Original article

Changes in frictional coefficient with increased tendon surface tear—An experimental animal model

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ABSTRACT

Aim: Surface tribological properties of a tendon in terms of coefficient of friction and lubrication mechanism are expected to change with the progression of surface tears which can affect the optimal function of the tendon. This study investigated whether coefficient of friction proportionally increases with the progression of a surface tear in a bovine tendon model.

Methods: The study was performed using a pin-on-glass tribometer and bovine tendon samples ($n = 16$) divided into 4 groups. One group of tendons had no surface tears and thus served as a control, whilst the other 3 groups comprised tendons with increasing severity of artificially-induced surface tears. The coefficient of friction and the lubrication mechanism of the four groups of samples were investigated, calculated and compared.

Results: Statistical analysis showed significant change in coefficient of friction between the control group and the group with minimal tear ($p < 0.05$) while no difference noted between the groups of moderate to severe tear suggesting that the coefficient of friction increases initially with appearance of surface tears, though further progression to a significant tear do not cause a further increase in the frictional coefficient. There was no change in the lubrication mechanism between the groups.

Conclusion: This finding appears to contradict the speculation that the frictional coefficient continues to increase with an increase in surface tear severity. The finding has not been reported before and requires validation in future with testing in human tissue.

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1. Background

Tendons primarily serve to transmit the forces generated by muscles to cause motion about a joint. Functional efficiency of the tendon primarily depends on its ability to glide with minimal friction.¹ Research continues to be performed to seek a better understanding of tendon excursion and their gliding properties, with multiple methods trialled to measure the coefficient of friction and to understand the lubrication mechanism at the tendon surface. Studies have also explored how the paratenon influences these frictional properties, with in vitro studies indicating that this tissue reduces tendon gliding resistance.²

An enhanced understanding of tendon tribology, and in particular the interaction of the tendon surface with neighbouring tissues, provides potential to alleviate tendon pathology, in

identifying less disruptive surgical techniques and to aid in developing novel therapeutic interventions. Indeed, it is widely reported that repair increases a tendon's frictional coefficient,³ with others now aiming to identify tendon grafts with inherently lower coefficient of friction, including intrasynovial grafts⁴ and the use of novel materials and methods.^{4–8} Other innovations are focussing on improving lubrication and preventing re-rupture of the tendon, preventing adhesion and failure of tendon repairs, tendon transfers and tendon grafting.

Maintaining the specialised tendon sliding surface ensures optimal frictional characteristics. Surface tears are common in supraspinatus tendon of the shoulder, possibly due to degeneration or as a consequence of bony or soft tissue impingement extrinsically. Tendon surface tears do continue to occur however, with little scientific data available to understand their progression and tribological properties of a tendon with surface tears. Whilst disruption of the outer tendon surface by a tear would likely increase tendon friction, it is as yet unknown whether the frictional coefficient continues to increase with progression of the surface tear.

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This study explores the progression of surface tears, by investigating the variation in frictional coefficient with increasing surface tear seeking to determine whether the coefficient of friction proportionally increases with increasing severity of a surface tear.

2. Materials and methods

Surface tears were created in a series of bovine tendon samples, to investigate the influence of tears on the frictional coefficient and the efficiency of lubrication. Extrasynovial flexor tendons were carefully dissected from mature bovine legs (Fig. 1a), which were obtained from a local abattoir following slaughter for the food industry. Ethical committee approval was not required as the animals had not been slaughtered for the study purpose but for the food industry. The tendons were visually examined for any obvious pathology, before the midsubstance was divided into 10 mm long samples (Fig. 1b). In total 16 samples were collected and divided into four groups of 4 samples. Four samples were retained with an intact surface for use as a control group (Group 1), with surface tears of 3 different severities created on the other samples, by rubbing the tendon surface with sand paper [emery tape P120 25 mm]. In Group 2, an early/mild surface tear was induced by abrading the tendon 50 times with sand paper. Group 3 samples were abraded 150 times to create a moderate surface tear, whilst the final 4 samples had a severe surface tear by being abraded 300

times (Group 4). For uniformity, the ventral side was always the surface of interest.

