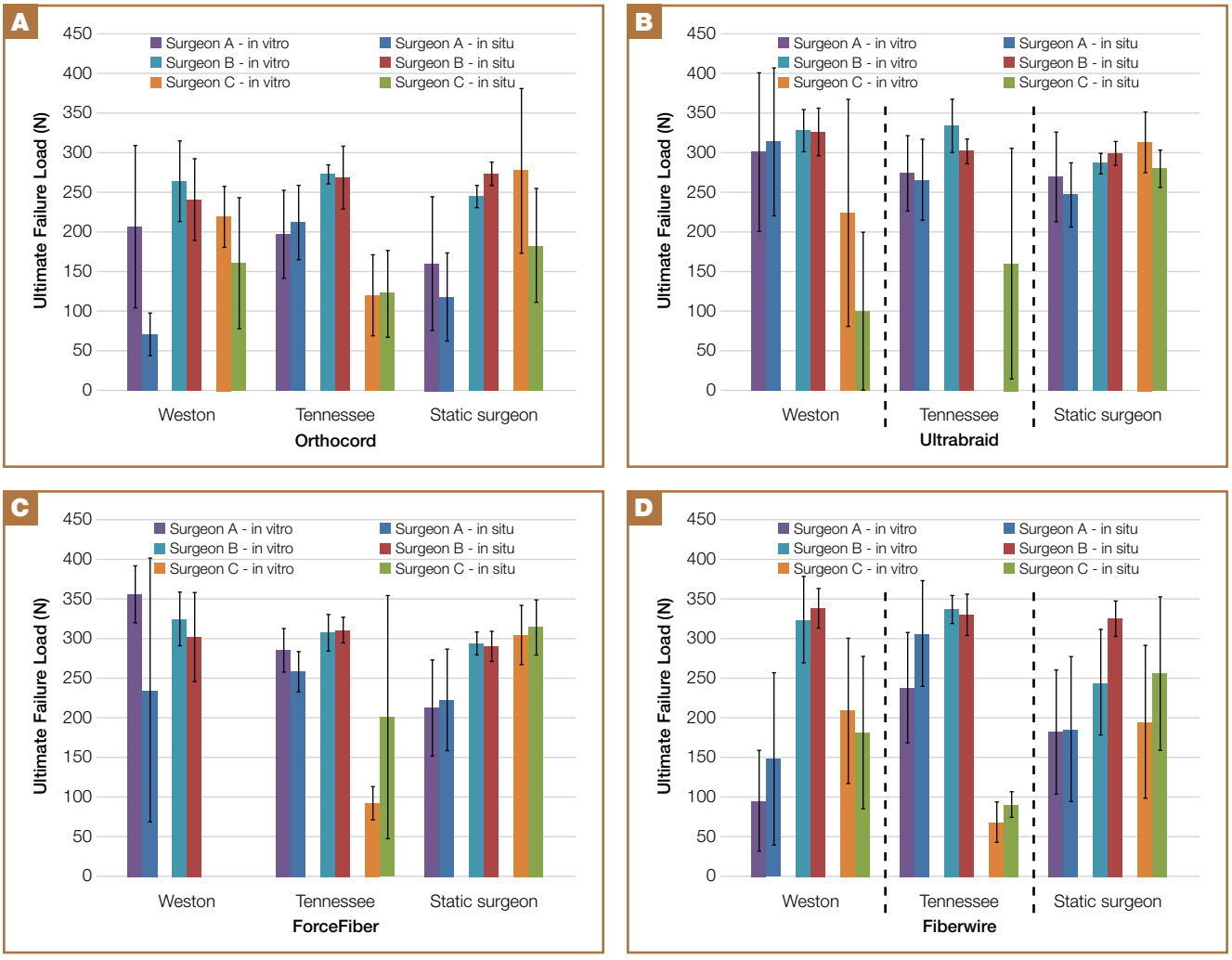

Figure 5. Mean ultimate failure load (complete structure failure) of sliding knots with 3 reversing half-hitches on alternating posts for 4 different braided polyblend sutures: (A) Orthocord (DePuy-Mitek, Warsaw, Indiana), (B) Ultrabraid (Smith & Nephew, Memphis, Tennessee), (C) ForceFiber (Stryker, San Jose, California), and (D) Fiberwire (Arthrex, Naples, Florida). Surgeon A, sports medicine fellowship–trained and 10 years of clinical experience; surgeon B, sports medicine fellowship–trained and 3 years of clinical experience; surgeon C, third-year orthopedic resident.

