

MUSCULOSKELETAL MODELLING OF HUMAN LOWER LIMB

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CENTRE FOR BIOMEDICAL ENGINEERING
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MUSCULOSKELETAL MODELLING OF HUMAN LOWER LIMB

by

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Centre for Biomedical Engineering

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to the



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Dedicated
to
my parents and teachers.

CERTIFICATE

This is to certify that the thesis entitled “**Musculoskeletal modelling of human lower limb**” being submitted by **Mr. Arnab Sikidar** to the **Indian Institute of Technology Delhi** for the award of **Doctor of Philosophy** in **Centre for Biomedical Engineering** is a record of bonafide research work carried out by him under my guidance and supervision. To the best of our knowledge, the thesis has reached the requisite standard. I hereby declare that the content of the thesis, in full or in part, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

The human body is an intricate network of organs, bones, muscles, and connecting tissues. Each part of human anatomy instigates macro and micro-scaled physiological phenomena governed by laws of physics. The coordinated functioning of all the features of human anatomy aids us in doing simpler to complicated tasks of our daily life. Activities quintessential for locomotion, like walking, running, and jumping crucially use the human body's lower extremities. The musculoskeletal artwork of the lower extremity is a complex network of structural elements like bones and soft tissues such as muscles, ligaments, and tendons. A musculoskeletal model of the lower extremity was modelled in OpenSim with 25 bundles of dense connective tissues, femoral cartilage, and meniscus in the knee joint and with 66 bundles of dense connective tissues, 65 muscles and 30 tendons in the ankle-foot complex, comprising of 13 rigid body segments and 24 degrees of freedom. Computed tomography (CT) data of human ankle joint-foot complex was segmented using Mimics[®] (Version 17.0, Materialise, Belgium) to obtain models of the cartilages and bones of the ankle joint-foot complex. The position and resting lengths of the DCTs were attained from the MRI data and literature. Five joints, namely, tibiotalar, subtalar, chopart, tarsometatarsal (TMT), and metatarsophalangeal (MTP) joints and their joint axes were formulated to yield 24 DOFs. Furthermore, the force-length characteristics of dense connective tissues (DCTs) vary non-linearly as a function of strain rate. However, there is no class of OpenSim[®] available to incorporate the effect of strain rate into the OpenSim[®] model. A plugin for the ligaments in OpenSim was modelled using a structural constitutive model with the ability to estimate tensile forces as a function of the subject's velocity. A new class object termed as NonLinearLigament was formulated using a customized plugin based on a structural constitutive model. An application of the comprehensive model was also discussed in the thesis to estimate the force in ligaments during different dynamic activities. a nonlinear strain rate dependent plugin developed for the

OpenSim® platform was used to estimate the instantaneous strain rate (ISR) and the forces on the ACL's anteromedial (aACL) and posterolateral (pACL) bundles during walking and sudden change of direction of running termed as '*plant-and-cut*' (PC). The authors obtained the kinematics data for walking via optical motion capture. PC movements, along with running kinematics, were obtained from the literature. A nonlinear plugin developed for ligaments was interfaced with OpenSim® platform to simulate walking and PC motions with a flexed knee and an extended knee. PC phase is sandwiched between an approach phase and take-off phase and was studied at various event velocities (1.8, 3, and 4.2 m s⁻¹), and angles of PC (23°, 34°, and 45°) as encountered in adult ball games. The proposed model is open source in SimTK for use and further development by researchers and medical practitioners.

