DESIGN AND EVALUATION OF MR-SAFE LOADING DEVICE FOR KNEE JOINT ASSESSMENT WITH MRI

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by

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Dedicated to,

Gurus, Parents, Wife, Shivansh, and Almighty God!

CERTIFICATE

This is to certify that the thesis entitled "**Design and Evaluation of MR-Safe Loading Device for Knee joint Assessment with MRI**", being submitted by **Mr. Sandeep Panwar Jogi**, to the Indian Institute of Technology Delhi, for the award of '**Doctor of Philosophy**' in Centre for Biomedical Engineering is a record of the bonafide research work carried out by him under our supervision and guidance. He has fulfilled the requirements for submission of this thesis, which to the best of our knowledge has reached the requisite standard. The material contained in the thesis has not been submitted in part or full to any other University or Institute for the award of any other degree or diploma.

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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 Coefficient ‘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.

सार

घुटने का जोड़ मानव शरीर के सबसे बड़े और सबसे जटिल जोड़ों में से एक है। जोड़ की कार्यक्षमता हड्डियों, मांसपेशियों, स्नायुबंधन, उपास्थि, मेनिस्कस, श्लेष द्रव और शरीर क्रिया विज्ञान पर निर्भर करती है। घुटने के जोड़ में बीमारी के कई कारण हो सकते हैं जैसे आनुवंशिक कारक, पश्चजनन सम्बन्धी कारक, रोग की स्थिति, थकान, सूजन और अन्य जैवयांत्रिकी मुद्दे। इस शोध प्रबंध में टिबिओफेमोरल (Tibiofemoral) जोड़ के भारोत्तोलन नरम-ऊतकों (मेनिस्कस और उपास्थि) पर शोध अध्ययन शामिल थे।

भार-वहन नरम-ऊतक घुटने के जोड़ की कार्यक्षमता में महत्वपूर्ण भूमिका निभाते हैं, जबकि मैग्नेटिक रेजोनेंस इमेजिंग (एमआरआई (MRI)) नरम-ऊतक की इमेजिंग के लिए स्वर्ण-मानक तकनीक है। इसलिए, इस शोध प्रबंध में, घुटने के जोड़ को अवेध्य रूप से आकलन करने के लिए एमआरआई(MRI) का उपयोग इमेजिंग तौर-तरीकों के रूप में किया जाता है। घुटने के जोड़ के नियमित एमआरआई अध्ययन एक उतान पड़ी हुई स्थिति में आयोजित किए जाते हैं, जो एक जोड़ की भार वहन करने वाली स्थितियों की अनदेखी करता है। हालांकि, जोड़ में परिवर्तन गतिशील हो सकते हैं जो केवल भार-वहन की स्थिति के दौरान स्पष्ट हो सकते हैं, जैसे कि भार वहन की स्थिति के दौरान दर्द उत्पन्न हो सकता है। इसलिए, क्रमवीक्षण के

दौरान घुटने के जोड़ की भार वहन करने वाली स्थिति जीवे विकृति-शारीरिक स्थितियों का प्रतिनिधित्व कर सकती है। एमआरआई (MRI) के दौरान गैर-भार-वहन और भार-वहन घुटनों के बीच नैदानिक बेमेल होने की भी सूचना है। इसलिए, शोध प्रबंध ने घुटने के स्वास्थ्य की जांच के लिए भारोत्तोलन एमआरआई(MRI) से अतिरिक्त जानकारी प्राप्त करने की क्षमता की परिकल्पना की है। इसके अलावा, नैदानिक दृष्टिकोण से, इमेजिंग के दौरान भार प्रारंभिक अवस्था में घुटने के स्वास्थ्य के निदान में संभावित रूप से सुधार कर सकता है।

