EDITOR'S CHOICE

Comparative Accuracy of 1.5T MRI, 3T MRI, and Static Ultrasound in Diagnosis of Small Gaps in Repaired Flexor Tendons: A Cadaveric Study

Kevin J. Renfree, MD,* Nirvikar Dahiya, MD,† Mark J. Kransdorf, MD,† Nan Zhang, MS,‡ Karan A. Patel, MD,* Patricia A. Drace, MD§

Purpose We hypothesized that magnetic resonance imaging (MRI) would more accurately diagnose small gaps (<6 mm) after flexor tendon repair than static ultrasound (US) and that suture artifact would negatively impair accuracy.

Methods A laceration of the flexor digitorum profundus was created in 160 fresh-frozen cadaveric digits and randomized to either an intact repair (0-mm gap) or repairs using a locked 4-strand suture repair with either 4-0 Prolene, Ethibond, or and gaps of 2, 4,or 6 mm; or no suture in which 2-, 4-, or 6-mm gaps were created without a suture crossing the repair site. We performed 1.5T and 3T MRI and static US studies; gap widths were estimated by radiologists blinded to suture presence and true gap widths.

Results The 1.5 and 3.0T MRI had a lower mean error than US for gap sizes 0 and 2 mm. All 3 modalities performed similarly for 4- and 6-mm gaps. Documentation of imaging artifact worsened error, and odds of seeing artifacts were 1.72 higher with MRI than with US. Suture did not worsen artifact nor impair accuracy for any of the 3 modalities. When no suture was used, all 3 modalities significantly overestimated the true gap.

Conclusions MRI is most accurate for small gaps less than 4 mm. Although all modalities overestimated gap sizes in specimens with a 0-mm gap (intact tendon repair), mean over-estimation (<2 mm) was not clinically relevant. Ultrasound overestimated 2-mm gaps (clinically intact repairs), whereas MRIs did not. We recommend MRI for evaluation of gaps after flexor tendon repair. The 1.5T has slightly better sensitivity and specificity for distinguishing clinically intact (gap < 3 mm) from clinically impaired (gap > 3 mm) repairs than the 3T.

Clinical relevance Accurate diagnosis of intact repairs or small gaps (<3 mm) might prevent unnecessary exploration or allow modification of rehabilitation protocols. Diagnosis of clinically relevant gaps (3−6 mm) may allow for earlier revision surgery before significant tendon retraction and adhesions develop, possibly necessitating a staged reconstruction. *(J Hand Surg Am. 2021;46(4):287−294. Copyright © 2021 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words Flexor tendon, gap, magnetic resonance imaging, ultrasound.

*From the *Department of Orthopaedic Surgery; the †Department of Radiology; the ‡Department of Biostatistics, Mayo Clinic Arizona; the §Department of Orthopaedic Surgery, Phoenix Children's Hospital, Phoenix, AZ.*

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Corresponding author: Kevin J. Renfree, MD, Department of Orthopaedic Surgery, Mayo Clinic Arizona, 5777 E. Mayo Blvd., Phoenix, AZ 85054; e-mail: renfree.kevin@mayo.edu.

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Reruptures after flexor tendon repair have a reported incidence of 4% to 6%.[1] Stronger, multistrand repairs continue to be described, but there is no evidence that this has reduced the risk of rupture. It is possible that the actual incidence is underreported because it can be difficult to make a definitive diagnosis of rerupture. Cases often develop insidiously via progressive gapping at the repair site over the first few weeks after repair[2–4] and may present as triggering or stiffness, with or without contracture. Clinical diagnosis of flexor tendon reruptures has been found to be unreliable, with a reported 60% accuracy rate.[5] If reexploration is not performed, the diagnosis often is unconfirmed. An accurate and precise diagnosis of gap formation after repair during the early phases of postoperative rehabilitation could have an important impact on decision-making with respect to exploration and rerepair. In addition, adjustments in the rehabilitation program (change from an active to a passive range of motion protocol) might prevent progression of a small, clinically insignificant gap (<3 mm in our opinion) to frank rupture. Furthermore, if larger gaps are not recognized early, direct rerepair may not be possible and late grafting could be required.[5] Therefore, there exists a need for accurate diagnosis of repair integrity when there is a clinical concern. Currently, magnetic resonance imaging (MRI) and high-resolution ultrasound (US) are the most commonly used imaging modalities for assessment of flexor tendon repair integrity. However, there is little information about the accuracy of either of these modalities, especially for evaluating gap sizes less than 10 mm. We embarked upon the current study to determine the accuracy of MRI and to compare this modality with static, high-resolution US for diagnosing small (<6-mm) tendon gaps. Secondarily, we sought to determine how accuracy might be affected by suture artifact using a contemporary, multistrand repair technique. We hypothesized that both MRI (1.5T, 3.0T) modalities would be more accurate than high-resolution US, particularly when suture was present.

