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Structural and material properties of human foot tendons

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ABSTRACT

Backgrounds: The aim of this study was to assess the mechanical properties of the main balance tendons of the human foot *in vitro* reporting mechanical structural properties and mechanical material properties separately. Tendon structural properties are relevant for clinical applications, for example in orthopedic surgery to elect suitable replacements. Tendon material properties are important for engineering applications such as the development of refined constitutive models for computational simulation or in the design of synthetic materials.
Methods: One hundred uniaxial tensile tests were performed to obtain the mechanical response of the main intrinsic and extrinsic human foot tendons. The specimens were harvested from five frozen cadaver feet including: Extensor and Flexor tendons of all toes, Tibialis Anterior and Posterior tendons and Peroneus Brevis and Longus tendons.
Findings: Cross-sectional area, load and strain failure, Young's modulus and ultimate tensile stress are reported as a reference of foot tendon mechanical properties. Two different behaviors could be differentiated. Tibialis and Peroneus tendons exhibited higher values of strain failure compared to Flexor and Extensor tendons which had higher Young's modulus and ultimate tensile stress. Stress–strain tendon curves exhibited proportionality between regions. The initial strain, the toe region and the yield point corresponded to the 15, 30 and 70% of the strain failure respectively.
Interpretation: Mechanical properties of the lesser-studied human foot tendons are presented under the same test protocol for different engineering and clinical applications. The tendons that work at the inversion/eversion plane are more deformable at the same stress and strain rate than those that work at the flexion/extension plane.

1. Introduction

Tendon is a white fibrous tissue that connects the extremes of the muscles to the bones. Its biomechanical role is to transmit the contraction of the muscles to the skeleton in order to produce force or movement of the body. This tissue is evolutionary mechanoadapted to work axially, analogous to a string, with a large length compared to its section.

Mechanical properties of tendons have been studied previously, particularly the Achilles tendon. It is one of the biggest tendon of the human body and very relevant clinically due to its high incidence of injury. Furthermore, its location and structure facilitate the measures *in vivo*. There is an extensive bibliography about this tendon which in certain situations is extrapolated to estimate the properties of other tendons, as in the case of other foot tendons where the information available is scarce and incomplete (Sharkey and Hamel 1998; Thordarson et al. 1995).

The material properties reported for tendons have a great variability. For example, the Young's modulus varies in an order of magnitude from 0.2 to 2 GPa (Ker 2007; Maganaris et al., 2008; Wang 2006). There are two main reasons for this disparity of results: one is the natural biological variation and the other is the different procedures used to assess the properties. To reduce the influence of the first factor some authors prefer to test animal specimens where the history of the subject can be controlled, although for clinical applications human material is frequently required. The second factor could be compensated applying the same methodology to calculate the properties, but there is no agreement about a proper method to evaluate mechanical tendon properties yet. Furthermore, different methodologies are needed depending on the objective pursued. For instance, in the field of simulation, the

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Abbreviations: CSA, cross-sectional area; EDB, extensor digitorum brevis; EDL, extensor digitorum longus; EHL, extensor hallucis longus; FDB, flexor digitorum brevis; FDL, flexor digitorum longus; FHL, flexor hallucis longus; PB, peroneus brevis; PL, peroneus longus; TA, tibialis anterior; TP, tibiales posterior.

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characterization of a tissue can be approximated by linear, hyperelastic or viscoelastic models, which requires different mechanical parameters. The positive aspect of the use of different techniques to assess the mechanical properties is that it prevents bias.

The mechanical properties of human foot tendons are valuable information in different fields. In orthopedic surgery, the use of tendon grafts is common to repair tendons and ligaments (Giannini et al. 2008; Sebastian et al. 2007; Zhao and Huangfu 2012). Among other characteristics, the mechanical structural properties of the potential graft are one of the prerequisites that surgeons evaluate in the election of a suitable replacement. Detailed information of structural properties of every foot tendon would help surgeons in the decision making process. Computational biomechanics is another field in which experimental data of actual behavior of human foot tendons would provide a significant advance. From the engineering perspective, the human foot is a complex structure of small bones supported by strong ligaments and controlled by a network of tendons and muscles. Considering that the current barrier in foot computational simulation is the inclusion of these musculotendinous structures in the models (Morales-Orcajo et al., 2015), a detailed description of their material properties will help in the definition and adjustment of foot tendon material models.

The purpose of this study is to assess the mechanical properties of the human foot tendons responsible for the stabilization of the ankle joint and control motion of toes. One hundred samples of these lesser-studied foot tendons were tested *in vitro*. Particular effort was made to proportionate a refined description of their hyperelastic feature. As outcome, a dataset of experimental values for engineering and clinical applications is provided.

