Mechanical Properties of Animal Tendons

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In medical and bioengineering research, animal tendons are commonly utilized as surrogates for human ones for mechanical testing. Due to the differences among human tendons of different anatomical districts, different animal species can be better suited for specific purposes. Indeed, the mechanical response of animal tendons to an external load is strictly related to its complex and highly organized hierarchical structure, which ranges from nano- to macroscale. In a broader sense, the mechanical properties of tendons during tensile tests are affected by several distinct factors, due in part to tendon nature (anatomical site, age, training, injury, etc.) but also depending on the experimental setup and settings. Thus, there are similarities between animal and human tendons that should be considered in the biomechanical evaluation.

Keywords: tendon ; animal tendons ; mechanical properties ; strain rate ; ultimate stress ; ultimate strain ; tendon and ligament injuries

1. Introduction

Tendon and ligament injuries are significant issues in medicine and biomedical engineering and remain an open problem. The most commonly observed lesions in humans localize to the rotator cuff, quadriceps, patellar, and Achilles tendons, as well as to knee collateral ligaments.

The discussion here is intended to highlight the most suitable animal subrogate model for testing traditional repair techniques (such as sutures) according to the human tendon destination, thus avoiding the use of human tissues and their related availability issues.

Indeed, the mechanical validation of novel repair techniques and materials is generally carried out on animal tendons and ligaments. Animal models are preferred in preclinical studies for two main types of research purposes: (i) the evaluation of tissue healing through different strategies (for example after growth factor and stem cell injection) and (ii) suture pattern validation.

The tendon healing process has been investigated in different species, including rats [1], mice [2], rabbits [3], and sheep [4]. Animal shoulder models are used to systematically investigate the factors influencing rotator cuff injury and repair [5]. For example, the rat model developed by Soslowsky et al. [6] is considered the most suitable rotator cuff model due to its similarity to human anatomy (the presence of an acromial arch) and its range of motion [5]. The determination of the most suitable animal rotator cuff model allows for in vivo simulation to analyze different factors affecting the repair process, thus improving the therapeutic process [7]. Several studies dealing with tissue reconstruction via suture patterns or scaffolds used animal specimens to perform tests, especially horse [8], dog [9], and swine [10] tendons. The consistency of the experimental animal model is mandatory to obtain comparable results. Despite their wide use, by comparing the results of different studies it is evident that the reported material properties—in particular, the ultimate stress and strain values—vary, even when the same animal model is used [11]. This issue seems to be particularly evident for the estimation of the ultimate stress and strain values, which are very important parameters for the laboratory testing of tendon repair devices.

A recent study by Dominik et al. [12] compared the biomechanical properties of human semitendinosus tendons with bovine extensor and porcine flexor tendons for surgical fixation and suture technique validation. They concluded that fresh-frozen bovine extensor and porcine flexor tendons are eligible surrogates for biomechanical in vitro studies of human ligament and tendon repairs [12]. On the other hand, porcine flexor and bovine extensor tendons can be also used as grafts for anterior cruciate ligament (ACL) reconstruction [12].

Other studies have affirmed that the ultimate failure loads of modified Kessler suture repair applied on human, porcine, and ovine tendons are comparable, thus leading us to believe that these tendons are appropriate surrogates to study suturing techniques [10]. However, Hausmann et al. [10] found that sheep tendons seem to be the most suitable animal tendon model for mimicking the biomechanical behavior of human tendons. The mechanical behavior of tendons is highly anisotropic, as they show great mechanical strength only in the parallel fiber direction [13]. Indeed, the tendon tissue anisotropy can be evaluated with direction-dependent experiments, such as compression tests, as suggested by Bol et al., 2015 [14]. The biomechanical characterization of the tendon can be assessed using different experimental methods; a widespread approach is based on ex vivo ultimate tensile strength testing. Other related parameters, such as load, deformation, and stiffness, can be obtained using the same method, providing information regarding the mechanical behavior of the tendon sample [11].