METHODS

Our primary outcome was a continuous variable, and we wished to determine its difference in a repeated-measure data setting. A sample size of 80 was calculated for 81% power to detect an effect size of 0.36 (medium effect size) using a repeated measure design with 1 within factor and with a .05 2-sided significance level. The ulnar 4 digits (thumbs excluded) from 40 completely thawed fresh=frozen cadaveric arms (amputated above elbow) were studied (160 digits). Computer randomization was used to pair digit (index, middle, ring, or little) gap at tendon repair site (0, 2, 4, or 6 mm), and suture type used for repair (4-0 Prolene, Ethibond, or FiberWire), or no suture in which a 2-, 4-, or 6-mm gap was created but no sutures were placed across it. A Brunner incision was made in each digit from the metacarpophalangeal to the distal interphalangeal joint flexion crease. The A3 pulley was excised and a complete transverse laceration was made in the flexor digitorum profundus (FDP) tendon, midway between the distal end of the A2 and the proximal end of the A4 pulleys. The flexor digitorum sublimis tendon was left intact. A 4-strand locked cruciate repair was performed, allowing 10 mm (from lacerated ends) of suture purchase in each stump[6] (Fig. 1). This repair configuration was chosen because 4-strand repairs are becoming more popular with early motion protocols, and they have a good combination of mechanical strength and minimal bulk.[7,8] Epitendinous repairs were not performed because of the potential for a disproportionately greater amount of suture material in the tendons with larger gaps. An electronic digital caliper accurate to 0.01 mm (Westward; Grainger International, Lake Forest, IL) was used to confirm gap width. For tendons with a 0-mm gap, the suture was locked when slight bunching of the tendon ends was visualized. Repairs were performed under 3.5× loupe magnification by the senior author (K.J.R.), a board-certified hand surgeon with 25 years' experience. After repair, digits were fully passively flexed and extended 25 times in order to stress the repair. Gaps were remeasured, ensuring that gap widths were precisely maintained, or the repair was redone. Skin wounds were closed with a running 4-0 nylon suture.

FIGURE 1: Specimen with a 4-mm sutured gap using 4-0 Ethibond in a locked cruciate repair. Dark arrow depicts the knot outside the repair site.

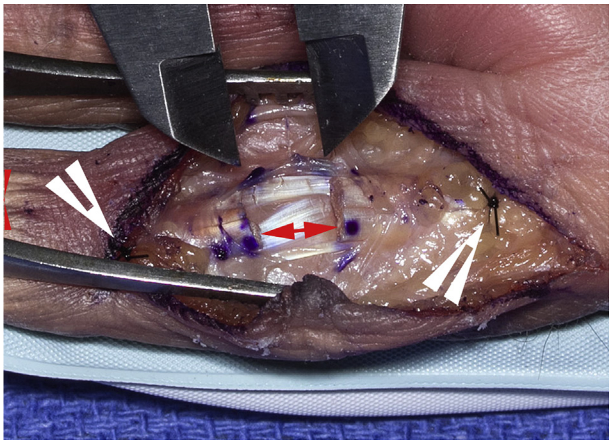

FIGURE 2: Specimen with a nonsutured gap (red double arrow) in the flexor digitorum profundus (FDP) tendon. The tendon gap is maintained by sutures placed through the FDP and pulleys proximal and distal to the repair gap (white arrows).

FiberWire (Arthrex, Inc., Naples, FL) suture is constructed of a multistrand, ultrahigh molecular weight polyethylene (UHMWPE) core with a braided jacket of polyester and UHMWPE. Ethibond (Ethicon Inc., 389065, Wound Closure Manual, 2007; Data on File) is a nonabsorbable, braided, suture prepared from fibers of high molecular weight, long-chain, linear polyesters. Prolene (Ethicon Inc., 389065, Wound Closure Manual, 2007; Data on File) sutures are nonabsorbable and composed of an isotactic crystalline stereoisomer of polypropylene, a synthetic linear polyolefin.

