Title: Design and Evaluation of MR-Safe Loading Device for Knee Joint Assessment with MRI
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Abstract

The knee joint is one of the human body's largest and most complex joints. The functionalities of the joint depend on bones, muscles, ligaments, cartilage, meniscus, synovial fluid, and physiology. There could be various causes of ailment in the knee joint such as genetic factors, epigenetic factors, pathological conditions, fatigue, inflammation, and other biomechanical issues. This thesis included research studies on the tibiofemoral joint's weight-bearing soft-tissues (meniscus and cartilage).

Weight-bearing soft-tissues play a significant role in knee joint functionalities, whereas magnetic resonance imaging (MRI) is the gold-standard technique for imaging soft-tissues. Therefore, MRI is used as an imaging modality to assess the knee joints in this thesis. The routine knee joint MRI studies are conducted in a supine position, which overlooks the weight-bearing conditions of a joint. However, the changes in the joint could be dynamic that might be evident only during the weight-bearing condition, such as pain might arise during the loading conditions. Therefore, the knee joint's weight-bearing condition during scanning may represent *in-vivo* patho-physiological conditions. There are also reported diagnostic mismatches between unloaded and loaded knees during MRI. Therefore, the potential to get additional information from weight-bearing MRI to examine knee health is hypothesized in the thesis. Also, from a clinical perspective, load during imaging might potentially improve the diagnosis of knee health in the early stages.

There are various existing solutions for weight-bearing knee joint MRI. One of the solutions is open-standing MRI, but it suffers from a low signal-to-noise ratio (SNR). Besides, few other devices are available to exert load on the knee joint during MR scanning, but these devices have a bulky design, are expensive, and have a large setup time. Some of these devices even require altering the MRI room settings. Further, the unidirectional loading mechanism of

these devices potentially induce motion artifacts. Thus, these devices are not well suited for a busy clinical routine setup and confined to a research setting.

This thesis aims to develop a low-cost, lightweight, portable, and MR-safe knee joint axially loading device during MRI scanning, which addresses some of the limitations of the existing solution. Further, assess the device-induced change in MR parameters for knee joint characterization. Besides, this thesis also explores the further clinical applications of the weight-bearing knee MRI.

The first study in this thesis developed a low-cost, lightweight, portable knee joint axial loading device. Further, the developed device is calibrated and assessed for MR-safety, device-induced image artifacts, ease of doing, and degree of comfort for a subject. The device is developed in an iterative process with feedback from imaging partners and clinicians.

The objective of the second study of this thesis was to evaluate the developed device behaviors and the changes due to load in MR quantitative parameters for characterizing knee joint. This study consisted of two sub-studies: i) to compare the loading behavior of the developed device with natural standing stance using open-standing MRI 0.25 Tesla, and ii) to assess the MR parameter changes due to load using the developed device with 3.0 Tesla MRI. In the first sub-study, the tibiofemoral bone gap during the device load was compared to a natural standing load of various stances. The device exerted load was observed similar to a natural stance of standing with both (Pearson Coeifficent ‘r’ > 0.9). The loading effect on the change in bone gap, cartilage thickness, and cartilage T2-value was evaluated in the second sub-study; the observations are found to be similar to the previously reported research observations.

The third work in this thesis was on developing a novel method to estimate the subject-specific in-vivo stiffness of the tibiofemoral joint non-invasively. This study consisted of two

sub-studies: experimental study and simulation study. In the experimental study, the MRI scanned images of a knee joint with and without load (using the developed loading device) were used to evaluate the mean tibiofemoral strain. In the simulation study, a subject-specific knee joint finite-element-analysis (FEA) was performed with varying tibiofemoral joint stiffness to develop the stiffness versus strain model. The subject-specific experimental strain was fed in the stiffness versus strain model to evaluate the subject-specific stiffness. Further, the thesis also presented a generalized mathematical model to estimate in-vivo tibiofemoral joint stiffness.

The research outcomes in this thesis might make the weight-bearing knee joint MRI more accessible. Further, this work might open new applications for weight-bearing MRI and expedite knee research.