Several studies have also focused on the analysis of different factors such as gender, physical activity (exercise or training), and injury or disease. In addition, results can also be influenced by the experimental setup, including the environmental conditions and test protocol [11]. Indeed, it is well documented that the mechanical properties of tendons are affected by a considerable number of intrinsic and extrinsic individual factors, including anatomical site, age, and loading history [11]. Certainly, despite common features, tendons from different locations within the body show remarkable variations in terms of their morphological, molecular, and mechanical properties, which are related to their specific function [15]. For example, tendons that experience relatively high physiological stresses and have a spring function during locomotion, such as Superficial Digital Flexor Tendon (SDFT) and Deep Digital Flexor Tendon (DDFT) in horses, develop different mechanical properties from those that experience only relatively low tension stresses, such as Common Digital Extensor Tendon (CDET) [16].

Two factors were reported in the biomechanical studies: (i) the strain rate value set during the test and (ii) the preconditioning before testing. The tendon is well-known to be a viscoelastic material, whose behavior is nonlinear and time-dependent [17]. Indeed, due to its time dependency, tendon tissue responds in different ways to strain rate variations during tensile tests; for instance, an increase in the stress and strain at failure has been observed when the strain rate increases [18].

2. Mechanical Property Evaluation

2.1. Results with Strain Rate in mm/s

The human tendons included in this section are the finger flexor and extensor tendons [19][20], human LHB tendon [21], and Achilles tendon [22].

The mechanical properties of extensor and flexor finger tendons were analyzed by Pring et al., 1985 [20] and Weber et al., 2015 [19] at a strain rate of 100 mm/s. Both studies reported contrasting ultimate strain values; the difference may have been due to samples slipping during the test conducted by Pring et al. [20]. Therefore, here the data from Weber et al., 2015 were used to perform the comparison [19].

The Young's modulus and ultimate strain values obtained by Weber et al., 2015 [19] for EI and ED finger extensors showed similarities with the results obtained for rabbit PT [3]. Conversely, there were no matches for ultimate stress between all the animal species. A partial similarity could be found between swine DDFT [16], rabbit flexor tendon [23], rat tail tendon [24], and mouse PT [25].

Regarding finger flexor tendons (FPL, FDP, and FDS), Young's modulus and ultimate strain values obtained by Weber et al., 2015 [19] also showed similarities with data obtained for rabbit PT [3]. Moreover, there was a similarity of Young's modulus and ultimate stress values with data reported in swine DDFT [16]; however, a comparison between ultimate strain could not be made as no data were obtained for ultimate strain for this tendon.

In a work, Wren et al. [22] analyzed the mechanical properties of the Achilles tendon with two different strain rate values. For both values, Young's modulus values were comparable with rabbit flexor tendon [23], swine extensor [26], and swine digital extensor [16]. Concerning the ultimate stress values for both strain rates, the results showed similarities with rabbit PT 3], sheep PT [27], swine DDFT [16], swine AT [28], and horse SDFT [29]. In addition, there was a similarity of ultimate strain for both the strain rate values with mouse PT [25] and rabbit PT [3]; however, the Achilles tendon with a strain rate of 1 mm/s also showed a match with rat tail tendon [24] and swine extensor [30]. Rat and mouse tendons are widely used in medicine to compare with the Achilles tendon in humans. Knockout mice have been used to investigate the composition variation of Achilles tendons from a histological point of view [31]. According to earlier studies evaluating mechanical behavior, contrasting results between rat/mouse and human samples have been obtained [32], which can be observed in the results here.