In specimens randomized to no suture, 2-, 4-, or 6-mm gaps were created between tendon ends, and widths were maintained by suturing the distal FDP stump to the A4 pulley and the proximal FDP stump to the A2 pulley (at least 1 cm from the gap in lacerated tendon) with a 4-0 nylon horizontal mattress suture (Fig. 2). All specimens were then evaluated within 24 hours after repair with both 1.5 and 3.0T MRI and US by a board-certified musculoskeletal radiologist (M.J.K) and ultrasonographer (N.D.), respectively, both of whom were blinded to suture presence/type, and gap width. For MRI evaluation, cadaver hands were positioned in the center of the magnet with the fingers in the extended position. Imaging was done on 1.5T GE Excite and 3T Siemens Sykra MR scanners utilizing a dedicated hand/wrist coil. The index through little fingers were scanned in the sagittal plane utilizing T1 (TR/TE; 664 ms/15 ms) and fat-suppressed PD (TR/TE; 300 ms/32 ms) sequences, with a slice thickness of 2 mm, 0.236-mm gap, nominal 6 cm × 10 cm field-of-view, and a 320−384 × 144−178 matrix. US examinations were performed in static mode using GE Logiq E9 ultrasound equipment (GE Healthcare, Milwaukee, WI). The ML6-15 and L8-18i transducers were used as found appropriate depending on the size of the finger being examined. Each radiologist also commented on whether they felt that there was any artifact (not quantified) on the images. Following imaging, surgical incisions were reopened and gaps remeasured to confirm that the original gap widths were maintained.

Statistical analysis

Accuracy of the modality (defined as the difference between observed and true gap) was calculated and a paired *t* test used to calculate 95% confidence interval for gap measurement error. To investigate the impact of all factors (imaging modality, artifact identification, digit type, gap size, suture presence, and suture type) on accuracy, an overall mixed model with repeated measures was used. Interaction effects between imaging modality, gap size, and suture presence/type were also included in the overall model. Influence of gap size, suture, or imaging modality on subjective impression of image artifact was analyzed by logistic regression (GEE method) using artifact as the outcome, and with gap size, suture type, and imaging modality as predictors.

RESULTS

Both 1.5 and 3.0T MRI had a lower mean error (difference between observed and true gap) than US for gap sizes 0 and 2 mm. All 3 modalities performed similarly for larger (4- and 6-mm) gaps, demonstrating improved accuracy. The 3.0T MRI had the lowest mean error for 0- and 4-mm gaps, and the 1.5T MRI had the lowest mean error for 2- and 6-mm gaps (Table 1). Main effect model results (least square means − model estimated from the model for each main effect) are summarized in Table 2, and interaction between imaging modality with gap size and suture type in Figures 3 and 4, respectively.

Table 3 shows sensitivity (ability to correctly diagnose a clinically impaired repair [gap > 3 mm]) and specificity (ability to diagnose a clinically intact repair [gap < 3 mm]) for all 3 modalities. US was less accurate ($P < .05$), than 1.5T or 3.0T MRI for all gap widths. However, gap width influenced ($P < .05$) accuracy for all 3 modalities. In Figure 3, for a true gap size of 0 mm (intact repair), US and both 1.5T and 3.0T MRI (combined because their results were similar) significantly ($P < .05$) overestimated gap width (difference > 0). Specificity for each modality was 90% (1.5T MRI), 88% (3.0T MRI),