The frictional coefficient and lubrication regime of each sample was ascertained using a pin on plate tribometer (Fig. 2), a validated experimental model for analysing the frictional properties and lubrication of the tendon surface, as published by Theobald et al.^{9,10} The pin on plate tribometer has been routinely used to study the tribological properties of articular cartilage^{11,12} with our setup described as a schematic presentation in Fig. 3. The principle relies upon the surface of interest being slid against a rotating glass surface, with the amount of friction measured by the subsequent rotation of a pivoted metal beam. Here, the glass surface was first lubricated with a phosphate buffered saline (PBS) layer approximately 1 mm thickness (i.e. 50 ml), as described by Theobald et al.⁹ Cyanoacrylate was then used to adhere the dorsal tendon surface to the free end of the metal beam (M1 in Fig. 3), with the tendon sample (Fig. 4) orientated such that when the glass plate rotates, the fibre direction is parallel to the frictional force and thus simulates a tendon gliding movement. Each sample was then preloaded once before conducting a set of experiments of increasing sliding speed (5, 10, 20, 26, 31 mm/s), with varying compressive loads (1N, 2N, 4N, 8N, 10N) applied perpendicular to the tendon surface. As the glass plate rotated, friction between the tendon and glass surfaces caused rotation of the metal beam, to which the former was attached. The extent of beam rotation was then measured and, in combination with the known stiffness of the

Fig. 1. a) A deep flexor tendon harvested from a bovine calf leg. b) Four 1 cm samples of 1 cm prepared from a deep flexor tendon, viewed from the dorsal surface. Each dot represents the identical sample allotted to group 1–4.

Fig. 2. Pin on plate tribometer. Experimental set up.

resisting spring, used to calculate the tendon's coefficient of friction.

2.1. Frictional analysis

The frictional coefficient was calculated as a ratio of the frictional force and the applied 'normal', (i.e. transverse) load. The frictional coefficient of all samples was calculated across each experimental testing condition. To establish the relative influence of friction across all surface tear severities, a single experimental condition was used that represented typical tendon mechanics, which was adopted from Momose et al.² (i.e. 1.01 mm/Ns). Statistical differences between each testing group were investigated using Student's *t*-test, with a *p*-value less than 0.05 being considered to be statistically significant. Analysis with ANOVA test was done to assess if statistically significant difference was present between the groups. Fisher LSD test was performed to locate the difference, if noted, between the groups.

2.2. Lubrication analysis

The relative lubrication of each tendon sample was analysed by generating an individual Stribeck plot. This was achieved by plotting each frictional coefficient data point against the 'reduced Sommerfeld number' (i.e. the ratio of sliding speed to normal load). Comparison of this data trend to the reference Stribeck curve

enables approximation of the lubrication regime. Essentially, a horizontal trend indicates 'boundary' lubrication – where there is significant contact between the two sliding surfaces, a negative gradient indicates 'mixed' lubrication – with some separation between the two surfaces, and a positive gradient indicates presence of a 'fluid-film' lubrication regime – where a layer of fluid develops between the two surfaces as a consequence of their relative motion. This analysis will provide an insight into the likely longer term consequence associated with surface tear severity.

2.3. Histological analysis

All samples were analysed histologically to confirm the presence of an intact paratendon in Group 1 samples, and progressive surface tears in Groups 2 to 4. Following frictional investigation, the bovine tendon samples were soaked in 10% neutral buffered formalin for 24 h, dehydrated in alcohols, cleared and then embedded in paraffin wax. Coronal sections were then cut at 8 μ m and stained with Haematoxylin & Eosin, and viewed under light microscopy.

3. Results

Our technique for artificially inducing tendon surface tears was first validated using histological analysis. The image presented in Fig. 5(a) demonstrates that the control group had an intact tendon

Schematic diagram of the experiment

$$\text{coefficient of friction } \mu = k * x * b / R * a$$

Fig. 3. A schematic representation of the testing apparatus. The metal beam (M1) is suspended over the glass disc (G) by pivoting on a pillar (P). The tissue is attached to the specimen holder (H) and the consequential arm deflection is resisted by a spring (S). The arm deflection is measured by an encoder, attached to the underside of the pillar.

