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Research Paper

Planar biaxial testing of soft biological tissue using rakes: A critical analysis of protocol and fitting process

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ABSTRACT

Mechanical characterization of soft biological tissue is becoming more and more prevalent. Despite the growing use of planar biaxial testing for soft tissue characterization, testing conditions and subsequent data analysis have not been standardized and vary widely. This also influences the quality of the result of the parameter fitting. Moreover, the testing conditions and data analysis are often not or incompletely reported, which impedes the proper comparison of parameters obtained from different studies.

With a focus on planar biaxial tests using rakes, this paper investigates varying testing conditions and varying data analysis methods and their effect on the quality of the parameter fitting results. By means of a series of finite element simulations, aspects such as number of rakes, rakes' width, loading protocol, constitutive model, material stiffness and anisotropy are evaluated based on the degree of homogeneity of the stress field, and on the correlation between the experimentally obtained stress and the stress derived from the constitutive model. When calculating the aforementioned stresses, different definitions of the section width and deformation gradient are used in literature, each of which are looked into. Apart from this degree of homogeneity and correlation, also the effect on the quality of the parameter fitting result is evaluated.

The results show that inhomogeneities can be reduced to a minimum for wise choices of testing conditions and analysis methods, but never completely eliminated. Therefore, a new parameter optimization procedure is proposed that corrects for the inhomogeneities in the stress field and induces significant improvements to the fitting results. Recommendations are made for best practice in rake-based planar biaxial testing of soft biological tissues and subsequent parameter fitting, and guidelines are formulated for reporting thereof in publications.

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1. Introduction

The performance of biomedical devices and procedures is increasingly assessed by means of finite element (FE) simulations (Migliavacca et al., 2002; Conway et al., 2012). Logically, using appropriate material properties is crucial for the outcome of the simulation. Hence, apart from elucidating relative trends between tissue types, the absolute characterization of the mechanical behaviour of biological tissue is gaining importance.

Mechanical characterization of soft biological tissue through planar biaxial testing is becoming more and more prevalent (Fung, 1981; Humphrey, 2002; Sacks, 2000; Sommer et al., 2013) and is used for all kinds of nearly incompressible thin tissues.

Three types of gripping mechanisms are commonly used (see Fig. 1): clamps, rakes, and sutures (also referred to as tethers). None of these result in a homogeneous stress state (Sun et al., 2005), the biggest confounding factors being discontinuous loading and unknown contra-lateral forces. Rigidly clamped specimens are loaded most continuously, but this method induces substantial unmeasured contra-lateral forces which are a.o. geometry- and displacement-dependent (Nolan and McGarry, 2016). Nolan and McGarry (2016) recently suggested that an inverse FE-based method is the only way to account for these contra-lateral forces in the case of non-linear anisotropic materials. These contra-lateral forces create a stress shield for the region of interest (Sun et al., 2005) causing an artificial increase in the apparent stiffness (Eilaghi et al., 2009; Waldman and Michael Lee, 2002). This stress shielding effect is typically reduced with cruciform-shaped samples. However, these imply substantial tissue loss during sample preparation, a luxury one can generally not afford when testing biological tissues (Fung, 1981).

On the other end of the spectrum, sutures do allow contra-lateral movement and rotation of the sample, and are typically used with square samples. Suture-based systems with pulleys, as shown e.g. in Zhang et al. (2015) are designed such that no shear stress is transferred onto the sample, and are therefore especially fit to deliberately induce shear deformation in samples with material axes that are rotated with respect to the testing axes. Deliberately inducing shear can be required when the material axes are an unknown parameter that require fitting, or when the material model contains specific terms activated only in shear. However, attaching sutures to the specimen is highly unrepeatable, even if a template is used, and results in a non-uniform application of the load.

Rake-based systems do transfer a limited amount of contra-lateral forces onto the sample and are less fit for large shear deformations, but are substantially easier to mount in a repeatable and equally spaced manner. Hence, although the applied load is still discontinuous, using rakes results in a more uniform load distribution. Therefore, when testing samples with symmetric material axes that can be aligned with the testing axes, and fitting them to material models that do not contain specific shear terms, rake-based systems are often the method of choice.

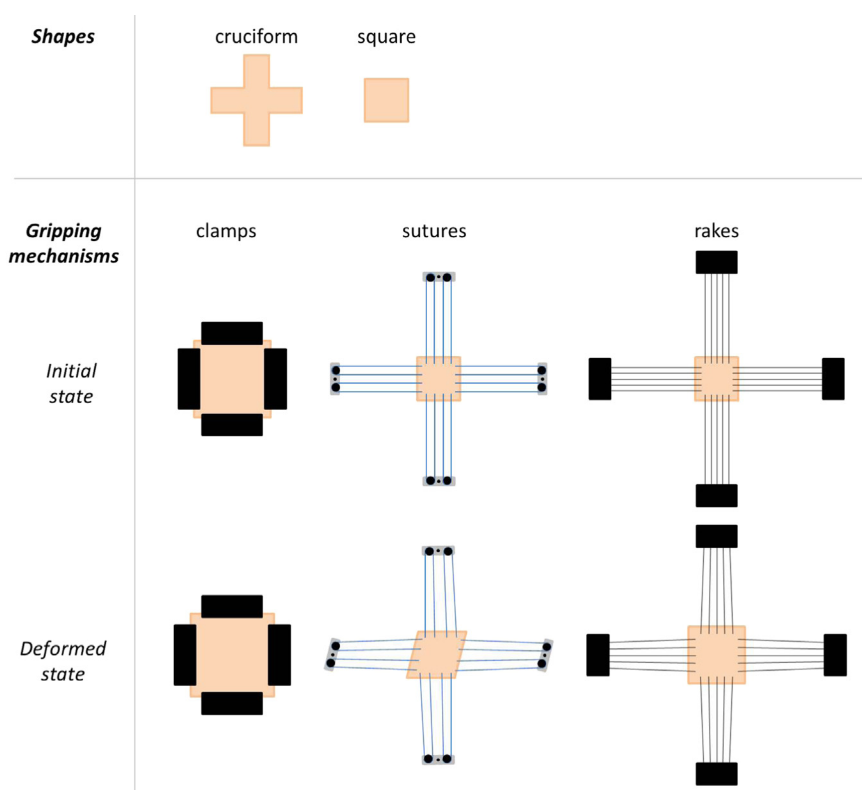

Fig. 1 – Different specimen shapes: cruciform and square; and different gripping mechanisms: clamps, sutures and rakes for planar biaxial experiments in initial and deformed state.