TABLE 1. Estimated Gap Summary Statistics by MRI Method and by Gap Size

MRI	Statistics	Gap 0	Gap 2	Gap 4	Gap 6
1.5T	Mean (SD), total n	0.3 (0.8), 41	2.0 (1.3), 42	3.7 (1.9), 43	6.0 (1.7), 26
	Median (range)	0 (0.0 to 3.5)	2.2 (0.0 to 5.4)	3.8 (0.0 to 6.8)	6.4 (0.0 to 8.8)
	Difference compared with actual gap difference (95% CI); *P* value*	0.3 (0.06 to 0.58); <.05	0 (−0.38 to 0.40); .94	−0.3 (−0.89 to 0.30); .32	0 (−0.70 to 0.64); .92
3.0T	Mean (SD), total n	0.3 (0.8), 42	2.1 (1.2), 42	3.7 (1.8), 44	5.6 (2), 28
	Median (range)	0.0 (0.0 to 3.9)	2.1 (0.0 to 4.4)	3.9 (0.0 to 6.8)	6.0 (0.0 to 9.3)
	Difference compared with actual gap difference (95% CI); *P* value*	0.3 (0.04 to 0.56); <.05	0.04 (−0.35 to 0.42); .9	−0.29 (−0.83 to 0.24); .3	−0.39 (−1.15 to 0.38); .3
US	Mean (SD), total n	1.9 (2.1), 43	2.9 (2.7), 43	3.8 (2.4), 44	5.6 (2.6), 26
	Median (range)	1.7 (0.0 to 8.0)	2.0 (0.0 to 14.0)	3.9 (0.0 to 9.2)	6.0 (0.0 to 13.0)
	Difference compared with actual gap difference (95% CI); *P* value*	1.9 (1.27 to 2.56); <.05	0.9 (0.08 to 1.72); <.05	−0.2 (−0.92 to 0.53); .6	−0.4 (−1.44 to 0.63); .4

95% CI, 95% confidence interval.
*Paired *t* test was used to calculate the difference and 95% CI.

and 71% (US). Sensitivity was less for all 3 modalities: 78% (both 1.5T and 3T MRI), and 69% (US).

When no suture was used, all 3 modalities significantly ($p < .05$) overestimated the true gap. When Ethibond, FiberWire, and Prolene suture were used (all sutured specimens combined and compared with the no suture group), gap estimates were not significantly different from 0, with US slightly overestimating and both 1.5T and 3.0T MRI underestimating the true gap (Fig. 4). Suture type did not affect accuracy.

Neither gap size nor suture type influenced artifact being reported. The MRI method, however, did have a difference with frequency in which artifacts were reported ($P < .05$). Signal artifact frequencies and percentages by all 3 imaging modalities are summarized in Table 4. Among 160 observations using 1.5T MRI, 96 (60%) reported artifact compared with 92 (57.5%) for 3.0T MRI, and 73 (45.6%) for US. Therefore, when using 1.5T or 3.0T MRI to image small gaps after flexor tendon repair, the odds of seeing artifacts was 1.72 (95% confidence interval, 1.22−2.43) higher ($P < .05$) compared with that using US. Documentation of imaging artifact led to much larger error ($P < .05$).

DISCUSSION

Published literature regarding flexor tendon imaging has largely focused on confirmation of ruptures and localization of the proximal stump for surgical planning.[9−12] With increasingly higher-resolution US probes, postprocessing software,[13] and 3.0T MRI scanners, diagnostic accuracy may be improving, although objective data are lacking. This is particularly true with respect to small, but clinically relevant, gap formation after tendon repair. A critical gap width, which will likely lead to repair failure, is not well defined, but felt to be between 1 and 3 mm.[4,14,15] Most reports evaluating the effects of gap size on tendon biomechanics have been done in animals or cadaveric specimens. US is relatively inexpensive and increasingly available, and there is growing interest for its use in musculoskeletal pathology[16]; however, it does have limitations. Flexor tendon repair failure can be difficult to diagnose due to small distances between the distal and the proximal stumps, small size of the tendons, potential signal artifact from suture, and tendon adhesions that can prevent assessment of tendon gliding during dynamic US scanning. Overzealous dynamic scanning in the early weeks after repair can also be risky because of potential for tendon repair disruption with passive motion, particularly if tendon adhesions are present. In addition, motion of the digit during dynamic imaging can interfere with appropriate placement of the transducer against the skin and gel pad, potentially interfering with an ability to obtain adequate transverse and axial views needed for localization and measurement of lesions. Tendons with small, but clinically relevant gaps (>3 mm) after repair may still