वजन-वहन करने वाले घुटने के जोड़ के एमआरआई(MRI) के लिए कई मौजूदा समाधान हैं। समाधानों में से एक ओपन-स्टैंडिंग एमआरआई है, लेकिन यह कम सिग्नल-टू-शोर अनुपात (एसएनआर(SNR)) से ग्रस्त है। इसके अलावा, एमआर(MR) क्रमवीक्षण के दौरान घुटने के जोड़ पर भार डालने के लिए कुछ अन्य उपकरण उपलब्ध हैं, लेकिन इन उपकरणों का भारी डिज़ाइन है, महंगे हैं, और एक बड़ा स्थापित करने का समय है। इनमें से कुछ उपकरणों को एमआरआई (MRI) कमरे की स्थापना बदलने की भी आवश्यकता होती है। इसके अलावा, इन उपकरणों का एक-दिशात्मक भारोत्तोलन तंत्र संभावित रूप से गति विरूपण साक्ष्य को प्रेरित करता है। इस प्रकार, ये उपकरण एक व्यस्त नैदानिक दिनचर्या स्थापना के लिए उपयुक्त नहीं हैं और एक शोध-स्थापना तक ही सीमित हैं।

इस शोध प्रबंध का उद्देश्य एमआरआई स्कैनिंग के दौरान कम लागत वाला, हल्का, उठाऊ और एमआर(MR)-सुरक्षित घुटने का जोड़ अक्षीय भार उपकरण विकसित करना है, जो

मौजूदा समाधान की कुछ कमियों को दूर करता है। इसके अलावा, घुटने के जोड़ के लक्षण वर्णन के लिए एमआर(MR) मापदंडों में विकसित उपकरण-प्रेरित परिवर्तन का आकलन करने के लिए है। इसके अलावा, यह शोध प्रबंध भारोत्तोलन घुटने की एमआरआई(MRI) के भविष्य के नैदानिक अनुप्रयोगों की भी पड़ताल करती है।

इस शोध प्रबंध में पहले अध्ययन ने एक कम लागत वाला, हल्का, उठाऊ, घुटने के संयुक्त अक्षीय भार-वहन उपकरण का विकास किया। इसके अलावा, विकसित उपकरण को एमआर(MR)-सुरक्षा, उपकरण-प्रेरित छवि विरूपण साक्ष्य, करने में आसानी, और किसी विषय के लिए आराम की मापदंड के लिए अंश-शोधन और मूल्यांकन किया गया है। इमेजिंग भागीदारों और चिकित्सकों से प्रतिक्रिया के साथ इस उपकरण को एक पुनरावृत्त प्रक्रिया में विकसित किया गया है।

इस शोध प्रबंध के दूसरे अध्ययन का उद्देश्य विकसित उपकरण व्यवहार और घुटने के जोड़ की विशेषता वाले एमआर मात्रात्मक मापदंडों में भार के कारण होने वाले परिवर्तनों का मूल्यांकन करना था। इस अध्ययन को दो उप-अध्ययनों शामिल थे: i) ओपन-स्टैंडिंग 0.25 टेस्ला(Tesla) एमआरआई MRI का उपयोग करके, विकसित उपकरण से भार के व्यवहार की तुलना प्राकृतिक स्टैंडिंग स्टांस के साथ करना, और ii) 3.0 टेस्ला(Tesla) एमआरआई(MRI) के साथ विकसित उपकरण का उपयोग करके भार के कारण एमआर(MR) मापदंडों में परिवर्तनों का आकलन करना। पहले उप-अध्ययन में, उपकरण से भार के दौरान

टिबिओफेमोरल(Tibiofemoral) हड्डियों के अंतर की तुलना विभिन्न मुद्रा के प्राकृतिक रूप से खड़े होने क भार से की गई थी। उपकरण द्वारा लगाया गया भार दोनों पैर के साथ खड़े होने के प्राकृतिक रुख के समान देखा गया (पियर्सन गुणांक (Pearson's Cofficient) 'आर'('r') > 0.9)। दूसरे उप-अध्ययन में हड्डी के अंतर, उपास्थि की मोटाई और उपास्थि T2-मूल्य में परिवर्तन से भार के प्रभाव का मूल्यांकन किया गया था; अवलोकन पहले बताए गए शोध टिप्पणियों के समान पाए गया हैं।