Our findings suggest that both experienced and less experienced orthopedic residents should be encouraged to practice arthroscopic knot tying in a nonsurgical environment in order to become comfortable tying arthroscopic knots.

Braided nonabsorbable polyester suture traditionally has been found to be stronger than monofilament absorbable polydioxanone (PDS) and to have less slippage potential.[8,9,25] Several studies have determined that the braided polyblend sutures now commonly used for arthroscopic knots have better strength profiles over more traditional materials.[12,26,27] Orthocord has a dyed absorbable core (PDS, 68%), an undyed nonabsorbable ultrahigh-molecular-weight polyethylene (UHMWPE, 32%) sleeve, and a polyglactin coating.[9,10] Both Ultrabraid and ForceFiber are made with braided UHMWPE and have just a few variations in weave patterns. Fiberwire has a multifiber UHMWPE core covered with braided polyester suture material. Several biomechanical studies[25,26,28] have evaluated different arthroscopic sliding knot configurations with different suture materials, and all concluded that a surgeon who is choosing an arthroscopic repair technique should know the differences in suture materials and the knot strengths afforded by different knot configurations, as suture material is an important aspect of loop security. Our findings agree with their findings, that suture materials have a major effect on knot security, even with a series of 3 RHAPs, as in theory the RHAPs should minimize suture friction, internal interference, and slack between knot loops—emphasizing the effect of material selection. Furthermore, our findings also indicated that suture materials with a core in their design (Fiberwire, Orthocord) tend to have the lowest incidence of knot slippage. We had suspected that suture surface characteristics and suture construction could be important factors in knot slippage.

Our experimental design had its limitations. First, although we simulated factors such as temperature, plasma environment,

