

Passive Biomechanical Properties of Sutured Mammalian Muscle Lacerations

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ABSTRACT Muscle trauma, such as laceration or transection, is a common occurrence, but repairing delicate tissue poses a clinical challenge. This is at least partially due to the lack of established muscle repair models. The purpose of this study was to compare the biomechanical properties of stitches in transected porcine and bovine muscle bellies. A biomechanical protocol was designed for measuring suture performance in muscle belly lacerations. Twenty simple stitches in porcine and 21 stitches in bovine specimens were tested. Individual stitches were placed in lacerated muscle bellies and tensioned on a biomechanical tester (model 8521S, Instron Corporation, Canton, MA). The mean maximum load for porcine (22.0 N) and bovine (23.9 N) stitches was not significantly different ($p = .48$). The difference in mean strains at maximum load between porcine (9.7%) and bovine (8.0%) groups was statistically significant ($p = .004$). Failure mechanisms were similar. One porcine stitch avulsed the muscle transversely, while 19 stitches tore out longitudinally. All 20 stitches tore out in bovine specimens. Sutured muscle was the weakest element in each test. The present study demonstrated that sutured muscles performed similarly for the two mammals regarding the parameters of maximum load and mechanism of failure. Regarding suturing of skeletal muscle lacerations, both mammalian models had similar biomechanical performance for maximum loads and failure mechanisms, while strain data differed. The stitch load magnitudes in this study approximate those required to successfully repair transected muscle. Knowledge introduced by this study fills a gap concerning muscle stitching relevant to clinical care.

KEYWORDS biomechanical testing, epimysium, laceration, load, muscle anatomy, muscle injuries, orthopedics, repair, stitch, surgery, suture, trauma

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Muscle trauma, such as laceration, transection, or rupture, is common in medicine, posing clinical challenges for surgeons to repair disrupted delicate tissue [1, 2]. Often, severe muscle trauma is treated without surgery, because historically, treatment outcomes of muscle injury without tendon involvement were suboptimal [3, 4]. Recently, investigators presented data supporting surgical repair over nonoperative care of complete muscle disruptions [5–9]. Models of muscle stitching are being developed, but comparisons of models have not been reported. A better understanding of the models and the biomechanics of muscle suturing is key to the development of optimal repair techniques. Surgical research of muscle repair is needed to improve patient care and rehabilitation, because early mobilization of sutured muscle improves healing [8, 9]. Early motion after repair leads to better healing, less scar, and less atrophy, but requires no stitch failure by pullout during early loading [8, 9]. As skeletal muscle has similarities among mammals, mammalian muscle is often used to model human clinical situations. Since porcine and bovine muscles appear similar to human skeletal muscle, it was hypothesized that both mammals would model muscle belly laceration repair similarly.

To improve the clinical performance of stitching muscle, a biomechanical study was designed to test stitches in porcine and bovine muscle belly transections, focusing on the passive traits of sutured muscles. The purpose of the present study is to compare maximum loads, strains, and failure mechanisms of sutured muscle bellies in porcine and bovine specimens.

MATERIALS AND METHODS

Skeletally immature female Yorkshire cross pigs, weighing approximately 40 kg, were acquired and then attended in an accredited facility for an approved study other than the present study. A pig cadaver extremity was acquired at the end of the other study, and the institutional review board approved the present study. The porcine quadriceps femoris muscle group from one animal used and was refrigerated at 4°C for 40 h. In a prior study at our laboratory,

we determined that refrigeration of muscle did not affect passive biomechanical properties compared to fresh specimen testing. Further, differing durations of refrigeration, as used in the current study, did not affect passive biomechanical properties.

A bovine steer tibialis anterior muscle was acquired freshly from a commercial slaughterhouse. One muscle from one animal was used and refrigerated at 4°C for 84 h. The porcine and bovine muscles selected had half-bellies of similar size and shape.