TABLE 2. Mixed Model Results Summary

Effect	Level	Estimate	95% CI	*P* Value
MRI1	1.5T or 3.0T	−0.09 (0.11)	−0.31 to 0.12	<.05
	US	0.58 (0.14)	0.30 to 0.85	
Artifact1	Mild or severe	0.52 (0.13)	0.27 to 0.77	<.05
	No	−0.03 (0.13)	−0.29 to 0.23	
Digit	Index	0.35 (0.19)	−0.02 to 0.72	.70
	Middle	0.27 (0.19)	−0.10 to 0.64	
	Ring	0.30 (0.19)	−0.07 to 0.67	
	Little	0.05 (0.19)	−0.33 to 0.43	
Gap	0	1.54 (0.19)	1.16 to 1.92	<.05
	2	0.42 (0.18)	0.06 to 0.78	
	4	−0.27 (0.18)	−0.63 to 0.09	
	6	−0.72 (0.24)	−1.19 to −0.25	
Repaired type	Ethibond	0.08 (0.19)	−0.29 to 0.46	<.05
	FiberWire	−0.05 (0.20)	−0.43 to 0.34	
	No suture	1.39 (0.21)	0.98 to 1.81	
	Prolene	−0.46 (0.19)	−0.84 to −0.08	
Interaction MRI and gap size		Estimated (Fig. 1)		<.05
Interaction MRI and repaired type		Estimated (Fig. 2)		.40

95% CI, 95% confidence interval.

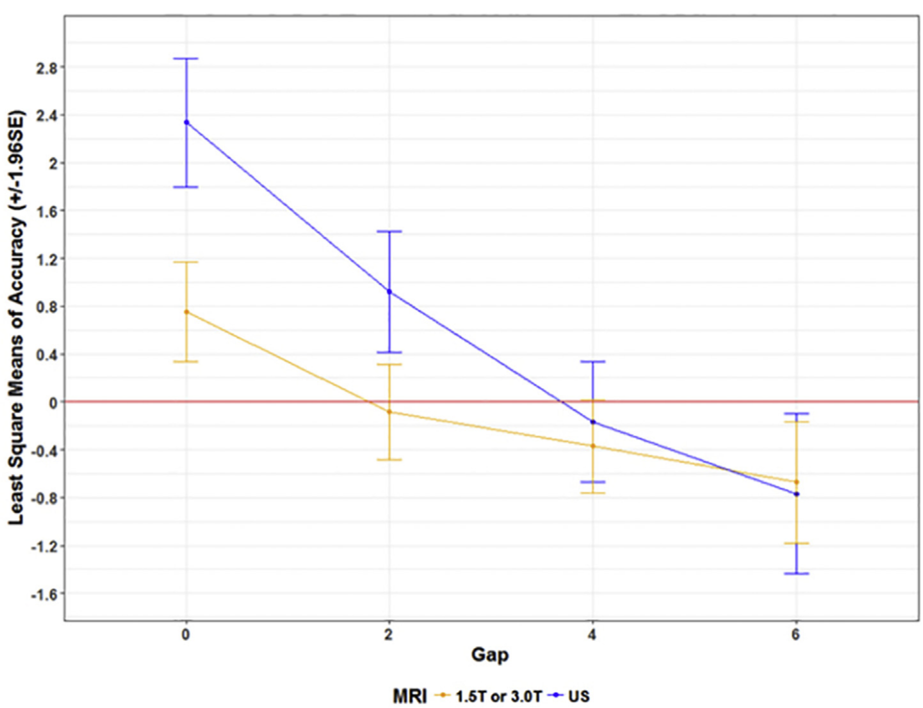

FIGURE 3: Graph depicts the interaction between imaging modality (1.5 and 3.0 T versus US) and tendon gap size. As gap size increases, accuracy improves for all 3 modalities ($P < .05$).

be able to glide in continuity during dynamic scanning, despite impending clinical failure. Adhesions may prevent tendon gliding. Complex injuries with associated fractures and joint injuries or after revascularization, as well as digits with significant joint contractures, can also be difficult to evaluate

