Continuously tagged MRI of non-periodic motion
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Citation for published version (APA):

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Chapter 1
General Introduction
1 Deformation of skeletal muscle tissue

Mechanical properties of soft tissue are relevant to many fields of research: impact biomechanics [1-3], rehabilitation engineering [4-6], tissue engineering [7,8], skeletal muscle behaviour simulation during gait [9] and surgical simulations [10-13]. Non-invasive mechanical property analysis is relevant for validation of constitutive models for living human tissue but also has many medical applications such as lesion detection [14], pressure ulcer research [15,16], diagnosis of pathologic muscle [17], assessment of limb immobilization and contracture [18].

*Figure 1:* Examples of soft tissue deformation in biomechanical research: impact biomechanics (Mo et al [19]), virtual surgery development, mechanical properties of soft tissue in residual limbs after amputation (Portnoy et al [5]) and study of sub-dermal tissue during sitting (Linder-Ganz et al [20]).
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 (based on diffusion tensor MRI e.g.) and accurate 3D soft tissue deformation measurement (e.g. based on tagged MRI [21]).

Non-invasive mechanical excitation of tissue (e.g. indentation) for mechanical property analysis inside an MRI scanner requires accurate computer controllable and MRI compatible actuators and force sensors. Ensuring safety and compatibility of such systems is not trivial. Although MRI compatible actuators and force sensors have been developed for other applications such as MRI robotics (e.g. [22,23]), MRI guided surgical interventions (e.g. [24-26]), MRI based catheterisation [27], functional MRI [28] and the study of pressure ulcer development [29], to date no computer controlled MRI based actuator system suitable for human skeletal muscle tissue mechanical property investigation has been proposed. Once mechanical excitation has been applied, MRI can be employed for the non-invasive measurement of 3D soft tissue deformation.
2 Motility in the Gastro-intestinal tract

Motion in the gastro-intestinal tract can be characterized as highly complex and comprised by multiple governing physiological processes [30-32]. Contractions along the whole gastrointestinal tract are based on two fundamental electrical patterns called slow waves and spikes [30,33,34]. These patterns originate in the interstitial cells of Cajal [30,33-38] and spread out to the smooth muscle cells in the bowel wall. When a spike coincides with the crest of a slow wave, the action potential is reached and a contraction occurs. The maximum contraction frequency is thus determined by the frequency of slow waves and spikes. Slow waves are highly regular in time and vary along the gastrointestinal tract from 3 cycles per minute in the stomach to 11-12 cycles per minute in the duodenum and then decreasing stepwise along the small intestine to 7-9 cycles per minute in the distal ileum (see Figure 2) [30,33,34].

![Figure 2](image)

**Figure 2:** Schematic representation of motility patterns during fasting and after feeding and slow wave frequencies varying along the gastrointestinal tract.

Motion during periods of fasting is highly organized into a set of cyclically recurring motion patterns known as the Migrating Motor Complex (MMC). After ingestion of food, the cyclic pattern is broken and replaced by a band of random contractions called the fed- or postprandial-pattern [30,33].

Techniques for assessment of gastric and small intestinal motility exist in abundance and are to a large extent complementary [34,39-43]. At present manometry is accepted as most reliable and is furthest implemented into clinical practice. Manometry uses a pressure sensitive valve that is inserted into the GI tract registering contractions and distension as changes in pressure. By monitoring the pressure change over time and location along the gastrointestinal tract, 2D or 3D topographic pressure maps can be reconstructed (see figure 3). High-resolution manometry measures motility through pressure changes in a catheter inserted into the GI tract either orally or rectally. Separate channels debouching at small intervals along the catheter enable spatial resolution in addition to the inherent high temporal resolution of the technique. This can be regarded as an invasive and discomforting test and alternative methods of
assessment should aim for lower levels of invasiveness providing equal, better or complementary information.

Over the past years, MRI has increasingly been proposed as an alternative technique for motility assessment and several studies demonstrated the feasibility of quantitative motility assessment in the stomach and small intestine [47-51]. These studies however have their own limitations in terms of tradeoffs between spatial and temporal resolution, breath holds during scanning and oral preparation. Furthermore the analysis of MRI motility data comprises a complicated high workload process requiring dedicated readers and sound statistical analysis [42,43,48,49].

**Figure 3:** Examples of manometry measurements. *a:* high resolution fibre optic manometry of the colon[44]; *b:* topographic representation of manometry of swallowing motion in the oesophagus[45]; *c:* colour intensity topographic plot of swallowing motion in the oesophagus[46].
3 Tagged Magnetic Resonance Imaging

Tagged magnetic resonance imaging, also known as SPatial Modulation of the Magnetization (SPAMM) is a Magnetic Resonance Imaging (MRI) technique capable of capturing soft tissue motion in high detail in vivo. The SPAMM prepulse periodically dephases magnetization to create visible markers or tags in the image that can be tracked (see Figure 4).