Young's modulus of the LHB tendon, analyzed by Carpenter et al., 2005 [21], showed clear similarities with the results obtained for swine digital extensor tendon [16], and a small similarity was noticed with mouse PT [31], rat AT [33], rat PT [34], and dog infraspinatus [35]. The LHB's ultimate stress [21] showed similarity with results reported for rat AT [32][33][36], rat PT [37][38][34], rabbit PT [39], sheep AT [40], swine extensor tendon [26], swine digital extensor [16], and swine AT [28]. The ultimate strain results showed similarities with data for mouse PT [25], mouse AT [41], rat AT [33], rat PT [38][24], rat tail tendon [24], rabbit PT [3], sheep PT [27], swine extensor tendon [26], and horse SDFT [29]. There was also a similarity between LHB's mechanical properties and those of the rat AT, rat PT, and swine digital extensor tendon. Indeed, rat and dog shoulder models are used to evaluate the factors that influence human rotator cuff injury and repair processes [5][6][42].

No similarities were found between human, swine, and bovine tendons; however, Dominick et al., 2016 [12] reported that swine flexor and bovine extensor tendons are eligible surrogates for human semitendinosus tendons in biomechanical studies.

2.2. Results with Strain Rate in %/s

The human tendons included in this section are the Achilles tendon [43], patellar tendon [44][45], anterior supraspinatus, middle supraspinatus and posterior supraspinatus [46].

The Young's modulus of the Achilles tendon obtained by Lewis et al., 1997 [43] showed similarities with mouse tail tendon [47], dog PT [48], rabbit gastrocnemius tendon [49], and goat PT [50]. In the same way, a similarity could be noticed between Achilles' ultimate stress and results obtained for rabbit gastrocnemius [49], goat PT [50], 11-month-old foal SDFT [51], horse CDET [52], and horse SDFT [52][53]. The ultimate strain data showed similarities with rat tail tendon [11], goat PT [50], bovine foot extensor [11], and horse SDFT [53]. Essentially, the mechanical properties of the Achilles tendon [43] were comparable with those of rabbit gastrocnemius [49] and goat PT [50]. In fact, the similarities between rabbit gastrocnemius and human Achilles tendons find confirmation by Young et al. [49] in the evaluation of Achilles tendon repair [27].

The mechanical characterization results for PT from a study conducted by Butler et al., 1986 [44] showed a value of Young's modulus that was similar with mouse tail tendon [47], goat PT [50], and bovine foot extensor [11] values. Similar mechanical results were obtained for human PT by Hashemi et al., 2005 [45]; in this case, there were similarities with dog PT [48] and rabbit gastrocnemius [49]. The results obtained in an additional study conducted by Haut et al. [48] suggest that knee tendon and ligament reconstruction is possible with canine PT, and this finding gives significance to the mechanical evaluation that was performed as the aim here.

Regarding the ultimate stress, the values obtained by Butler et al. [44] showed similarities with data from goat PT [50] and horse SDFT [53], while the results of Hashemi et al. [45] showed similarities with rabbit gastrocnemius [49]. There was a clear difference in the PT ultimate strain values obtained in both articles [18][37]. The ultimate strain reported by Butler et al. [44] for PT showed similarities with rat tail tendon [11], goat PT [54], and horse SDFT [52][53]. These results were also found for PT tested by Hashemi et al. [45]; in addition, their results showed similarities with rabbit AT [55] and goat PT [50]. Essentially, the data obtained in both studies presented similarities with the mechanical properties of goat PT [50]. This result is confirmed by the fact that the goat knee model was used to evaluate patellar tendon remodeling [27]. Furthermore, Hausmann et al. [10] reported that sheep tendons seem to be the most suitable animal tendon model for mimicking human tendons; this statement has been proved valid here for PT but not for other human tendons. However, the mechanical properties achieved by PT as tested by Hashemi et al. [45] showed a similar Young's modulus and ultimate stress to data obtained from rabbit gastrocnemius [49], with no ultimate strain data reported for this tendon. This result explains the fact that in literature, the effects of the healing process on knee ligaments and tendons are studied with rabbit knee models [3][32].

In a work, Itoi et al. [46] evaluated the ultimate stress properties of the anterior supraspinatus, middle supraspinatus, and posterior supraspinatus tendons. No similarities with animal tendons were found, except for the anterior supraspinatus tendon, which shows slight similarities to rabbit gastrocnemius [49]. Several studies evaluated the healing of rotator cuff tendons in canine animal models; however, no evaluation could be performed for the results obtained [4][42].