2. Methods

2.1. Tendon specimens

A total of one hundred tendons samples were taken from five male elder donors, with the approval of the ethical committee of clinical research of the Hospital Clínico San Carlos in Madrid. A sample of each tendon was cut from the most relative uniform cross-sectional area (CSA) removing all the soft tissue around the tendon. After the dissection, the samples were frozen and kept at a temperature of −20 °C (Devkota and Weinhold 2003; Schechtman and Bader 1997; Sebastian et al. 2007; Zhao and Huangfu 2012) until the day of testing (8–12 months) (Vergari et al. 2011).

The tendons included in the experiments were sorted in two groups: the long tendons involved in flexion and extension of the toes, on the one hand and the thick tendons intervening on the inversion and eversion of the ankle, on the other hand. The former includes the Extensor Digitorum Brevis (EDB) and the Extensor Digitorum Longus (EDL) which extent lesser toes, the Extensor Hallucis Longus (EHL) which extends the great toe, the Flexor Digitorum Brevis (FDB) and the Flexor Digitorum Longus (FDL) which flex the four lateral toes and the Flexor Hallucis Longus (FHL) which flexes the hallux. The latter involves the Tibialis Anterior (TA) and the Tibialis Posterior (TP) which invert the foot, and the Peroneus Brevis (PB) and Peroneus Longus (PL) which evert the foot (Fig. 1). These tendons enable us to stay balanced in upright position.

2.2. Testing procedure

Specimens were gradually thawed and kept hydrated until the time of testing at room temperature (~25 °C). The CSA was measured right before testing taking the average of three measures along the longitudinal axis of the sample. The maximal and minimal diameters of the tendon were measured with a digital caliper to calculate CSA by approximating it as an ellipse (Giannini et al. 2008; Vergari et al. 2010). A pair of screw lock clamps was specifically designed to perform the tests. The inner sides of the stainless steel clamps were milled with small holes to improve the grip. No cycle of tissue preconditioning was applied to the samples (Butler et al. 1984; Giannini et al. 2008; Schechtman and Bader 1997; Zhao and Huangfu 2012).

A universal testing machine (Instron Ltd., U.K., model 5548) was used to perform the tests (Fig. 2). An initial stretch of 1 MPa was applied to remove any slack in the samples. Then, a displacement was applied at a rate of 0.1 mm/s to failure. This rate corresponds with approximate 10–20% s^{-1} depending on length sample. Strain was measured using clamp-to-clamp displacement. The trials with evidences of slipping or initial damage were discarded.

2.3. Tendon stress–strain curve

The stress–strain curve is the normalized curve of the load–displacement graph provided by the test machine. This curve represents the main material parameters. The x coordinate indicates the strain failure, the y coordinate indicates the ultimate tensile stress and the Young's modulus is the slope of the linear region of the curve. Stress (σ) is

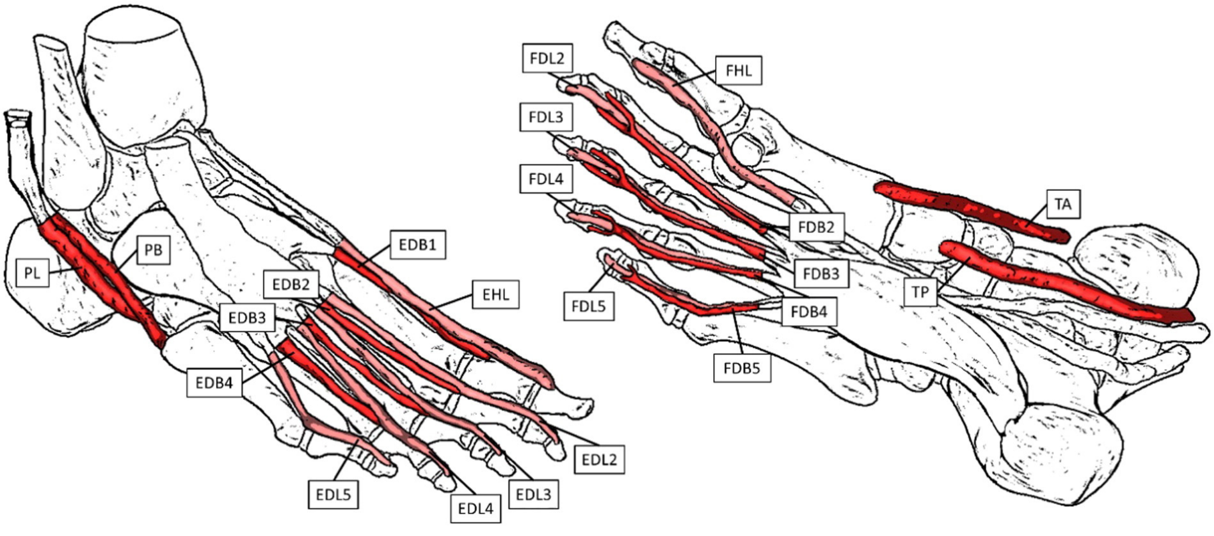

Fig. 1. Schematic view of the anatomical position of the specimens tested.