BIOMECHANICAL EVALUATION OF FEMORAL NECK FRACTURE FIXATION

LAUREB RAO

TRANSPORTATION RESEARCH AND INJURY PREVENTION CENTRE (TRIP-C)

INDIAN INSTITUTE OF TECHNOLOGY, DELHI

HAUZ KHAS, NEW DELHI, INDIA – 110016

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LAUREB RAO

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Certificate

This is to certify that the thesis entitled **'Biomechanical Evaluation of Femoral Neck Fracture Fixation'** being submitted by **Laureb Rao** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy,** is a bonafide record of original research work carried out by him under our supervision in conformity with the rules and regulations of the institute.

The results of this thesis have not been submitted, in part or in full, to any other University or Institute for the award of any degree or diploma.

Prof. Anoop Chawla
Professor
Department of Mechanical Engineering,
Indian Institute of Technology Delhi
New Delhi-110016, India

Dr. Kaushik Mukherjee
Associate Professor
Department of Mechanical Engineering,
Indian Institute of Technology Delhi
New Delhi-110016, India

Date: April 2, 2026

Place: New Delhi

Declarations

I declare that

a. I am the sole author of this thesis, and the work presented herein is the result of my own original research, which has been performed under the guidance of my supervisors.
b. The work has not been submitted to any other Institute for any degree or diploma.
c. I have followed the guidelines provided by the Institute for preparing the thesis.
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Laureb Rao

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Indian Institute of Technology Delhi **Laureb Rao**

Date:

Abstract

The femoral neck is the weakest and most common site for hip fractures. Pauwels type III fracture, wherein the fracture plane makes an angle of 50°-70° with the transverse plane, is the most unstable femoral neck fracture. Open reduction internal fixation (ORIF) is the preferred technique for younger populations with non-osteoporotic bones. There are various internal fixation devices for treating Pauwels type III fractures. Cannulated cancellous screws (CCS) and dynamic hip screw (DHS), and DHS+Anti-rotation screw (DHS+ARS) are the most used internal fixators for treating femoral neck fractures. In 2018, a new fixation technique, known as the Femoral Neck System (FNS), was introduced by DePuy Synthes. This implant system features a divergent screw mechanism comprising a bolt and an anti-rotational screw. Patients treated with internal fixators often experience complications like non-union (14%) and osteonecrosis (11%). These complications subsequently led to the failure of the fracture reconstruction surgery. Recent global reports have highlighted instances of failure of FNS implants. A few cases of FNS failure have also been observed at the All India Institute of Medical Sciences (AIIMS), wherein all the implant failures occurred within two months of partial weight-bearing. Fractographic analysis, along with scanning electron microscopy, has been conducted on the fractured surfaces of the failed FNS implants to identify probable failure mechanisms. Fracture characteristics showed a mixed ductile-brittle in two failure cases and predominantly fatigue-induced in the other two implant failure cases. In one case, a difference in grain structure was observed near the screw's outer periphery compared to its middle; this discrepancy indicates inadequate cooling during the heat treatment. Experiments were conducted on sawbones® to validate the developed FE modeling framework. The FE-predicted values were close to the experimental values, with deviations of 5.6%, 2%, and 4.9% for intact bone, CCS, and FNS, respectively. Furthermore, subject-specific finite element (FE) models were developed to gain insight into the stresses and strains in implants and bones. Patient-specific heterogeneous femoral FE models were developed from preoperative CT scans. Under stair climbing loading, the elevated von Mises stress (Case 1: 486 MPa, Case 2: 229 MPa, Case 3: 208 MPa, and Case 4: 213 MPa) was observed at the failure site. Additionaly, an FE-based computational study was conducted to compare the biomechanical performance of FNS with other internal fixation devices, such as CCS, DHS, and DHS+ARS. Normal walking and stair-climbing loading conditions were considered in this study. FNS showed the highest inferior axial displacement (normal walking: 3.51 mm and stair climbing: 4.19 mm) of the femoral head, while DHS+ARS exhibited the least inferior axial displacement (normal walking: 2.27 mm and stair climbing: 2.87 mm). DHS+ARS also demonstrated superior performance in terms of long-term bone remodeling response. Finally, an improved design of the FNS implant has been proposed, which provides better stability and reduced von Mises stress in the cortical screw, therefore, reducing the risk of implant failure.