3. Strain Rate Analysis

The analysis of the influence of strain rate on the mechanical properties of tendons did not show univocal results. The mechanical properties of rabbit PT obtained with a velocity of 0.333 mm/s [39] and 2.5 mm/s [3] did not show statistically significant differences for Young's modulus (1390 ± 53 MPa vs. 1581.4 ± 374.9 MPa), while ultimate stress (57.1 ± 2.5 MPa vs. 100.7 ± 16 MPa) and ultimate strain (5.1 ± 0.2% vs. 7.4 ± 1.5%) presented statistically significant differences; in particular, an increment in the values was observed.

Rat AT mechanical properties using a strain rate of 0.1 mm/s [32] and 1 mm/s [33] presented statistically significant differences for Young's modulus (179 ± 36 MPa vs. 405 ± 115 MPa, respectively), and this was related to an increase in tissue stiffness. On the other hand, ultimate stress (45 ± 10 MPa vs. 51.6 ± 10.8 MPa) did not present statistically significant differences when comparing the two strain rates. No definitive evaluation could be made for the ultimate strain since one article [32] did not report any value for this parameter.

The results obtained by testing rat PT with a strain rate of 0.05 mm/s [34] and 0.1 mm/s [38] showed no statistically significant differences for both Young's modulus (386 ± 88 MPa vs. 323.88 ± 56.48 MPa) and ultimate stress (40.5 ± 8.95 MPa vs. 30.24 ± 4.41 MPa). Furthermore, no evaluation could be made regarding the ultimate strain, as [38][34] did not report any value. Thus, the increases in strain rate did not cause any changes in the mechanical properties of the tissue. Considering the study of Robinson et al., 2004 [18], the mechanical properties of mouse fascicles with modified and unmodified composition were analyzed according to the strain rate. Robinson et al., 2004 [18] showed that the mechanical properties related to the linear region are strain rate-independent over the range from 0.5%/s to 50%/s; in contrast, the failure properties are highly dependent on strain rate.

The mechanical properties of goat PT with a strain rate of 50%/s [50] and 100%/s [54] showed statistically significant differences for all mechanical properties analyzed. The strain rate increment caused an increase in Young's modulus and ultimate stress; thus, an ultimate strain reduction is advocated, in accordance with the results obtained for rabbit PT.

Concerning human tendons, according to Wren et al., 2001 [22], the influence of strain rate increment (1 mm/s and 10 mm/s) does not cause statistically significant differences in the mechanical properties of Achilles tendons. Several authors have reported that strain rate has an important influence on the mechanical properties at failure (stress and strain); however, once again, there were no statistically significant differences even if a wide range of strain rates was evaluated. However, Abraham et al., 1967 [56] found that for the human Achilles tendon, different strain rates modified the stress magnitude and the shape of the stress-strain curve. In addition, the scientists presented a double logarithmic relationship between stress magnitude and strain rate [56].

According to Herrick et al. [57], they performed some tests on the equine flexor tendon to validate the relationship reported by Abrahams et al. [56]. They found that this relationship might be valid for low strain rate values. In conclusion, they affirmed that strain rate has a small and inconsistent effect on stiffness in the range from 5%/s to 50%/s [57]. Lewis et al. [43] evaluated the effects of a ten times strain rate increase (10%/sec and 100%/sec) on human Achilles tendons. The data reported showed that the strain rate increase produced a statistically insignificant increase in the value of ultimate tensile strength (73 ± 13 MPa vs. 81 ± 14 MPa), a statistically insignificant decrease in the value of ultimate strain (25 ± 3% vs. 21 ± 1%), and a statistically significant increase in Young's modulus (401 ± 59 MPa vs. 545 ± 43 MPa) [43].