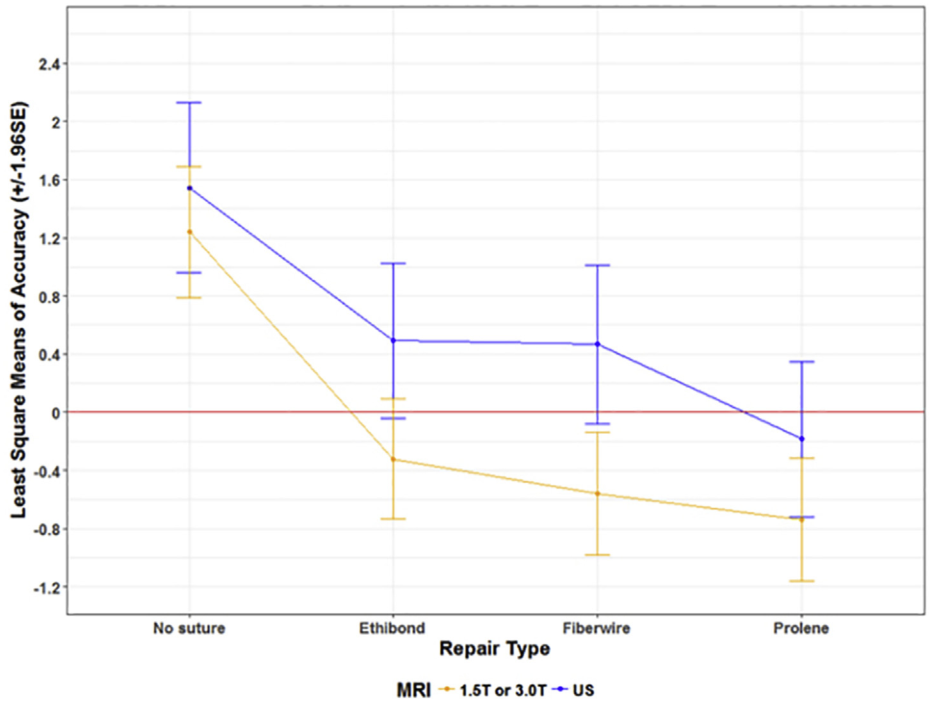

FIGURE 4: Graph demonstrates that all 3 modalities overestimate ($P < .05$) gap size when no suture is present. No real difference in gap estimates is seen with respect to the 3 suture types (Ethibond, FiberWire, and Prolene) studied.

TABLE 3. Sensitivity and Specificity by Modality

Modality		Clinically Significant Gap (Gap 4 and 6 mm)	Clinically Insignificant Gap (Gap 0 and 2 mm)	Sensitivity (%)	Specificity (%)
1.5T	Predicted significant gap (>3 mm)	54	8	78.3	90.4
	Predicted nonsignificant gap (≤3 mm)	15	75		
3.0T	Predicted significant gap (>3 mm)	56	10	77.8	88.1
	Predicted nonsignificant gap (≤3 mm)	16	74		
US	Predicted significant gap (>3 mm)	48	25	68.6	70.9
	Predicted nonsignificant gap (≤3 mm)	22	61		

dynamically. No definitive advantage of dynamic over static US has been shown, and the latter is technically easier because flexor tendons are relatively superficial and run a straight course parallel to the skin.[17] For this reason, we chose to compare static US evaluation to MRI. Zhang et al[18] reported that US allowed localization of the distal end of the ruptured tendons and was consistent with surgical findings in all cases (95 of 95, 100%). However, in their study, mean gap distance between the proximal and distal ends of the complete ruptures was 9.2 ± 3.6 mm.[18] Our findings confirm these—US is quite accurate in diagnosing larger gaps greater than 6 mm—but we wished to also determine its accuracy for diagnosing intact repairs and small gaps (<3 mm) that are clinically significant and to compare with MRI.

MRI may be superior to US for tendon imaging in terms of soft tissue contrast and resolution, especially given the contemporary use of surface coils and reduced field-of-view imaging to enhance spatial resolution.[19] MRI also allows for multiplanar imaging without manipulation of the digit. There are very

TABLE 4. Artifacts Reported by Modality

	Method			
	1.5T	3.0T	US	
	(n = 160)	(n = 160)	(n = 160)	OR (95% CI); *P* Value
Artifact, n (%)				
No	64 (40)	68 (42.5)	87 (54)	1.7 (1.22−2.43); <.05
Mild or severe	96 (60)	92 (57.5)	73 (46)	

95% CI, 95% confidence interval; OR, odds ratio.

few blinded studies that compare MRI with US,[16] especially when compared with the reference standard, exploration, and documentation of exact gap size. Many MRI studies evaluating repaired tendons are case-based, do not report estimated nor confirmed gap sizes, and present cases in which MRI was inconclusive and tendon repairs were found to be intact at the time of exploration.[5] MRI has drawbacks including expense, accessibility, required use of specialized surface coils, claustrophobia, and movement-related or hardware artifacts, and it is contraindicated in patients with cardiac pacemakers, defibrillators, or prior cerebral aneurysm surgery.[13,16] Therefore, it would be helpful to have a clear understanding of the true diagnostic value.