सार

फीमर का गर्दन कूल्हे के फ्रैक्चर का सबसे कमजोर स्थान है। पॉवेल्स प्रकार III फ्रैक्चर, जिसमें फ्रैक्चर तल अनुप्रस्थ तल के साथ 50°–70° का कोण बनाता है, सबसे अस्थिर फ्रैक्चर होता है। गैर-ऑस्टियोपोरोसिस हड्डियों वाले युवा मरीजों में ओपन रिडक्शन इंटरनल फिक्सेशन को प्राथमिक उपचार तकनीक माना जाता है। पॉवेल्स प्रकार III फ्रैक्चर के उपचार के लिए विभिन्न आंतरिक फिक्सेशन उपकरण उपलब्ध हैं। कैन्यूलेटेड कैंसिलस स्क्रू (CCS), डायनामिक हिप स्क्रू (DHS), तथा DHS + एंटी-रोटेशन स्क्रू (DHS+ARS) फीमरल नेक फ्रैक्चर के उपचार में सबसे अधिक उपयोग किए जाने वाले उपकरण हैं।

वर्ष 2018 में, डीप्यू सिंथेस द्वारा एक नई फिक्सेशन तकनीक, जिसे फीमरल नेक सिस्टम (FNS) कहा जाता है, प्रस्तुत की गई। इस इम्प्लांट प्रणाली में एक डाइवर्जेंट स्क्रू तंत्र होता है, जिसमें एक बोल्ट और एक एंटी-रोटेशनल स्क्रू शामिल होता है। आंतरिक फिक्सेशन से उपचारित मरीजों में अक्सर नॉन-यूनियन (14%) और ऑस्टियोनेक्रोसिस (11%) जैसी जटिलताएं देखी जाती हैं, जो अंततः फ्रैक्चर पुनर्निर्माण सर्जरी की विफलता का कारण बनती हैं। हाल के वैश्विक अध्ययनों में FNS इम्प्लांट की विफलता के मामले सामने आए हैं।

अखिल भारतीय आयुर्विज्ञान संस्थान में भी FNS विफलता के कुछ मामले देखे गए, जिनमें सभी इम्प्लांट विफलताएं आंशिक भार वहन के दो महीनों के भीतर हुईं। संभावित विफलता तंत्र की पहचान के लिए विफल FNS इम्प्लांट की फ्रैक्चर सतहों पर फ्रैक्टोग्राफिक विश्लेषण तथा स्कैनिंग इलेक्ट्रॉन माइक्रोस्कोपी का उपयोग किया गया। फ्रैक्चर विशेषताओं में दो मामलों में डक्टाइल-ब्रिटल मिश्रित व्यवहार तथा अन्य दो मामलों में मुख्यतः थकान प्रेरित विफलता देखी गई। एक मामले में स्क्रू की बाहरी परिधि और मध्य भाग के निकट दानेदार संरचना में अंतर पाया गया, जो हीट ट्रीटमेंट के दौरान अपर्याप्त शीतलन को दर्शाता है।

