Penetration mechanics of low-velocity shrapnel in soft tissues and their surrogates

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 though 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.