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The experimental and numerical study of indirect effect of a rifle bullet on the bone

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ABSTRACT

We study the transient indirect effect of a rifle bullet on bone in the gelatin-bone composite target experimentally and computationally. The process of a 56 type 7.62-mm rifle bullet penetrating the composite target has been simulated using numerical method. The experiment provided the criteria for verifying the correctness of the numerical model. We have obtained tomographic data of bone by CT scans, and also defined the bone as different layers by the gray scale to simulate its heterogeneity. The computed results are in good agreement with the experimental data. Effects of the impact velocity and bone location on damage caused to the composite target have also been studied. The numerical results imply the follows: When the velocity of bullet increases, the stress on bone also increases with the earlier pressure peak; When the bone is located in a certain distance from the trajectory, it will not be fractured, although it is affected by the stress wave.

1. Introduction

When a bullet is penetrating the human body, a part or even all of the kinetic energy will be transmitted to the body tissue. As a result, the performance of the bullet will be changed and the tissues of the human body will be damaged.

Bone consists of brittle material, which is significantly denser and harder than soft tissue [1]. If a bullet hits the bone directly while its velocity/energy is sufficiently high, the bone will fracture [2]. Amato et al. found the critical velocity for fracturing bone (femur of calf) is approximately 60.9 m/s [3]. But even if the bullet does not hit the bone directly, an indirect fracture may occur when the bullet passes close by. This is due to the rapid yawing of the bullet.

The study of the transient indirect effect of bullet on bones helps not only in the diagnosis and treatment of wounds, but also in the design of the weapon. Many researches are mainly based on animal test. Kieser et al. [4] filmed 42 deer femora embeded in ballistic gelatin and shot with four different bullets at varying distance off the bone (0–10 cm) to study the ballistic fracture. Kneubuehl et al. [5] regarded a synthetic long bone structure as a substitute for human tissue in gunshot experiments. But it still takes quite a long time to prepare test, and there are large individual differences. Moreover, it is unrepeatable to study the basic principles.

With the development of the computer science, numerical simulation has been widely used in ballistic impact studies in recent years. It has many advantages of replacing a real object with a physical model and constructing a numerical experiment. The most obvious advantage is that this approach makes it possible to conduct parameter studies of unlimited scope simply and economically.

In 1972, Brekelmans et al. [6] first studied the mechanics of bone by finite element method. Mota et al. [7] established the viscoelastic model of skull. The space-discretized equations of motion are explicitly integrated in time with Newmark's time-stepping algorithm. The impact of the projectile on the skull, as well as the collisions between flying fragments, were controlled through a nonsmooth contact algorithm. Numerical results compared well with forensic data of actual firearm wounds to human crania. Fan et al. [8,9] regarded compact bone as an anisotropic material and established a failure criterion based on Hoffman criterion. The predicted failure load of cancellous bone was only 0.5% lower than the experimental data and the predicted failure load of compact bone was 4.2% higher than the experimental results. The study provided the pattern to rebuild the model of bone. Wen [10] studied the penetration of a steel sphere into a block of ballistic gelatin at a moderately high speed experimentally and computationally. His study provided the material properties of gelatin in our paper. Huang

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and Liu [11,12] did some researches about the transient indirect effect of 9 mm pistol bullet on bone in the gelatin-bone composite target. The numerical simulation results are in good agreement with the experimental results. However, in their papers, the bone in the composite target was replaced by tubular bone and there was a certain difference between tubular bone and real bone.

In this paper, the indirect effect of a rifle bullet with high speed on bone in the composite target has been studied. We simulated the composite target by inhomogeneous anisotropic bone which is based on the experimental data. The effects of impact velocity and the location of bone on damage to the target have also been studied.

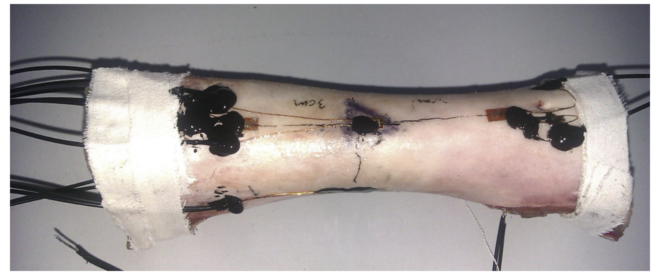

Fig. 2. The prepared bone before experiment.