![Figure 4: Schematic representation of a basic SPAMM preparation pulse with the pulse sequence (panel a), the effects on the magnetization (panel b) and the resulting sinusoidal modulated magnetization (panel c). The roman numerals I, II, III and IV demark chronological correspondence between the panels. At point I, no RF pulse or gradient has been applied and the magnetization is in equilibrium (i.e. aligned with the external magnetic field). At point II the first RF pulse has flipped the magnetization towards the x-y plane. The magnetization is then dephased along the direction of the gradient (point III). The second RF pulse flips the magnetization again, now rotating spins either towards the x-y plane or back the z-axis depending on the location along the gradient direction, resulting in a sinusoidal modulated magnetization along the gradient direction (point IV).]

The technique was developed for studying cardiac motion (see Figure 5) [52-55] and as such exploits the periodicity of the beating heart. This repetitive motion of the heart allows for spreading out the image acquisition over a series of heart beats and can be used to increase the signal to noise ratio (SNR) and resolution of the image and to capture the deformed tags at several cardiac phases.

![Figure 5: Examples of myocardial tagging. Figure 5a shows vertical taglines in non-deformed and deformed state[55]. Figure 5b shows several cardiac phases using a 3D Complementary SPAMM (C-SPAMM) sequence [52-56]. C-SPAMM combines two identical acquisitions with an inverted tag pattern, resulting in suppression of the underlying anatomy and improved tag pattern contrast [55,57].]

The SPAMM sequence has been applied to other types of motion using repetitions either performed by the subject’s physiology, by voluntary movement or enforced using external devices, for instance motion of the tongue [58] (16 volunteer speech repetitions per slice), brain [59] (144 volunteer rotational head accelerations) and eye [60] (>135 repeated left to right movements). This preserves the image quality that is customary for the repeated tagged sequence, but can lead to patient discomfort.
Furthermore, most tissue motion outside the heart can be considered as semi-repetitive in the sense that there is always some sort of hysteresis involved. There is also tissue motion that is simply non-repetitive, such as Rapid Eye Movement, involuntary muscle spasms and bowel motion. The subject of this thesis is to attempt to apply the SPAMM sequence with a minimal amount of repetitions to semi-repetitive tissue motion and non-repetitive tissue motion: deformation of skeletal muscle tissue (the biceps) and bowel motion.

4 Aim of this thesis

The aim of this thesis is to develop a framework (i.e. experimental setup, data acquisition and post-processing) for the application of tagged MRI to two types of non-periodic motion, muscle indentation and bowel motility. Tagged MRI could offer several potential improvements to the current methods available for assessment of muscle deformation and bowel motility. The tagged sequence provides its own contrast, which reduces the need for high spatial resolution and tissue contrast so that a larger (i.e. 3D) FOV can be scanned at a higher temporal rate. Limiting the amount of repetitions in measurement of muscle deformation will help to maintain acceptable comfort levels for patients but also improves the quality/relevance of gathered information for medical applications and soft tissue models as it helps to preserve any hysteresis in muscle behaviour. For motility assessment the tag pattern offers the possibility of automated analysis and thus a decrease in workload per time frame. This in turn could enable monitoring of the complex temporal motility patterns over longer time periods. The added contrast of the tag pattern could also reduce the required level of oral preparation decreasing the burden of the method.

5 Outline of this Thesis

Since tagged MR was developed for periodic motion, the tagging prepulse sequence was reconfigured to sample motion real time. For controlled and repeatable soft tissue deformation in the MRI scanner, we present a novel MRI compatible soft tissue indenter with a fibre Bragg grating force sensor in chapter 2. This indenter is computer controlled, hydraulically driven and capable of highly repeatable indentations of soft tissue. Chapter 3 describes the application of the novel indenter and non-periodic SPAMM sequence to indentation of a MRI compatible gel phantom and biceps muscle (in-vivo). 3D motion information of static (ramp and hold) deformation was obtained in 3 motion cycles. In chapter 4 we used the continuously tagged MR technique to sample deformation of the gel phantom and biceps muscle during continuous indentation. Again 3D deformation was reconstructed using only three motion cycles and improved post-processing techniques based on Gabor filter analysis were presented. In chapter 5, development of an automated post-processing algorithm is described based on scale space analysis. This algorithm is capable of tracking deformed taglines without the use of the initial positions, which are unavailable in non-periodic, continuously tagged imaging and in an automated manner, indispensable for processing large data sets and the feasibility of clinical applications. To prove the validity of this approach for motility assessment we demonstrated the methods sensitivity to the effects of administration of the bowel relaxants glucagen hydrochloride during dynamic scanning in chapter 6. In chapter 7 we demonstrate the method’s ability to sample bowel motion and assess the intra
subject variability of tagged motion in the abdomen in a group of ten healthy volunteers. Chapter 8 expands on the interpretation of continuously tagged motion in the abdomen and focuses on detailed frequency analyses to study the complex low frequent mechanisms governing motility.
REFERENCES


52. Zerhouni EA, Parish DM, Rogers WJ, Yang A, Shapire EP. Human heart:


