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A novel MRI compatible soft tissue indentor and fibre Bragg grating force sensor

Kevin M. Moerman [a,b,*], Andre M.J. Sprengers [b], Aart J. Nederveen [b], Ciaran K. Simms [a]

[a] *Trinity Centre for Bioengineering, School of Engineering, Parsons Building, Trinity College, Dublin 2, Ireland*
[b] *Radiology Department, Academic Medical Centre, Meibergdreef 9, 1105 AZ Amsterdam, The Netherlands*

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ABSTRACT

MRI is an ideal method for non-invasive soft tissue mechanical properties investigation. This requires mechanical excitation of the body's tissues and measurement of the corresponding boundary conditions such as soft tissue deformation inside the MRI environment. However, this is technically difficult since load application and measurement of boundary conditions requires MRI compatible actuators and sensors. This paper describes a novel MRI compatible computer controlled soft tissue indentor and optical Fibre Bragg Grating (FBG) force sensor. The high acquisition rate (100 Hz) force sensor was calibrated for forces up to 15 N and demonstrated a maximum error of 0.043 N. Performance and MRI compatibility of the devices was verified using indentation tests on a silicone gel phantom and the upper arm of a volunteer. The computer controlled indentor provided a highly repeatable tissue deformation. Since the indentor and force sensor are composed of non-ferromagnetic materials, they are MRI compatible and no artefacts or temporal SNR reductions were observed. In a phantom study the mean and standard deviation of the temporal SNR levels without the indentor present were 500.18 and 207.08, respectively. With the indentor present the mean and standard deviation were 501.95 and 200.45, respectively. This computer controlled MRI compatible soft tissue indentation system with an integrated force sensor has a broad range of applications and will be used in the future for the non-invasive analysis of the mechanical properties of skeletal muscle tissue.

1. Introduction

Magnetic Resonance Imaging (MRI) is an ideal modality for the non-invasive analysis of soft tissue biomechanics as it provides excellent soft tissue contrast without exposing subjects to ionizing radiation. In addition it allows for the measurement of various biomechanical boundary conditions required for inverse analysis of tissue properties, such as 3D tissue geometry (segmentable from anatomical MRI), 3D architecture (e.g. based on diffusion tensor MRI [1]) and accurate 3D soft tissue deformation measurement (e.g. based on tagged MRI [2,3]). The non-invasive investigation of soft tissue mechanical properties allows for the validation of detailed constitutive laws enabling derivation of in vivo tissue loading conditions and prediction of injury. Hence it has a wide array of applications including impact biomechanics [4], rehabilitation engineering [5] and surgical simulation [6].

However the MRI based investigation of the mechanical properties of soft tissue often requires an MRI compatible soft tissue loading system consisting of actuators (to mechanically palpate/excite the tissue) and sensor devices (to measure the applied load). Designing such devices to be safe within the MRI environment and compatible with the imaging is non-trivial [7]. Detailed evaluation of constitutive properties (including visco elasticity) requires dynamic load application capabilities and, since imaging may require motion repetitions, displacement or force control and control of timing with respect to imaging. This paper describes a novel computer controlled MRI compatible soft tissue indentation system and force sensor enabling the MRI based analysis of the non-linear (visco) elastic and anisotropic behaviour of skeletal muscle tissue. The current focus is non-painful and non-damaging indentation of the biceps region of the upper arm using a 45 mm diameter, which places a load constraint in the order of 15 N. Both quasi-static (load is held static during measurement of boundary conditions) and dynamic applications are of interest (non-painful indentation speeds whereby boundary conditions are continuously sampled as the tissue deforms).

Actuator and sensor devices which can safely be used within the MRI environment (are MRI conditional or MRI safe) are relevant to many research areas. As such a large array of MRI compatible actuators [8] (review paper) and sensor systems [9] (review paper) have been proposed. Applications include: MRI robotics (e.g.[10,11]), MRI guided surgical interventions (e.g. [12–14]), MRI based catheterisation (e.g. [15]), functional MRI (e.g. [16,17]) and the study of pressure ulcer development (e.g. [18–23]). In addition, as is relevant here, they have been employed

* Corresponding author at: Academic Medical Centre, Department of Radiology, Meibergdreef 9, 1100 DD, Amsterdam, The Netherlands. Tel.: +31 20 56 68327.
E-mail address: k.m.moerman@amc.uva.nl (K.M. Moerman).

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for non-invasive investigation of soft tissue biomechanics (e.g. [2,18,22–26]).

Two main groups of actuator and sensor devices suitable for the MRI environment can be distinguished: (1) devices employing electric principles and/or ferromagnetic components in the MRI room and/or close to the imaging region and (2) devices which are intrinsically MRI compatible since they employ non-conducting and non-ferromagnetic materials and sensor signal transmission occurs using magnetically inert media within the MRI room. The latter group is the focus here since these do not significantly affect image quality and sensor performance. In addition they do not require shielding or anchoring and can safely be used in close proximity to the test subject. Therefore the applicability, safety and compatibility with MRI are more easily established for these devices which simplifies evaluation and approval (e.g. ethical) for a research setting.

A variety of soft tissue loading systems that can be used in the MRI environment have been proposed in the literature (e.g. [18,22–27]), however their design is often tailored to suit their particular application (e.g. ranging from rat lower limb [18], to human footpad [25] and pigs buttock [23]) which, to date, has not included indentation of the upper arm. Despite this, a brief discussion of current soft tissue loading systems for the MRI environment is presented here. Most current soft tissue loading systems do not have dynamic displacement or force control capabilities during imaging (e.g. [22,24,25]) and have so far been limited to quasi-static applications (e.g. [18,22–26]). In some cases the load can only be applied prior to imaging and cannot be altered during scanning (e.g. [22,24]) which does not enable dynamic analysis and MRI based deformation measurement techniques such as SPAMM (Spatial Modulation of the Magnetisation) (e.g. [2,3]) tagged MRI. Hence some researchers have employed contour tracking from matched anatomical MRI scans prior to and after loading (e.g. [24]) and registration techniques (e.g. [26]) or finite element analysis (FEA) for estimation of deformation instead (e.g. [21,22]). However these measures are more limited than full 3D deformation measurement based on SPAMM tagged MRI [3]. In addition the studies employing soft tissue loading devices have limited their analysis to the evaluation of isotropic hyperelastic constitutive models (e.g. [18,21,22,24,26,28,29]). Evaluation of more detailed constitutive models incorporating non-linearity, visco elasticity and anisotropy require more detailed boundary condition measurement which is the focus of the current study.

Recently more advanced soft tissue loading devices have been proposed for the MRI environment such as Fu et al. [27] (a hydraulic actuator for lower leg indentation) and Solis et al. [23] (pigs buttock compression using a flat plate connected by a ∼3 m rod (which passes through a wall) to a servo motor and force transducer outside the MRI room). Although both these systems feature dynamic displacement control capabilities and motion triggering toward the imaging, the latter can only operate approximately parallel to the MRI bore axis through the particular hole in the wall and for the former the displacement or force control and measurements achieved are not elaborated in sufficient detail.

For the soft tissue loading devices mentioned above the force measurement systems included the application of static weights [24], repetition of the experiment outside the MRI environment [22], the application of electric force sensors which suffer from electromagnetic interference [18] or force transducers outside the MRI room [23]. Other force sensors for the MRI environment have also been developed such as piezoelectric sensors. However these do not allow static force measurements and may induce image artefacts [12]. Since for the current study intrinsically MRI compatible devices are of interest optical force sensors are the focus. MRI compatible optical force sensors have been proposed for analysis of needle deflection and force feedback measurement during MRI based catheterisation have also been developed [15,30] however these are applied to relatively low forces in the range 0–0.5 N. Tokuno et al. [31] developed a force sensor based on optical micrometry and demonstrated accuracy within 1.6% for forces up to 6 N. Tada and Kanade [32] presented a tri-axial force sensor based on optical micrometry consisting of 5 optical fibres (1 emitting and 4 receptor fibres) and demonstrated under 3% errors for forces up to 15 N. However when in a later study [26] the authors used the system for human finger-tip indentation the force, acquired at 1 Hz, was found to vary with a standard deviation of up to 0.3 N around a static mean load of 2.35 N. The causes for these increased deviations, with respect to the calibration, were not discussed. Recently Song et al. [14] designed an advanced Fibre Bragg Grating (FBG) based tri-axial force sensor mounted on a robot arm. Forces where calibrated up to ∼10 N and a maximum force error of 0.5 N was recorded.

In this study a FBG sensor system is proposed because these have several advantages over other optical force sensing systems [14]: (1) measurement is independent of fluctuating light levels, (2) multiple gratings can be applied in series and (3) they have simple wiring and a compact implementation.

This paper outlines the design of a complete system for soft tissue indentation which is MRI compatible. This system is computer controlled and incorporates dynamic displacement control and motions can be triggered to be synchronised with the imaging (enabling the use of repeated image acquisitions common for MRI based deformation measurement techniques). Embedded in the MRI actuator is a novel high speed (100 Hz) MRI compatible optical FBG based force sensor enabling dynamic force measurement suitable for viscoelastic (e.g. ramp and hold type) analysis and fast detection of timing of motion and load application. The system is evaluated for the MRI based investigation of soft tissue biomechanics based on phantom tests and indentation of the upper arm of volunteers.

2. Methods

This section describes: (1) Fibre Bragg Grating based optical force sensing, (2) The soft tissue indentor system, (3) Optical force sensor calibration and (4) Evaluation of the indentor system performance. All signal and image processing methods were developed in MATLAB (R2012a v7.14.0.739, The Math works Inc., USA).

2.1. Fibre Bragg Grating based optical force sensing

In Fibre Bragg Grating (FBG) a periodic perturbation of the refractive index is introduced along an optical fibre acting as a local wavelength specific reflector [33,34]. The reflected (Bragg) wavelength λ_B for a specific grating is defined by [35]:

$$\lambda_B = 2\eta_{eff}\Lambda \tag{2.1}$$

Here η_{eff} is the effective refractive index of the fibre core and Λ is the period of the grating. From this equation it is clear that λ_B is both strain and temperature dependant since η_{eff} varies with temperature and Λ is altered following longitudinal fibre strain and thermal expansion/contraction [35]. Under isothermal conditions a linear relationship exists between reflected wavelength and the applied strain where tensile and compressive strains increase and decrease the wavelength reflected respectively. For the current study only the mechanical strain induced effect is of interest since it is linearly dependent on the force exerted on the optical fibre. In order to separate the effect of mechanical strain from the effects of temperature fluctuations two gratings are placed close together in series whereby one is subjected to both mechanical strain and local temperature variations, while the other is isolated