Biomechanical studies suggest that a gap greater than 3 mm after flexor tendon repair increases the risk of rerupture.[4,14] Therefore, the ability to diagnose intact repairs or small gaps (<3 mm) may prevent unnecessary surgical exploration. Conversely, accurate diagnosis of small, but clinically relevant gaps (3−6 mm) may allow for earlier revision surgery before significant tendon retraction and adhesions develop that might necessitate a staged reconstruction. Gap formation usually occurs in the first few weeks after tendon repair.[12] Zhao et al[14] concluded that there is a "threshold effect of 2 to 3 mm, beyond which catastrophic failure of the repair was likely" if motion continued. Therefore, accurate assessment of repair integrity in the weeks after repair, particularly if clinical assessment of motion is concerning (mismatch of active and passive motion), would be helpful during rehabilitation and may prevent unnecessary explorations, which can place neurovascular structures at risk and promote adhesions. In addition, it may help to modify rehabilitation protocols. Digital stiffness after flexor tendon repair may be due to adhesive scarring. If repair integrity can be accurately confirmed, more rigorous hand therapy may improve tendon gliding and range of motion. Similarly, therapy can be restricted (switched from active to passive motion) if a small (<3-mm) gap is identified. Popular clinical methods of assessment such as the Strickland formula are not reliable for early assessment of tendon repair integrity.[5,20]

We hypothesized that suture may produce echogenic foci on US or signal artifact on MRI that could be confused with a repair gap or prevent clear distinction of tendon ends. In a recent survey of members of the American Society for Surgery of the Hand, a majority reported using a 4-strand repair; with 3-0 or 4-0 core braided, nonabsorbable sutures, which encouraged us to use this configuration.[21] We also used 3 different types of suture material that are popular for flexor tendon repair. Signal artifact was reported more commonly with both 1.5T and 3.0T MRI than with US, and when artifact was reported it significantly reduced accuracy of gap estimation. Interestingly, neither the presence of suture nor suture type had an effect on frequency of artifact being reported compared with gaps with no suture. Gap size also had no effect on artifact reporting. Some authors have reported poor success in diagnosing tendon ruptures in the little finger owing to the more-diminutive tendon size and have even recommended against using US to image tendons in this digit.[13,22] Our results, however, do not show less accurate gap assessment for any of the 3 imaging modalities in the little finger, nor any significant effect related to specific digit involvement.

Shortcomings of our study include a lack of soft tissue edema and hemorrhage in cadaver tendons, as has been shown surrounding postsurgical reruptures in previous MRI studies.[20] Air artifact from a freshly closed incision, ice crystals, metallic debris created during tendon laceration, as well as any tendon dehydration may have adversely affected both MRI signal and US. Omission of an epitendinous suture could potentially have a negative impact on clinical applicability; however, the presence of suture was not found to decrease accuracy with any of the modalities compared with no suture. Whereas dynamic US evaluation is often helpful for distinguishing adhesions from rupture, we only used static imaging because our primary goals were to identify any adverse effect on accuracy due to gap size, suture presence and/or type, and digit size.

In conclusion, US was less accurate than both MRI modalities. False-positive results were seen with all 3 modalities at 0-mm gaps; however, the mean error was less than 2 mm, so would most likely be interpreted as intact repairs clinically. If a 3-mm gap is considered a clinical failure, MRI can correctly diagnose this in about 80% of cases versus about 70% for US. It is important to recognize that the maximum gap size in our specimens was 6 mm. Sensitivity may, therefore, be improved for gaps larger than 6 mm, which is felt to be common with reruptures seen in clinical practice. Specificity is quite good for MRI (88%−90%) but suboptimal for US (71%). Therefore, a repair that is interpreted as having a less than 3-mm gap (clinically intact) by MRI can be relied upon in most cases, which may help surgeons make appropriate decisions with respect to treatment. Specificity of US is likely to improve as higher-resolution probes become more available, and should be a subject of future study. Suture does not impair accuracy of small-gap diagnosis with MRI nor US. Currently, we use MRI as the primary diagnostic modality for suspected flexor tendon reruptures, although gaps interpreted between 3 and 6 mm may be falsely interpreted as intact in 22% of cases. Surgical exploration may be advisable in these cases.

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