The compartmental fascia was removed from specimens, and care was used to preserve epimysium. Muscle belly lacerations were made in areas where no tendon was present. The laceration made with a surgical blade was transverse to the long axis of the muscle, and the laceration completely severed the muscle belly into two half-bellies without connection. Saline was used to moisten the specimens throughout testing. Sutures were placed around the laceration edge to repair with simple stitches with metric size 2 braided polyester suture. A stitch was placed in the tendon using a running interlocking technique. Both stitches were secured by tightening in both grips before loading on a biomechanical machine (Figure 1). The stitch tested in each test was the stitch in the sutured portion of the muscle, and the stitch in the sutured tendon was used simply to secure the specimen. In prior work with this setup, we ascertained that no slippage occurred at the loads used. No rigor mortis occurred. No measured strain of the sutures or tendon occurred, and only the sutured portion of the muscle deformed. The weakest element in each test was the sutured portion of the muscle.

A biomechanical protocol was designed for measuring suture performance in muscle belly lacerations in a porcine specimen and in a bovine specimen. Parameters compared were maximum load, strain at maximum load, and mechanism of failure. The gauge length was the length of the specimen, not including the sutures.

A servohydraulic materials tester (model 8521S, Instron Corporation, Canton, MA) was used to apply tension. Under position control with a 0.1-kN load cell, the machine applied tension along the long axis of the muscle, and the sutures were held in grips with

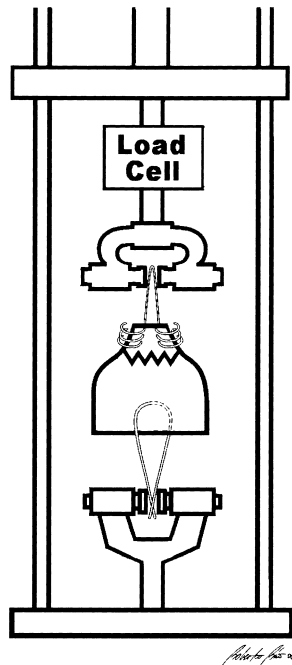


FIGURE 1 Testing setup of materials testing system with connected specimen. The tester includes the base platform, two uprights, upper crossbar, and two grips. The load cell is labeled, and grips hold stitches. The simple suture is gripped below, and the tendon suture is gripped above. The muscle specimen is a half belly transected in the middle.

leather facing. The scientific model tested the passive properties of the specimen similar to the clinical situation [8]. The specimen was preloaded minimally with 5 to 8 N to remove slack immediately prior to testing. Stitched muscles were loaded at an elongation rate of 25 mm/min until failure. Two failure modes were defined. Suture tear-out occurs when sutures pull out longitudinally from the muscle. Avulsion is the mechanism of failure when the muscle fails transversely and a portion of muscle is removed as the suture cuts out of the muscle.

Software (Series IX, Instron Corporation, Canton, MA) was used for data collection, and the system recorded the maximum load in newtons and the strain at maximum load in mm per mm expressed as a percent. Further, the mechanism of failure was observed directly and recorded.

Independent sample *t*-tests were used as the test statistic for loads and strains, and Levene's test was used for assessing equality of variances. For mechanism of failure analysis, a 2×2 contingency test was used with Fisher's exact test because of the small sample sizes. A *p* value of less than .05 was consid-

TABLE 1 Mean maximum load ($\pm$ SD expressed in newtons), mean strain at maximum load ($\pm$ SD expressed as mm/mm in a percentage), and significance (*p* value) for porcine and bovine muscle stitches

	Porcine muscle, mean $\pm$ SD	Bovine muscle, mean $\pm$ SD	<i>p</i> Value
Maximum load (N)	23.9 $\pm$ 8.93	22.0 $\pm$ 7.98	.48
Strain (mm/mm $\times$ 100%)	8.0 $\pm$ 1.79	9.7 $\pm$ 1.83	.004

ered significant. Clinically significant load and strain differences were set at 6 N and 3% based on unpublished work by us with this setup, and sample size estimation confirmed adequate power. Software (version 11.5 SPSS, Inc., Chicago) was used for statistical analysis.