इस शोध प्रबंध में तीसरा काम अवेध्य रूप से टिबिओफेमोरल संयुक्त की विषय-विशिष्ट जीवे कठोरता का अनुमान लगाने के लिए एक नव विधि के विकास पर था। इस अध्ययन में दो उप-अध्ययन शामिल थे: प्रायोगिक अध्ययन और अनुकरण अध्ययन। प्रायोगिक अध्ययन में, बिना भार और भार के साथ (विकसित भार-वहन उपकरण का उपयोग करके) घुटने के जोड़ की एमआरआई(MRI) क्रमवीक्षण की गई छवि का उपयोग माध्य टिबिओफेमोरल(Tibiofemoral) तनाव का मूल्यांकन करने के लिए किया गया था। अनुकरण अध्ययन में, एक विषय-विशिष्ट घुटने के संयुक्त परिमित-तत्व-विश्लेषण (FEA) को अलग-अलग टिबिओफेमोरल(Tibiofemoral) जोड़ की कठोरता के साथ कठोरता बनाम तनाव मॉडल विकसित करने के लिए किया गया था। विषय-विशिष्ट कठोरता का मूल्यांकन करने के लिए विषय-विशिष्ट प्रयोगात्मक तनाव को कठोरता बनाम तनाव तंत्र में डाला गया था। इसके

अलावा, शोध प्रबंध जीवे टिबिओफेमोरल(Tibiofemoral) संयुक्त कठोरता का अनुमान लगाने के लिए एक सामान्यीकृत गणितीय मॉडल को भी पेश किया गया है।

इस शोध प्रबंध में शोध के परिणाम वजन वहन करने वाले घुटने के जोड़ के एमआरआई को अधिक सुलभ बना सकते हैं। इसके अलावा, यह कार्य भारोत्तोलन एमआरआई के लिए नए अनुप्रयोग खोल सकता है और एमआरआई(MRI) घुटने की अनुसंधान में तेजी ला सकते हैं।

Table of Contents

List of Abbreviations

50%BW	50% of body-weight
ΔmTFBG	Mean tibiofemoral bone gap difference
A	Anterior
ACL	Anterior cruciate ligament
AIC	Akaike Information Criterion
AICc	Akaike Information Criterion corrected
AL	Augmented Lagrange
ASTM	American Society for Testing and Materials
C	Central
CAD	Computer aided design
CCS	Combined-compressive-stiffness
CT	Computed Tomography
dGEMERIC	Delayed Gadolinium Enhanced MRI of Cartilage
ECE	Extracellular matrix
FASE	Fast-advanced-spin-echo
FCT	Femoral-cartilage-thickness
FCT2	Femoral-cartilage T_2-values
FEA	Finite-element-analysis
FEM	Finite-element-modeling
FFE	Fast-field-echo
FID	Free induction decay
FOV	Field of view
FSE	Fast-spin-echo
FS-PD	Fat-suppressed proton-density
FSPGR	Fat Saturated 3D-Fast Spoiled Gradient Echo
GF	Gravitational force
GRE/GE	Gradient-echo sequence
G_{ro}	Frequency gradient

G_{pe}	Phase encoding gradient
G_{ss}	Slice selective gradient
IE	Isotropic elastic
IEC	Institutional ethics committee
INR	Indian rupee
JSW	Joint space width
KL	Kellgren-Lawrence
LC	Lateral compartment
LCL	Lateral collateral ligaments
MC	Medial compartment
MCL	Medial collateral ligament
MF	Magnetic force
ML	Meniscal-length
MPC	Multi-Point Constraint
MR	Magnetic resonance
MRI	Magnetic resonance imaging
mTFBG	Mean tibiofemoral bone gap
NMR	Nuclear magnetic resonance
OA	Osteoarthritis
OCT	Optical coherence tomography
P	Posterior
PCG	Preconditioned conjugate gradients
PCL	Posterior cruciate ligament
PD-T_2	Dual Proton Density-T_2-weighted
RF	Radio-frequency
RGA	Region growing algorithm
ROI	Region of interest
RPC	Relative percentage change
RSM	Radial-search method
SB45	Standing on both legs against gravity at 45° aligned
SB84	Standing on both legs against gravity at 84° aligned

SE	Spin-echo pulse sequence
SNR	Signal-to-noise ratio
SPGR	Spoiled-gradient-recalled-echo
SS84	Standing on a single leg against gravity at 84° aligned
SSIM	Structural similarity index measurement
STL	Standard Triangle Language
T	Tesla
TCT	Tibial-cartilage-thickness
TCT2	Tibial-cartilage-thickness
TE	Time of echo
TFBG	Tibiofemoral-bone-gap
TR	Time of repetition
WB-ST	Weight-bearing soft-tissue