Fig. 4. Pin on plate tribometer with sample attached.

surface, meaning that the bovine tendon surface was intact and that the experimental protocol does not induce any additional mechanical wear. The remaining tendon samples were then subjected to a systematic wear protocol, to achieve qualitative classifications of ‘mild’ (Group 2), ‘moderate’ (Group 3) or ‘severe’ (Group 4) surface tears. Group 2 surface tears comprised disruption of the superficial paratenon surface, although the underlying tendon fibrils remained entirely covered (Fig. 5(b)). In the samples with *moderate* tears (Group 3), the entire paratenon had been removed, revealing the tendon fibrils (Fig. 5(c)). Considerable disruption to the underlying tendon fibrils was evident in those tendons with severe tendon surface tears (Group 4, Fig. 5(d)).

Frictional coefficients across all tendon samples and speed/load conditions were then measured. The Stribeck plots for the 4 groups are presented in Fig. 6a. The positive gradient of all plots indicates, through comparison with the Stribeck curve (Fig. 6b), the likely presence of a fluid film lubrication separating the tendon surface and glass plate; hence, an increasing surface tear severity does not appreciably influence the trend describing the lubrication *regime*, across the breadth of testing conditions. The Stribeck plot of the intact tendon (i.e. Group 1) can also provide further validation of the experimental protocol, by considering the positive correlation with equivalent data published in Theobald et al.⁹

The data presented here indicates that, despite complete removal of the paratenon, the tendon is likely to remain separated from the surrounding tissues by a very thin, but complete, layer of lubricant, thereby minimising the wearing of the opposing surfaces. There does appear, however, to be a reduction in the efficiency of this layer, as noted when considering how the data from the experimental groups is ‘offset’ when compared to those from the control group (i.e. Group 1). There was little appreciable difference in friction with increasing surface tear severity (i.e. Groups 2 to 4, Fig. 7). This is in contradiction to the common speculation of the frictional coefficient proportionally increasing with increase in the surface tear.

Considering the frictional coefficient at conditions most representative of human physiology (as cited from Momose et al.²), these data describe a significant increase in friction between Group 1 and 2 (Fig. 6; $p < 0.05$). There is further, though more modest, increases in frictional coefficient between the mild (Group 2) and moderate (Group 3) tears but statistically not significant ($p > 0.05$). Surprisingly, the comparison between the moderate (Group 3) and severe (Group 4) surface tears show no significant increase in the coefficient of friction ($p > 0.05$).

ANOVA analysis showed presence of significant difference between the groups and further analysis by fisher's LSD test

Fig. 5. a) Histology image of cross section of sample from group 1 showing intact paratenon. b) Histology image of cross section of sample from group 2 showing damage to paratenon simulating early surface tears. c) Histology image of cross section of sample from group 3 showing no paratenon and exposure of subsurface tendon fibrils. d) Histology image of cross section of sample from group 4 showing completely damaged tendon surface.

Fig. 6. a) Mean data from tendons with artificially-induced surface tears worn tendons, displayed in the format of a Stribeck plot. Square data = control data, circle data = mild surface tear, triangle = moderate surface tear, diamond = severe surface tear. b) a typical stribeck curve.

Fig. 7. comparison of the Coefficient of friction between the control group (group1) and the study groups (group 2 to 4).

confirmed the location of statistically significant difference between the group 1 with intact surface and group 2 with minimal wear while no significant difference between the groups 2, 3 and 4.

4. Discussion

Whilst tribological properties of a normal tendon surface have been extensively studied, studies which have investigated the change in tribological properties due to progressive damage to a tendon surface are not in huge numbers. The data confirms that the increase in friction plateaus after mild surface disruption. Further surface tears do not appear to negatively influence the lubrication regime or frictional coefficient. The lubrication mechanism on the tendon surface irrespective of the presence of surface tear seems to be persistently fluid film mechanism, as confirmed from comparison of the individual Stribeck plots to the reference Stribeck curve. This suggests that the lubrication mechanism is driven by the fluid around the tendon from the sheath or the synovial fluid and the lubrication mechanism is independent of the tendon surface.