RESULTS

The results of load testing are summarized in Table 1 and Figure 2. The mean maximum load for porcine repairs was 23.9 N, while that for bovine repairs was 22.0 N. The difference between groups was not significant (*p* = .48). The ranges, standard deviations, and 95% confidence limits were similar between groups.

The results of strain testing are displayed in Table 1 and Figure 3. The mean strain at maximum load for porcine repairs was 8.0%, while that for bovine

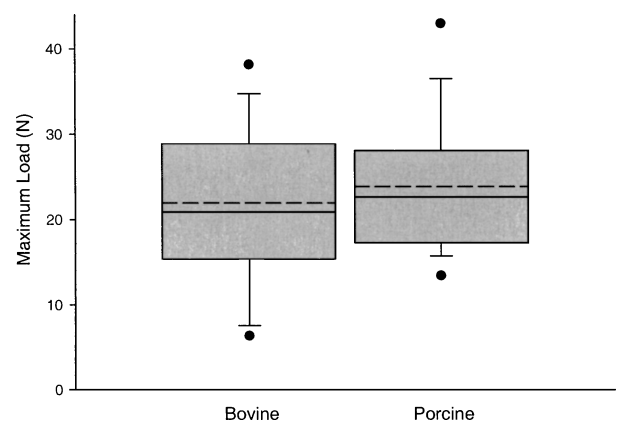


FIGURE 2 Maximum loads for sutured bovine and porcine muscle bellies. The gray box plots have the 25th and 75th percentile confidence limits as the lower and upper borders respectively. The bars are the 95% confidence limits. The dots are outliers. The mean is a dashed line within the gray box, and the median is a solid line within the gray box. The difference between groups in mean maximum load is not significant.

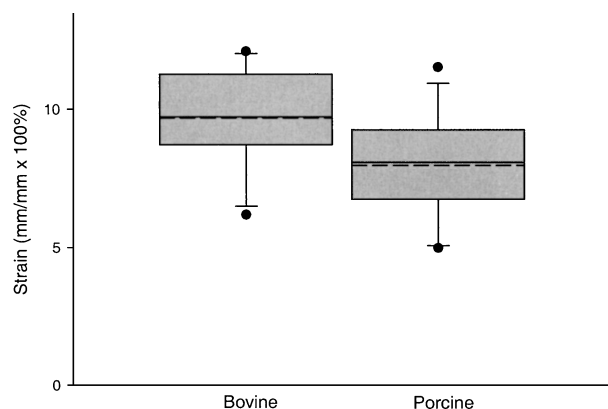


FIGURE 3 Strain at maximum load for stitches in bovine and porcine muscle. Strain is expressed as mm/mm as a percent. The gray box plots have the 25th and 75th percentile confidence limits as the lower and upper borders, respectively. The bars are the 95% confidence limits. The dots are outliers. The mean is a dashed line within the gray box, and the median is a solid line within the gray box. The difference between groups in mean strains at maximum load is significant by a clinically insignificant amount. The data overlap considerably between groups.

repairs was 9.7%. The difference between groups was statistically significant ($p = .004$). The ranges, standard deviations, and 95% confidence limits were similar between groups.

The mechanisms of failure were not significantly different between groups ($p = .49$). One porcine stitch avulsed the sutured portion of the muscle, while 19 sutures failed by tearing out longitudinally from the muscle. No bovine stitch avulsed muscle, while 20 sutures tore out (Table 2). The sutured portion of the muscle was the weakest link in each specimen and test.

