

**PENETRATION MECHANICS OF LOW-VELOCITY
SHRAPNEL IN SOFT TISSUES AND THEIR SURROGATES**

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**PENETRATION MECHANICS OF LOW-VELOCITY
SHRAPNEL IN SOFT TISSUES AND THEIR SURROGATES**

by

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Department of Mechanical Engineering

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*Dedicated to my wife and daughter, and
to my parents and family, for their unwavering
love and support!*

“Karaa kee hundaan Isa beekamtii kenni, inni karaa kee ni qajeelcha.” Fakk. 3:6

“በመንገድህ ሁሉ እርሱን እወቅ፣ እርሱም ጎዳናህን ያቀናልሃል።” ምዕሌ 3:6

Certificate

This is to certify that the thesis entitled “**Penetration mechanics of low-velocity shrapnel in soft tissues and their surrogates**” being submitted by **Tesfaye Olana Terefe** 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 rules and regulations of the institute.

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

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Tesfaye Olana

Abstract

In conflict zones, terrorist activities, and urban warfare, injuries caused by low-velocity projectiles, such as sharp objects, shrapnel, and fragments, have become increasingly prevalent. Unlike high-velocity ballistic penetration, low-velocity penetration (typically under 100 m/s) remains insufficiently understood and poses challenges for trauma diagnosis, injury reconstruction, and forensic analysis due to irregular wound cavities and complex soft tissue failure mechanisms. This thesis investigates the biomechanics of low-velocity shrapnel-induced soft tissue injury through an integrated experimental and finite element (FE) modeling approach. Porcine skin and muscle tissues, along with validated tissue simulants including ballistic gelatin (10% wt) and Perma-Gel[®], were used to replicate anatomical and mechanical behavior of human soft tissue. Custom-designed experimental setups enabled systematic measurement of transmitted force (TF), depth of penetration (DoP), cavity formation, and injury morphology across varying shrapnel geometries and velocities. In the first phase, this work quantified the force-penetration relationship in porcine muscle and gelatin under low-speed (i.e., < 5 m/s) sharp object (nail) penetration. Results demonstrated that gelatin consistently underestimated the penetration forces by 23.9% to 46.5% compared to porcine muscle tissue, depending on nail diameter and penetration speed. A corresponding FE model accurately replicated experimental trends, providing a validated simulation platform for future studies. The second phase examined damage mechanisms in ballistic gelatin subjected to low-velocity shrapnel penetration (25 to 100 m/s). Distinct differences in TF response and cavity formation were observed between chisel and blunt-nose shrapnel, with blunt-nose designs inducing higher energy absorption and cavity sizes. The FE models predicted maximum TF within 15% error, thereby validating their suitability in force-damage correlation studies. Subsequent investigations focused on skin-specific injury patterns using porcine tissue, revealing multiple wound mechanisms, including tearing, radial cracking, and spallation. Blunt-nose shrapnel consistently generated higher TF and larger cavity formations. The injury features were replicated using an FE model that reasonably predicted residual velocities and TF, thus reinforcing its reliability for forensic analysis and wound reconstruction. The final study expanded these insights to combined skin/Perma-Gel[®] composite surrogates, offering a more comprehensive understanding of soft tissue interaction. Results indicated a linear relationship between energy absorption and cavity size, and validated simulations reproduced TF within 8% and DoP within 2%. The role of the Perma-Gel[®] backing material in altering skin failure modes, particularly through shear-dominated mechanisms, was also identified. Overall, this work advances the understanding of low-velocity penetrative trauma by experimentally validated force-damage relationships and a robust computational framework, with direct implications for forensic interpretation, trauma care, and biofidelic surrogate development. More importantly, this work establishes a framework for future studies on soft tissue shrapnel injuries.