फाइनाइट एलिमेंट (FE) मॉडलिंग फ्रेमवर्क को सत्यापित करने के लिए sawbones® पर प्रयोग किए गए। FE द्वारा पूर्वानुमानित मान प्रयोगात्मक मानों के निकट पाए गए, जिनमें अक्षुण्ण हड्डी, CCS, और FNS के लिए क्रमशः 5.6%, 2% और 4.9% का अंतर था। इसके अतिरिक्त, इम्प्लांट और हड्डियों में तनाव एवं विकृति को समझने के लिए विषय-विशिष्ट फाइनाइट एलिमेंट मॉडल विकसित किए गए। मरीज-विशिष्ट विषम फीमरल FE मॉडल प्रीऑपरेटिव CT स्कैन से तैयार किए गए। सीढ़ी चढ़ने के लोडिंग के दौरान विफलता स्थल पर उच्च वॉन मीज़ेस तनाव (केस-1: 486 MPa, केस-2: 229 MPa, केस-3: 208 MPa, केस-4: 213 MPa) देखा गया।

अतिरिक्त रूप से, FNS की बायोमैकेनिकल कार्यक्षमता की तुलना अन्य आंतरिक फिक्सेशन उपकरणों जैसे CCS, DHS, और DHS+ARS के साथ करने हेतु FE-आधारित संगणनात्मक अध्ययन किया गया। इस अध्ययन में सामान्य चलना और सीढ़ी चढ़ना लोडिंग स्थितियों को शामिल किया गया। FNS में फीमरल हेड का अधिकतम निम्न अक्षीय विस्थापन (सामान्य चलना: 3.51 मिमी और सीढ़ी चढ़ना: 4.19 मिमी) पाया गया, जबकि DHS+ARS में न्यूनतम विस्थापन (सामान्य चलना: 2.27 मिमी और सीढ़ी चढ़ना: 2.87 मिमी) देखा गया। DHS+ARS ने दीर्घकालिक हड्डी पुनर्निर्माण के संदर्भ में भी बेहतर प्रदर्शन प्रदर्शित किया।

अंततः, FNS इम्प्लांट के एक उन्नत डिज़ाइन का प्रस्ताव किया गया है, जो बेहतर स्थिरता प्रदान करता है तथा कॉर्टिकल स्क्रू में वॉन-मीज़ेस तनाव को कम करता है, जिससे इम्प्लांट विफलता के जोखिम में कमी आती है।

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List of Abbreviations

FEA	-	Finite element analysis
CCS	-	Cannulated Cancellous Screws
DHS	-	Dynamic Hip Screw
ARS	-	Anti-Rotation Screw
FNS	-	Femoral Neck System
FE-SEM	-	Field Emission Scanning Electron Microscope
EDS	-	Electron Dispersive Spectroscopy
FNF	-	Femoral Neck Fractures
PFN	-	Proximal Femoral Nail
TAD	-	Tip Apex Distance
MSK	-	Musculoskeletal
CT	-	Computed Tomography
CAD	-	Computer-Aided Machining
EDM	-	Electric Discharge Machining
EPMA	-	Electron Probe Microanalysis
ISO	-	International Organization for Standardization
STL	-	Standard Triangle Language
CCD	-	Caput-Collum-Diaphyseal
SED	-	Strain Energy Density

List of Symbols

E	=	Young's Modulus
μ	=	Poisson's Ratio
F_x	=	X-Component of the Hip Joint Reaction or Muscle Forces
F_y	=	Y-Component of the Hip Joint Reaction or Muscle Forces
F_z	=	Z-Component of the Hip Joint Reaction or Muscle Force
$F_{Resultant}$	=	Resultant Hip Joint Reaction or Muscle Force
Ti	=	Titanium
Al	=	Aluminium
V	=	Vanadium
Nb	=	Niobium
E_r	=	Reduced Modulus obtained from nano-indentation
dp/dh	=	Slope of the unloading curve of nano-indentation
v_i	=	Poison's ratio of the Indenter
E_i	=	Young's modulus ratio of the Indenter
ρ	=	Elemental density of bone
U	=	Strain energy density
S	=	Bone remodelling stimulus (Elastic strain energy per unit bone mass (in $J \cdot g^{-1}$)
B	=	Bone remodelling constant
k	=	Reference stimulus