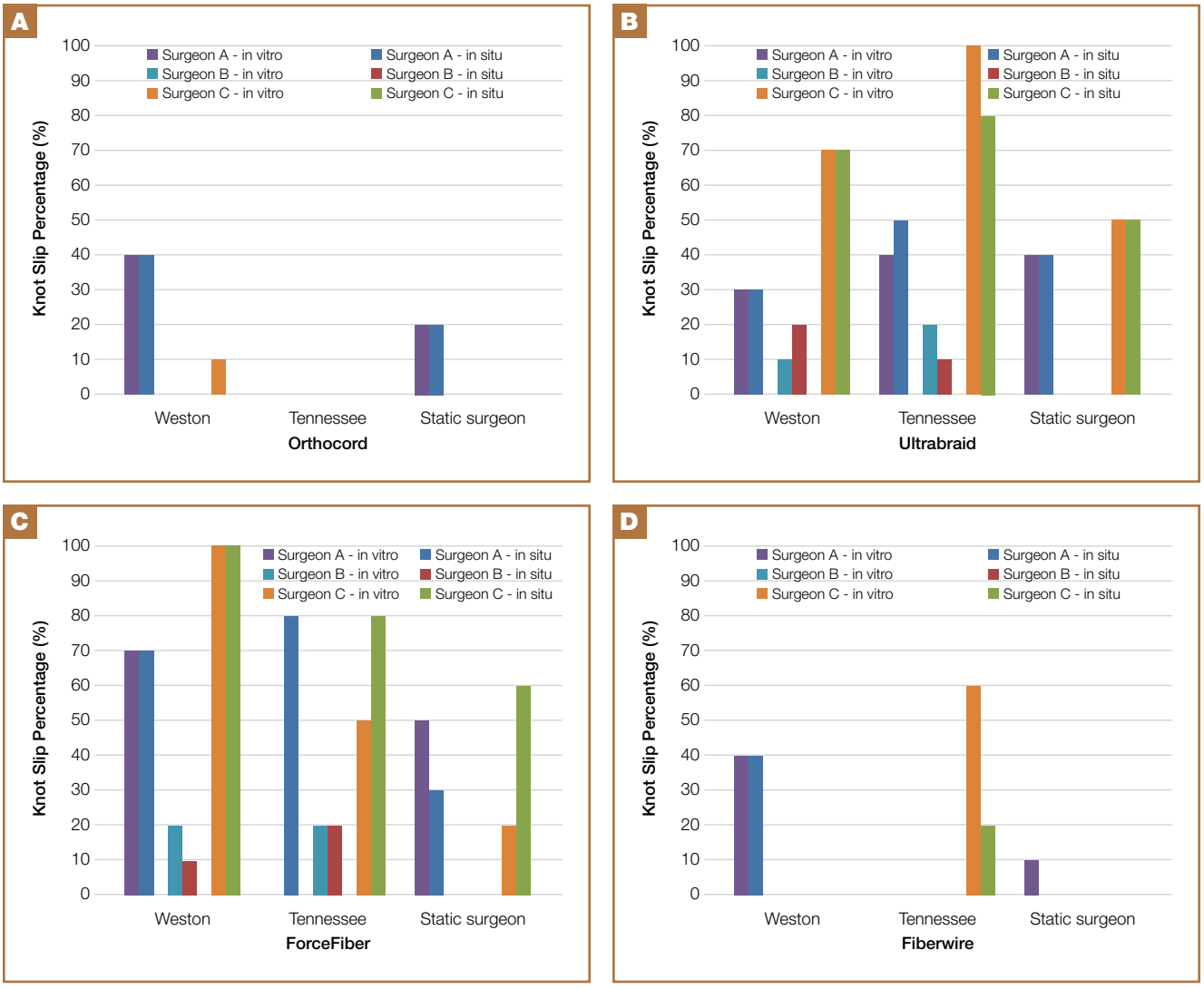

Figure 6. Percentage of knot slipping at constant clinical failure load for 4 different braided polyblend sutures: (A) Orthocord (DePuy-Mitek, Warsaw, Indiana), (B) Ultrabraid (Smith & Nephew, Memphis, Tennessee), (C) ForceFiber (Stryker, San Jose, California), and (D) Fiberwire (Arthrex, Naples, Florida). Surgeon A, sports medicine fellowship–trained and 10 years of clinical experience; surgeon B, sports medicine fellowship–trained and 3 years of clinical experience; surgeon C, third-year orthopedic resident.

and surgeon experience, tying a knot on a standardized post (30 mm in circumference) differed from what is typically done clinically. Second, the metal hooks used in this study were not compressible and did not interpose in the substance of the knot as soft tissue does in the clinical setting. Third, knots were tied with no tension against the sutures, whereas clinically knots are tied under tension as tissues are pulled together in reconstructions. Fourth, it was assumed that soaking in a physiologic solution bath (human blood plasma) at 37°C (body temperature) for 24 hours before testing was sufficient to simulate the aqueous medium in vivo after surgery, but these parameters may not represent conditions in a patient who has just undergone an arthroscopic shoulder repair and adheres to a passive motion protocol. Fifth, there was no blinding of knot type, and there was no randomization of tying order or testing order. Sixth, only a single LTF test was performed, and incremental cyclic loading can be more useful, as it has long been recognized as a leading source of failure in orthopedic repairs.

Conclusion

These study results advance our overall understanding of the biomechanics of the different knot configurations and loop security levels of the different braided polyblend sutures used in arthroscopic procedures through LTF in both in vitro and in situ conditions. Overall, no suture material was superior to any other in a fluid environment, as the combination of aqueous environment and surgeon level of experience with arthroscopic knot tying has a major effect on knot security under single LTF test scenarios. However, our data showed that Ultrabraid suture material had no effect on knot effectiveness over the fluid environment and the temperature. Furthermore, the study showed that the Tennessee slider knot had the steep-

est learning curve. This study may provide an alternative arthroscopic knots option for soft-tissue repair in which use of certain suture materials is limited.

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