DISCUSSION

This study demonstrated that sutured muscles performed similarly for the two mammals, regarding the

TABLE 2 Failure mechanisms and significance (p value) of sutures pulled from porcine and bovine muscles

	Porcine muscle	Bovine muscle	p Value
Number of stitches	20	21	
Failure mechanisms	19/1	21/0	.49
Tear-outs/avulsions			
Tear-out proportion (Tear-outs/total) $\times$ 100%	95%	100%	

parameters of maximum load and mechanism of failure. The strain parameter was statistically different by a small amount. Both animal models approximated closely the human clinical situation and validated the testing method by showing the weakest link to be the muscle in each test. The finding that the bovine model had higher strain at maximum load was probably because the bovine model appeared to have more muscular connective tissue. The epimysium of the bovine tissue seemed slightly more robust than the porcine muscle, and the greater connective tissue likely permitted greater elongation and strain prior to failure. The small statistical difference in strain between the two muscles is not clinically significant. The two different muscles selected from the two species have obvious differences and may have different length-tension diagrams, but despite differences, the muscles tested had measured biomechanical properties that are similar or differ little.

The findings of the present study apply to human and veterinary surgical care of muscle disruptions. Both porcine and bovine muscle tissues handle grossly similar to human muscle, and both models offer usefulness to investigators studying severe muscle disruption. Both porcine and bovine muscles can provide clinicians a refrigerated practice material prior to facing the clinical challenge of human or veterinary muscle laceration repair. Both species can be used to model clinical applications, as the biomechanical properties of interest differed little or not all.

The clinical relevance of the loads pertains to rehabilitation of muscle injury, and the estimation of muscle and stitch loads can help explain clinical success and failure. Let us assume a biceps brachii muscle is repaired as the belly is commonly repaired [7, 8], and the belly is architecturally simpler than many muscles. Forearm supination torque averages 9 N·m [10] maximally at 90° of elbow flexion. If the biceps contributes 5 times more than the supinator muscle, since the biceps cross sectional area is 5 times greater than its synergist, then the biceps contributes five-sixths; 7.5 N·m ($9 \text{ N} \cdot \text{m} \times 5/6$), of total supination torque. If the bicipital tuberosity is 15 mm from the center of supination (longitudinal rotation axis of the radius) at 90° of elbow flexion, then the moment arm is 0.015 m. Therefore, the maximum biceps

force is 500 N ($7.5 \text{ N} \cdot \text{m}/0.015 \text{ m}$) [11]. If individual stitches can bear loads of 20 N, as in the current study, then 25 stitches can bear the 500-N requirement. As the biceps circumference is 16 cm [$2\pi \times (2.5 \text{ cm})^2$], many stitches can be used clinically to bear load successfully [7, 8], but the difference between success and failure is small. As rehabilitation forces are typically below maximum, stitches may be able to bear estimated loads successfully, but risk of failure by tear-out remains. Three limitations of the calculation are notable. First, noncompliant patients may contract repaired muscle without control, and thus, risk failure. Second, biomechanical testing was immediately after repair, but maximum loads during healing could be less than those immediately after repair. Third, positions other than 90° of flexion may demand higher loads. Nonetheless, calculations offer context to current muscle knowledge and detail how clinical repair can both succeed and fail. The small difference between success and failure and ongoing model development help explain why muscle belly repair is so challenging, and substantial increases in stitch performance would improve chances of success.

The new knowledge introduced by the present study addresses a specific knowledge gap concerning muscle belly stitching. We are not aware of any previous such model comparison regarding laceration repair of muscle bellies. Comparing porcine and bovine muscle suturing added new knowledge that the stitch load magnitudes are relevant to clinical laceration repair. The application of biomechanical data to the rehabilitation context added an original perspective that explained clinical challenges based on estimated forces and clinical needs.

The strengths of this study regard the expansion of current knowledge regarding muscle laceration repair. Systematically adding new knowledge to fill specific knowledge gaps is important to solve clinical challenges of skeletal muscle disruption care. Improved understanding and awareness of how muscle tissue can be stitched successfully is important to clinicians.

The weaknesses of the present study regard the focused nature of the experiment. The generalizability

of the laboratory findings beyond the narrow scope of the current study may be limited. Further model development is needed to address the complex and poorly understood problem of surgical repair of muscle laceration.

CONCLUSIONS

This study established that porcine and bovine muscle suturing performs similarly in biomechanical testing, except for strain at maximum load. The present study adds new knowledge to a growing understanding of skeletal muscle repair, and techniques of repair may now be investigated with more developed models.

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