Qualitative histological evaluation verified that, whilst somewhat crude and primitive, the mechanical wearing technique developed in this study enabled production of both consistent paratenon disruptions that appeared similar to surface tears. Whilst the superficial surface of the tendon was marginally disrupted (Fig. 5(b)) when subject to minimal wear, the standardised frictional coefficient increased from 0.011 to 0.030. Despite greater wear causing substantially greater surface disruption (Fig. 5(c) and (d)), there was only a relatively minor change in the frictional coefficient. A similar trend in the consequence of wearing was noted when considering the respective Stribeck plots, with the data from the mild, moderate and severe wear testing conditions all being consistently offset versus the control results (Fig. 7). Hence, whilst the positive trend in all the data indicates that the interaction of even severely worn tendon remains optimally lubricated by a fluid-film layer, there is superior gliding efficacy associated with the 'healthy' tendon.

Considering the data in the format of the frictional force enables direct comparison with other studies. Momose et al.² explored the consequence of the human flexor digitorum profundus tendon (i.e. another extrasynovial tendon), reporting an increase in frictional force (from ~0.20N, to ~0.35N) as a consequence of mechanical wear to the paratenon, following 100 cycles gliding against its natural pulley. Whilst our study is consistent with these data, the relatively significant increase in frictional coefficient reported by Momose et al.² as a consequence of exposure to unremarkable loading is both surprising and, in a physiological environment, probably unsustainable.

It appears from our data that the outer surface of tendon is highly specialised, with even mild disruption being of detriment to its otherwise optimal bio-tribological performance. Certain conditions like impingement syndrome of shoulder^{13–17} are thought to cause progressive surface wear of the tendons resulting in mechanical failure due to mechanical rubbing.

The study raises the question for the reason for absence of relation between the coefficient of friction at the surface and the progression of the tears. The histological sample analysis has shown that when the surface tear appears, the tendon fibrils in the subsurface area are exposed with damaged paratenon. But with progression of tear, deeper tendon fibrils are exposed, which have similar structure as the fibrils of the subsurface area but are devoid of paratenon.

It is likely that the coefficient of friction increases with the damage of paratenon when the surface tear appears but as the tear progresses, the coefficient of friction does not significantly changes as further wear exposes deeper tendon fibrils which have similar

structure to the subsurface tendon fibrils as confirmed by the histological sample analysis done for the samples having minimal wear (50 rubs) and higher wear (150 and 300 rubs). Since the primary aim of the study was neither to identify the above mentioned finding nor to find the cause for it, further studies may be necessary to substantiate the finding.

The study supports the possibility that the frictional properties of a tendon rely predominantly on the paratenon and tendon sheath whilst the tendon deeper surface has limited role in surface tribology. The significance of lubricin molecules in reducing the friction at the articular cartilage has been widely accepted whilst the^{18–22} function of lubricin molecules in tendon surface is an area of interest.^{18,19} Mapping of the lubricin molecules in relation to the tendon layers and its role in gliding resistance has been on focus.¹⁸ Studies mapping the lubricin molecules have shown presence on the surface and at the interface of the fibre bundles in the tendon tissue.¹⁸ The distribution of the lubricin molecules is not uniform and it is predominantly present over the tendon surface.²⁰ The expression of the lubricin molecules is thought to be influenced more by the mechanical factors of relative sliding motion between the tendon fibrils.^{21,22} Conflicting evidence is present about the role of lubricin in relation to gliding resistance at the tendon surface as studies has shown that lubricin alone does not reduce the gliding resistance but only does so when it adheres on the tendon surface.

5. Conclusion

The study provides a validated model for future experiments aimed at further understanding of the tendon friction and tribology as the set up used is quite simple and is reproducible. This study is limited by an inability to relate the extent of our mechanical wear with that observed in tendinopathies, with an extensive literature search failing to identify any comparative data or images. Hence, whilst it is acknowledged that our mechanism of inducing tendon wear was, without doubt, un-physiological, the use of emery paper did provide a systematic technique to produce a consistent range of paratenon degeneration. Given the extremes of surface disruption that we have presented – and that the bio-tribological performance appears largely *independent* of the extent of wear, we believe that our techniques provide a valid indication as to the likely consequence of the *in vivo* wear process.

This study has provided bio-mechanical data to reinforce the importance of the paratenon in achieving optimal gliding conditions, whilst also indicating the significance of ensuring that this superficial surface remains intact. It is anticipated that our data may be of relevance to orthopaedic scientists and engineers focussing on the management of tendons subjected to mechanical wear. As the finding has not been reported before, further studies are required to validate our findings. Further exploration using human tissue is advised to assess the reproducibility of our finding.

Conflict of interest

None.

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