सार

संघर्ष क्षेत्रों, आतंकवादी गतिविधियों और शहरी युद्ध में, कम-वेग वाले प्रोजेक्टाइल, जैसे तेज वस्तुओं, छर्रे और टुकड़ों से होने वाली चोटें तेजी से प्रचलित हो गई हैं। उच्च-वेग बैलिस्टिक पैठ के विपरीत, कम-वेग पैठ (आमतौर पर 100 मीटर/सेकेंड से कम) अपर्याप्त रूप से समझा जाता है और अनियमित घाव गुहाओं और जटिल नरम ऊतक विफलता तंत्र के कारण आघात निदान, चोट पुनर्निर्माण और फोरेंसिक विश्लेषण के लिए चुनौतियां पैदा करता है। यह थीसिस एक एकीकृत प्रयोगात्मक और परिमित तत्व (एफ-ई) मॉडलिंग दृष्टिकोण के माध्यम से कम-वेग छर्रे से प्रेरित नरम ऊतक चोट के बायोमैकेनिक्स की जांच करती है। मानव नरम ऊतकों के शारीरिक और यांत्रिक व्यवहार को पुनरुत्पादित करने के लिए बैलिस्टिक जिलेटिन (10% वजन) और पर्मा-जेल® सहित मान्य ऊतक सिमुलेंट्स के साथ सुअर की त्वचा और मांसपेशियों के ऊतकों का उपयोग किया गया था। कस्टम-डिज़ाइन किए गए प्रयोगात्मक सेटअप ने अलग-अलग छर्रे ज्यामिति और वेगों में प्रेषित बल (टी-एफ), प्रवेश की गहराई (डीओपी), गुहा गठन और चोट आकृति विज्ञान के व्यवस्थित माप को सक्षम किया। पहले चरण में, इस कार्य ने कम गति (यानी, <5 मी/से) तेज वस्तु (कील) के प्रवेश के तहत सुअर की मांसपेशी और जिलेटिन में बल-प्रवेश संबंध की मात्रा निर्धारित की। परिणामों से पता चला कि कील के व्यास और प्रवेश की गति के आधार पर, जिलेटिन ने सुअर की मांसपेशी ऊतक की तुलना में प्रवेश बलों को लगातार 23.9% से 46.5% तक कम करके आंका। संबंधित एफ-ई मॉडल ने प्रयोगात्मक रुझानों को सटीक रूप से दोहराया, जो भविष्य के अध्ययन के लिए एक मान्य सिमुलेशन मंच प्रदान करता है। दूसरे चरण में कम-वेग छर्रे (25 से 100 मीटर/सेकेंड) के प्रवेश के अधीन बैलिस्टिक जिलेटिन में क्षति तंत्र की जांच की गई। टी-एफ प्रतिक्रिया और गुहा गठन में विशिष्ट अंतर छेनी और कुंद-नाक छर्रे के बीच देखा गया, कुंद-नाक डिजाइन उच्च ऊर्जा अवशोषण और गुहा आकार को प्रेरित करते हैं। एफ-ई मॉडल ने 15% त्रुटि के भीतर अधिकतम टी-एफ की भविष्यवाणी की, जिससे बल-क्षति सहसंबंध अध्ययन में उनकी उपयुक्तता को मान्य किया गया। बाद की जांच में सुअर की ऊतक का उपयोग करके त्वचा-विशिष्ट चोट पैटर्न पर ध्यान केंद्रित किया गया, जिसमें फाड़ने, विकिरणीय दरारें और छितरन सहित कई घाव तंत्रों का खुलासा हुआ। कुंद-नाक छर्रे लगातार उच्च टी-एफ और बड़े गुहा निर्माण उत्पन्न करते हैं। चोट की विशेषताओं को एक एफ-ई मॉडल का उपयोग करके दोहराया गया था जिसने उचित रूप से अवशिष्ट वेग और टी-एफ की पूर्वानुमान किया गया, इस प्रकार फोरेंसिक विश्लेषण और घाव पुनर्निर्माण के लिए इसकी विश्वसनीयता को मजबूत किया गया था। अंतिम अध्ययन ने इन अंतर्दृष्टियों को संयुक्त त्वचा/पर्मा-जेल® मिश्रित सरोगेट्स तक विस्तारित किया, जिससे नरम ऊतकों की परस्पर क्रिया की अधिक व्यापक समझ प्रदान की गई। परिणामों ने ऊर्जा अवशोषण और गुहा आकार के बीच रेखीय संबंध का संकेत दिया, और मान्य सिमुलेशन ने टी-एफ को 8% और डीओपी को 2% के भीतर पुनः उत्पन्न किया। विशेष रूप से कतरनी-प्रधान तंत्र के माध्यम से त्वचा की विफलता के तरीकों को बदलने में पर्मा-जेल® समर्थन सामग्री की भूमिका की भी पहचान की गई। कुल मिलाकर, यह कार्य फोरेंसिक व्याख्या, आघात देखभाल और बायोफिडेलिक सरोगेट विकास के लिए प्रत्यक्ष निहितार्थ के साथ प्रयोगात्मक रूप से मान्य बल-क्षति संबंधों और एक मजबूत कम्प्यूटेशनल ढांचे द्वारा कम-वेग भेदक आघात की समझ को आगे बढ़ाता है। इससे भी महत्वपूर्ण बात यह है कि यह कार्य नरम ऊतक चोट पर भविष्य के अध्ययन के लिए एक रूपरेखा स्थापित करता है।

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Acronyms

CV	Coefficient of variation
DAQ	Data acquisition
DoP	Depth of penetration
EoS	Equation of State
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
IDEs	Improvised explosive devices
mTBI	Mild traumatic brain injury
NATO	North Atlantic Treaty Organization
PMHS	Post-mortem Human Subjects
PBI	Primary blast injury
QBI	Quaternary blast injury
RPGs	Rocket-propelled grenades
RMSE	Root-mean square errors
SBI	Secondary blast injury
SPH	Smooth particle hydrodynamics
TBI	Tertiary blast injury
TF	Transmitted force

List of symbols

μ	Coefficient of friction
F_c	Cutting force
DC	Decay constant
ρ	Density
F_D	Dynamic coefficient
F_d	Dynamic force
ε^p	Effective plastic strain
E_a	Energy absorbed
E_d	Energy dissipation
F_f	Friction force
k	Hugoniot constant
E_i	Impact energy
V_i	Incident velocity
ρ_o	Initial density
σ_o	Initial stress
G_o	Long-term shear modulus
$C_{0,1,2,3}$	Material constants
$C_{10,01}$	Materials parameters
E	Modulus
F_p	Penetration force
ν	Poisson's ratio

P	Pressure
$\lambda_{1,2,3}$	Principal stresses
V_{rel}	Relative velocity
τ_i	Relaxation
G_i	Shear moduli
E_r	Residual energy
V_r	Residual velocity
m_{sh}	Shrapnel mass
c_o	Speed of sound
F_S	Static coefficient
F_{st}	Stiffness force
W	Strain energy density
E_h	Strain hardening modulus
\bar{I}_1, \bar{I}_2	Stress invariants
E_t	Tangent modulus
t	Time
σ_y	Yield stress