सारांश

मानव शरीर अंगों, हड्डियों, मांसपेशियों और संयोजी ऊतकों का एक जटिल नेटवर्क है। मानव शरीर रचना का प्रत्येक भाग भौतिकी के नियमों द्वारा शासित स्थूल और सूक्ष्म-स्तरीय शारीरिक घटनाओं को प्रेरित करता है। मानव शरीर रचना विज्ञान की सभी विशेषताओं की समन्वित कार्यप्रणाली हमें अपने दैनिक जीवन के सरल से जटिल कार्यों को करने में सहायता करती है। गति के लिए सर्वोत्कृष्ट गतिविधियाँ, जैसे चलना, दौड़ना और कूदना मानव शरीर के निचले छोरों का महत्वपूर्ण रूप से उपयोग करती हैं। निचले छोर की मस्कुलोस्केलेटल कलाकृति हड्डियों और कोमल ऊतकों जैसे मांसपेशियों, स्नायुबंधन और टेंडन जैसे संरचनात्मक तत्वों का एक जटिल नेटवर्क है। निचले छोर का एक मस्कुलोस्केलेटल मॉडल ओपनसिम में घने संयोजी ऊतकों, ऊरु उपास्थि और घुटने के जोड़ में मेनिस्कस के 25 बंडलों और टखने-पैर परिसर में घने संयोजी ऊतकों, 65 मांसपेशियों और 30 टेंडन के 66 बंडलों के साथ तैयार किया गया था। 13 कठोर शरीर खंड और 24 डिग्री की स्वतंत्रता। मानव टखने के जोड़-पैर के कॉम्प्लेक्स के कंप्यूटेड टोमोग्राफी (सीटी) डेटा को टखने के जोड़-पैर के कॉम्प्लेक्स के उपास्थि और हड्डियों के मॉडल प्राप्त करने के लिए मिमिक्स® (संस्करण 17.0, मटेरियलाइज़, बेल्जियम) का उपयोग करके खंडित किया गया था। डीसीटी की स्थिति और आराम की लंबाई एमआरआई डेटा और साहित्य से प्राप्त की गई थी। पांच जोड़ों, अर्थात् टिबिओटालार, सबटालर, चोपार्ट, टासोमेटाटार्सल (टीएमटी), और मेटाटार्सोफैलेन्जियल (एमटीपी) जोड़ों और उनके संयुक्त अक्षों को 24 डीओएफ उत्पन्न करने के लिए तैयार किया गया था। इसके अलावा, घने संयोजी ऊतकों (डीसीटी) की बल-लंबाई विशेषताएँ तनाव दर के कार्य के रूप में गैर-रैखिक रूप से भिन्न होती हैं। हालाँकि, OpenSim® मॉडल में तनाव दर के प्रभाव को शामिल करने के लिए OpenSim® की कोई श्रेणी उपलब्ध नहीं है। ओपनसिम में स्नायुबंधन के लिए एक प्लगइन को विषय के वेग के एक फ़ंक्शन के रूप में तन्य बलों का अनुमान लगाने की क्षमता के साथ एक संरचनात्मक संवैधानिक मॉडल का उपयोग करके तैयार किया गया था। एक नया क्लास ऑब्जेक्ट जिसे नॉनलाइनरलिगामेंट कहा जाता है, एक संरचनात्मक संवैधानिक मॉडल के आधार पर एक अनुकूलित प्लगइन का उपयोग करके तैयार किया गया था। विभिन्न गतिशील गतिविधियों के दौरान स्नायुबंधन में बल का अनुमान लगाने के लिए थीसिस में व्यापक मॉडल के अनुप्रयोग पर भी चर्चा की गई। OpenSim® प्लेटफ़ॉर्म के लिए विकसित एक नॉनलाइनियर स्ट्रेन रेट डिपेंडेंट प्लगइन का उपयोग तात्कालिक स्ट्रेन रेट (ISR) और चलने के दौरान ACL के एंटेरोमेडियल (aACL) और पोस्टेरोलेट्रल (pACL) बंडलों पर बलों और दौड़ने की दिशा में अचानक परिवर्तन का अनुमान लगाने के लिए किया गया था। 'प्लांट-एंड-कट' (पीसी)। लेखकों ने ऑप्टिकल मोशन कैप्चर के माध्यम से चलने के लिए कीनेमेटिक्स डेटा प्राप्त किया। पीसी मूवमेंट, रनिंग किनेमेटिक्स के साथ, साहित्य से प्राप्त किए गए थे। लचीले घुटने और विस्तारित घुटने के साथ चलने और पीसी गति को अनुकरण करने के लिए लिगामेंट्स के लिए विकसित एक नॉनलाइनियर प्लगइन को ओपनसिम® प्लेटफ़ॉर्म के साथ जोड़ा गया था। पीसी चरण एक दृष्टिकोण चरण और टेक-ऑफ चरण के बीच सैंडविच होता है और इसका अध्ययन विभिन्न घटना वेगों (1.8, 3, और 4.2 मीटर एस -1) और पीसी के कोणों (23 डिग्री, 34 डिग्री और 45 डिग्री) पर किया गया था जैसा कि सामने आया था। वयस्क गेंद का खेल, प्रस्तावित मॉडल शोधकर्ताओं और चिकित्सा चिकित्सकों द्वारा उपयोग और आगे के विकास के लिए सिमटीके में खुला स्रोत है।

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LIST OF ABBREVIATIONS

Abbreviated Form	Full form
ACL	Anterior cruciate ligament.
AIIMS	All Indian Institute of Medical Science.
AJF	Ankle joint foot complex.
CAP	capsules.
CT	Computed tomography.
DCT	Dense connective tissue.
DICOM	Digital Imaging and Communications in Medicine.
DOFs	Degrees of freedom.
EMG	Electromyogram.
ER	External rotation.
FATC	Femur-ACL-tibia complex.
FEM	Finite Element modelling.
FL	fibular ligament.
GRF	Ground reaction force.
GUI	Graphical user interface.
IR	Infra-red.
IR	Internal rotation.
ISR	Instantaneous strain rate
LCL	Lateral collateral ligament.
IPFL	lateral patella-femoral ligament.
MBD	Multi-body dynamics.
MCL	Medial collateral ligament.
MFL	menisco-femoral ligament.
mPFL	medial patello-femoral ligament.
MRI	Magnetic resonance imaging.
MTP	Metatarsophalangeal.
NLSR	Non-linear strain rate dependent.
OFM	Oxford Foot Model
PC	Plant and cut
PCL	Posterior cruciate ligament.
PFL	patello-femoral ligament.
PL	Popliteofibular ligament.
PT	Patella-tibial ligament.
STL	Standard Tessellation Language.
TL	Transverse ligament.
TMT	Tarsometatarsal.