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Research Paper

Shear load transfer in high and low stress tendons

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ABSTRACT

Background: Tendon is an integral part of joint movement and stability, as it functions to transmit load from muscle to bone. It has an anisotropic, fibrous hierarchical structure that is generally loaded in the direction of its fibers/fascicles. Internal load distributions are altered when joint motion rotates an insertion site or when local damage disrupts fibers/fascicles, potentially causing inter-fiber (or inter-fascicular) shear. Tendons with different microstructures (helical versus linear) may redistribute loads differently.

Method of approach: This study explored how shear redistributes axial loads in rat tail tendon (low stress tendons with linear microstructure) and porcine flexor tendon (high stress with helical microstructure) by creating lacerations on opposite sides of the tendon, ranging from about 20% to 60% of the tendon width, to create various magnitudes of shear. Differences in fascicular orientation were quantified using polarized light microscopy.

Results and conclusions: Unexpectedly, both tendon types maintained about 20% of pre-laceration stress values after overlapping cuts of 60% of tendon width (no intact fibers end to end) suggesting that shear stress transfer can contribute more to overall tendon strength and stiffness than previously reported.

All structural parameters for both tendon types decreased linearly with increasing laceration depth. The tail tendon had a more rapid decline in post-laceration elastic stress and modulus parameters as well as a more linear and less tightly packed fascicular structure, suggesting that positional tendons may be less well suited to redistribute loads *via* a shear mechanism.

1. Introduction

Tendon is a unique, hierarchical structure serving the essential musculoskeletal function of transferring muscle contraction to joint movement or stability. Tendon hierarchy begins on the smallest level with collagen molecules and builds up to microfibrils, fibrils, fibers, and finally fascicles which form tendon as the overall structure. This study will primarily discuss the 2 largest sections of this hierarchy, the tendon fiber and fascicle. Collagen molecules have a triple-helical structure (Ramachandran and Kartha, 1955) forming fibrils, however helical structure at larger levels of hierarchy in some

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tendons has only recently been investigated in terms of structure/function. Fibrils from various tendon types, ranging from equine superficial digital flexor tendon to rat tail tendons, spiral within fibers (Jozsa et al., 1991), which, in turn, are organized in a helix (Vidal, 2003; Thorpe et al., 2013). Fascicles exhibit a helical organization within the whole tendon structure as well (Kalson et al., 2012; Kannus, 2000; Khodabakhshi et al., 2013).

Tendons that experience high stress (often termed energy storing tendons which also experience larger strains and help decrease energy loss) and low stress (often called positional tendons, primarily used for intricate movements) are morphologically different in their structural organization and may have different mechanical properties (Birch, 2007; Shadwick, 1990; Batson et al., 2003; Woo et al., 1980; Woo et al., 1981; Blanton and Biggs, 1970; Benedict et al., 1968; Thorpe et al., 2013; Screen et al., 2013). Interestingly, it has been reported that stress relaxation is greater in bovine digital extensor, a largely positional tendon, than the deep digital flexor, a more energy storing tendon (Shepherd et al., 2014), indicating not only a difference in mechanical strength but also in time-dependent adaptation to loading between tissue types. Although there has been little investigation into why these differences are present, it has been shown that inter-fascicular binding is greater in the flexor tendon and that fascicles in the bovine deep digital flexor tendon are less linearly oriented along the length of the tendon than fascicles in the digital extensor tendon (Shepherd et al., 2014). The difference in angulation of fascicles has also been confirmed by demonstrating a greater helical pitch angle in equine energy storing (superficial digital flexor) tendons than positional tendons (common digital extensor) (Thorpe et al., 2013).

While extensive research has defined the longitudinal behavior of tendons *in vitro* when the load distribution is as uniform as possible (Abrahams, 1967; Rigby et al., 1959), shear behavior has been less scrutinized. Understanding the shear behavior during loading is clearly important for redistribution of internal tendon loads 1) as insertion sites rotate during joint motion, 2) during fiber breakage or enzymatic local remodeling, and 3) around damage such as partial tears, lacerations, or other tendinopathies. It is also relevant for tendon lengthening procedures used to treat conditions such as diabetic plantar forefoot ulceration (Mueller et al., 2003) or gastrocsoleus equinus contracture (Hoke, 1931; Salamon et al., 2006). In these procedures up to 50% of the tendon width is transected at multiple locations (often 3) on alternating sides of the tendon, necessitating shear transfer to prevent complete tendon rupture (Mueller et al., 2003; Hoke, 1931; Salamon et al., 2006). However, studies report that shear force transmission between fascicles, carried by the interfascicular connective tissue, is nearly negligible compared to load born by intact fascicles (Haraldsson et al., 2008; Purslow, 2009), and that, in equine digital flexor (high stress, energy storing) tendon, sliding between fascicles allows for the large strain seen by these tendons (Thorpe et al., 2012). Fiber sliding is also shown as a dominant mechanism of motion during tendon stretch (Khodabakhshi et al., 2013; Li et al., 2013), particularly in more energy storing, flexor tendons of porcine (Screen et al., 2013) and primarily positional, extensor tendons of equine (Thorpe et al., 2013) where it has been demonstrated that more fiber sliding occurs than their positional or energy storing counterparts. Taken together, these studies suggest that shear transfer at both hierarchical levels in various tendon types, depending on location and species, may be minor, leaving unexplained the residual strength after tendon lengthening procedures.

Previous studies, including a couple completed in our lab investigating the mechanical properties of partially lacerated flexor tendons (high stress) have shown that mechanical compromise of lacerated tendon is not proportional to the laceration area, indicating that longitudinal loading of fibers and fascicles is not the only load-bearing mechanism within tendon (Kondratko et al., 2012; Pensalfini et al., 2014; Ahmadzadeh et al., 2013; Szczesny and Elliott, 2014). This supports the importance of understanding their shear properties during longitudinal loading. Shear transfer between fibers and fascicles would redistribute internal loads around the defect. Therefore, the purpose of the current study is to investigate how shear transfer affects tendon behavior in both high and low stress tendons, describing the elastic and viscoelastic responses after partial laceration. We hypothesize that low and high stress tendons exhibit different shear behaviors due to their different tendon structures, with high stress tendons having greater axial strength *via* internal shear.

2. Materials and methods

2.1. *Specimen preparation*

Thirty (30) porcine deep digital flexor tendons and 30 rat tail tendons were used in this study. Digital flexor tendons, high stress tendons (often considered as energy storing tendons), were excised from forelimbs of sexually mature 6 month old pigs obtained from a local abattoir. The flexor tendons were isolated from muscle and excess connective tissue, while the distal bone insertion site was left intact. The distal bone was potted in lightweight polyester resin filler in a mold with the internal dimensions of the custom grip used for testing. Rat tail tendons, obtained from sexually mature, 2–3 month old animals with a mass of about 300 g were defined in this study as low stress, more positional tendons. The tails were removed at their base from the rat and the tendons were carefully dissected free from tail vertebrae. It is recognized that rat tail tendons differ from other tendons in that they operate in allowing the tail to bend actively. These tendons are nevertheless appropriate for the present research because they have been widely studied by others and there is much literature for comparison.

Tendon width and thickness were measured on each tendon using a digital caliper prior to tendon preloading. Each dimension was measured in 3 locations along the tendon, one approximately 15 mm from either grip and one near the middle of the tendon to ensure the average was representative of the experimental length. The averages were used to determine the cross-sectional area, assuming an elliptical cross-section, similar to Boyer et al. (2001), Duenwald et al. (2009), and LaCroix et al. (2013). Specimen hydration was maintained throughout setup and testing with physiologic buffered saline (PBS).