Here highlighted how a change in strain rate does not have a unique effect on the mechanical properties of tendons. Analyzing the results of four different tendon tissues (rabbit PT, rat AT, rat PT, and human AT) tested with a strain rate in mm/s, it is observed that a strain rate increment caused a significant increase in Young's modulus only in rat AT. A similar result was obtained for human AT by increasing the strain rate by ten times. However, this increase in Young's modulus was not statistically significant. In all the other studies, there was no appreciable change in Young's modulus. Considering the four comparisons made for strain rate values in mm/s, it is observed statistically significant differences for ultimate stress and ultimate strain in rabbit PT only. In particular, the strain rate increment caused an increase in ultimate stress and a decrease in ultimate strain.

Regarding the effects of the strain rate increase in %/s, the results showed a significant increase in Young's modulus for both goat PT and human AT. This could be due to the application of a drastic increase in the strain rate considering the measurement unit itself; as a result, setting a strain rate of 50%/s results in a tendon deformation of half its initial length in one second, e.g., a strain rate increase in goat PT from 50%/s to 100%/s produces an increment of Young's modulus by three times.

According to Abrahams et al. [56] a low strain rate increase may have no effect. This evidence, in agreement with the findings, shows that Young's modulus is affected only in the case of a high strain rate increment.

A 10-fold increase in strain rate in human AT [22] did not present statistically significant differences for ultimate stress and strain. However, an increase in ultimate stress and in ultimate strain could be found. Analyzing the strain rate in %/s only for goat PT [54][50] showed statistically significant differences between the results for ultimate stress and ultimate strain, while human AT [43] showed differences, but not statistically significant differences. The increment in strain rate causes an increase in ultimate stress and a decrease in ultimate strain in both tendons.

In conclusion, there is evidence that the value of strain rate can cause a change in Young's modulus of tendons. Nevertheless, this change in strain rate must be of a significant quantity. The data analysis showed that an increase in strain rate of ten times or greater compared to a reference strain rate value can change the properties of the tissue. The change in strain rate influences tendons' ultimate stress and ultimate strain values. A significant strain rate increase can cause an increase in tendons' ultimate stress and a reduction in ultimate strain.

4. Conclusions

Most of the experimental research for human tendon injury and repair is generally performed in animal models, at least in the earliest research stages before human studies. However, animal models have several shortcomings, such as inherent biologic variability, metabolic and hormonal differences between species, and anatomical differences, introducing potential bias to the interpretation of mechanical results during preclinical experiments [31]. As a result, medical, veterinary, and bioengineering researchers must be cautious (i) in applying their results to humans and (ii) in selecting the most appropriate animal tendon for their applications.

Herein aimed to define the most suitable surrogate for mimicking the behavior of human tendons when subjected to uniaxial tensile tests. Differences and similarities with human tendons from different anatomical regions were highlighted and commented upon. For each region, the best candidates were determined and discussed.

The key findings make it evident that different animals' tendons show different mechanical properties. Therefore, not every animal tendon can be employed to make a direct comparison to their human counterparts (or to any other human tendon or ligament). The results showed similarities between some animal and human tendons that should be considered in the evaluation of scaffolds and sutures.

Considering the results in mm/s:

- The flexor tendon of the hand (FPL, FDP, and FDS) shows partial similarities for Youngs' modulus and ultimate stress with swine DDFT.
- The extensor tendon of the hand (EI and ED) has similarities with the rabbit PT.
- The LHB tendon shows similarities with the mechanical properties reported for the rat AT, rat PT, and swine digital extensor tendon.

Considering results the obtained for data in %/s:

- The human PT tendon has some similarities with the results obtained for the goat PT.
- The human AT tendon shows comparable mechanical properties with the goat PT, but there are other partial similarities.

However, these results were found only for data in %/s; no clear similarities were visible in the data in mm/s. Thus, it seems highly probable that the choice of strain rate significantly affects the results; unfortunately, different authors reported their results with different settings. Therefore, further studies will be needed to evaluate tendons from different animals and anatomical regions with the same test conditions and strain rate, in a fully comparable way. Future research may enhance the understanding of the best animal tendon species by considering (i) age, (ii) loading history, and (iii) composition.

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