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Figure 1.10: *The figure explains the MR physics with signal acquisition steps. a) bar magnet represents the dipole moment of nuclei, b) shows the random distribution of magnetic dipole moment in the absence of B_0 field. c) shows the magnetic moment vector aligned parallel or antiparallel to B_0, in the presence of B_0 field. d) shows these magnetic moment vectors precess about B_0 field direction with a Larmor frequency (ω) and hence induce net magnetization or bulk magnetization(M_z) along the z-direction, whereas $M_{xy}=0$. e) shows the excitation stage with RF pulse of 'ω', where net magnetization flips into the transverse plan and results in $M_{xy} \neq 0$. f) depict the recovery of longitudinal magnetization after the removal of RF pulse. g) represent the decay of M_{xy} due to the T_2-relaxation process. h)shows the decay of the M_{xy} in a helical shape, i) shows the free induction decay curve of the induced signal (S(t)), and (j) shows the receiver coil perpendicular B_0 field.*

Figure 1.11: *Shows the T1 and T2 relaxation process graphs in a) and b), respectively.*

Figure 1.12: *Shows the sequence of events during scanning as a pulse sequence. a) shows a simple pulse sequence where events 1 to 5 are marked in a step manner. 1 switch on the slice select gradient (Gss); then 2^{nd} step switch on the 90° RF-pulse from transmitter coil as excitation stage; in step 3, phase encoding gradient (Gpe) trigger, and step 4 switch on the frequency encoding gradient/readout (Gro) during free induction decay (5) acquired. b) represents the spin-echo sequences where 180° RF-pulse re-phases the Mxy magnetization, and the next echo's peak develops just after the TE time.*

Figure 1.13: *Represents the Gradient-echo sequence steps. Step 1 starts from the slice selection (G_{ss}), then 2 is the excitation step triggered by RF-pulse. The 3^{rd} step is phase encoding by gradient coil (G_{pe}). Then in the 4^{th} step, frequency encoding gradient (G_{ro}) first triggers negative polarity and turns to positive, and signal (5) is acquired during readout.*

Figure 3.3: *Flow-chart of data processing for generating Tibiofemoral-bone-gap (TFBG), femoral-cartilage-thickness (FCT), tibial-cartilage-thickness (TCT), femoral-cartilage T_2-values (FCT2), and tibial-cartilage T_2 (TCT2). (a) shows an overlay of a bone gap on the FSPGR image, (b) and (c) shows an overlay of cartilage-thickness on FS-PD and T2-W images, respectively. (d) and (e) show representative masks of bone gap, cartilage thickness, and (f) shows a map of cartilage T2 values; the green arrows in (d) show the bone gap is evaluated normal to each pixel, red arrows in (e) represent the cartilage-thickness is evaluated tangential to each pixel, and red arrows in (f) show the cartilage T2-value is evaluated as tangentially average across each pixel; (g), (h), and (i) shows 2D-WearMaps for bone-gap, cartilage-thickness, and cartilage T2-values, respectively. Rectangular boxes on (g), (h), and (i) represent the whole lateral region (red-box), the entire medial region (red-dotted line) of each 2D-WearMap; lateral and medial regions of each 2D-WearMap where both cartilage contact with each other shows in yellow-box and yellow-dotted line, respectively.*

Figure 3.4: *Shows the flow of development of 2D-WearMap, a) shows the extraction of parameters from each slice, b) extracted parameters fed in a single image of 2D-WearMap, and c) shows the division of 2D-WearMap regions for averaging of parameters.*

Figure 4.1: *The stepwise workflow of the study is presented in the figure; Figure shows two phases of the study: experimental and simulation; mTFBG is the mean tibiofemoral bone gap, ΔmTFBG is the difference between unloaded and loaded mTFBG*

Figure 4.2: *The stepwise processing of data. a) representative slice of 3D-FSPGR image of knee joint, b) segmented tissues (cartilage, bone, and meniscus) and overlaid on the grayscale MRI image, c), d) development phase of 3D surface geometry at MIMICS 20.0 and 3-MATIC Research 12.0, respectively, e) SpaceClaim platform used to convert STL files in the solid CAD model and assembly formation. f) Anterior and posterior view of mesh model. g) Zoom-in*

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