2. Experimental study

The bone-gelatin composite targets were impacted by 56 type 7.62-mm rifle bullets in the experiments. During the process of penetration, we can observe physical phenomena directly and monitored dynamic response of the target by test instrument.

2.1. Materials

2.1.1. Gelatin

A number of studies have demonstrated that gelatin is suitable for studying wound ballistics. It can become transparent after decoloring, which is better for observing the movement of bullet and the change of temporary cavity. We have made 30 cm × 30 cm × 30 cm gelatin blocks in our experiments. The mass fraction of gelatin is 10% (4 °C).

2.1.2. Marrowbone of pig

The fresh pig marrowbones (The length of bone is 10 cm and the minimum diameter of the bone is 2.7 cm approximately) were debrided of soft tissue and asepticized by alcohol. Before the experiment, we acquired tomographic data of bone by CT scans (Philips/Brilliance 64-slice spiral CT machine). We got 284 serial cross-sectional pictures with 512 × 512 pixel. The three dimensional model of bone was generated from these CT scans by Mimics. After the above preparation, strain gauges are affixed on the surface of bone and waterproof treatment was conducted. The CT image of bone and the prepared bone before experiment are shown in Figs. 1 and 2, respectively.

2.1.3. Production of composite target

The prepared gelatin liquid was poured into the mould. The bone and pressure sensor were embedded into the gelatin liquid before it coagulated. The axial direction of bone and the bullet's path should be orthogonal. The mould was left to coagulate in a refrigerator (4 °C). The composite target is shown in Fig. 3.

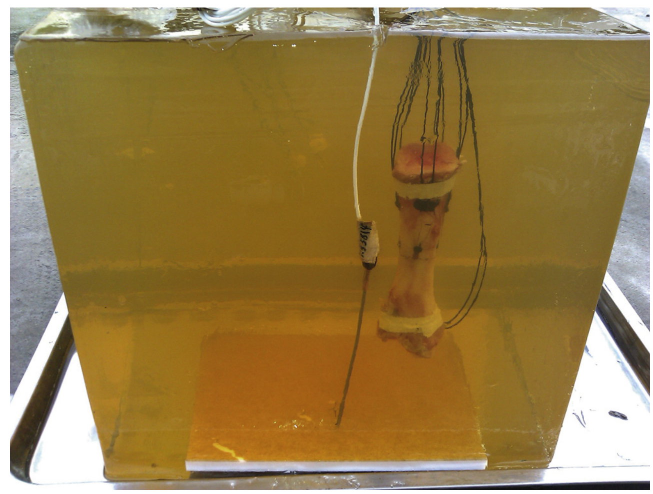

Fig. 3. Composite target.

2.2. Experimental facilities

The experiment facilities are shown in Fig. 4. The 30 cm × 30 cm × 30 cm composite gelatin block resting on a table was impacted by 56 type 7.62-mm rifle bullet (weight: 7.9 g, length: 26.8 mm) using a rifle with its muzzle 5 m away from the front face of the gelatin. The strain on the surface of bone and the pressure in gelatin near the bone were measured using strain gauges (with a range of 0–2000 μm/m) and a pressure sensor (with a range of 0–13 MPa), respectively. The speed of the bullet before impacting the target was measured by a double base optical detector. The size and position of temporary cavity, and speed of the bullet in the gelatin were measured by using high-speed camera (Phantom V120, 16,000 frames per second with a resolution of 640 × 544 pixel). In addition the coordinate system used in this paper is also displayed in Fig. 4.

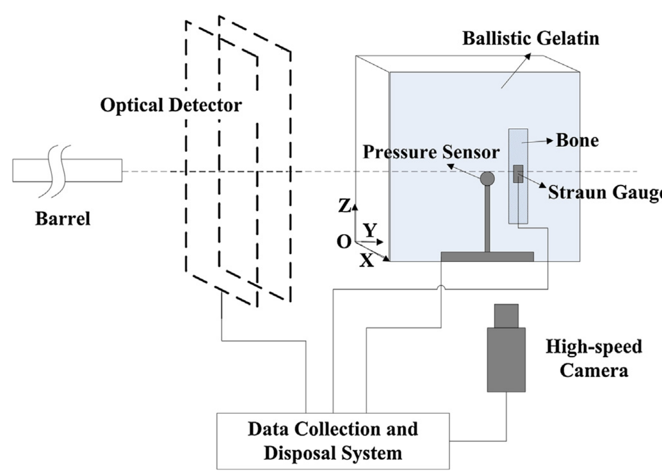

Fig. 4. Experiment set up.

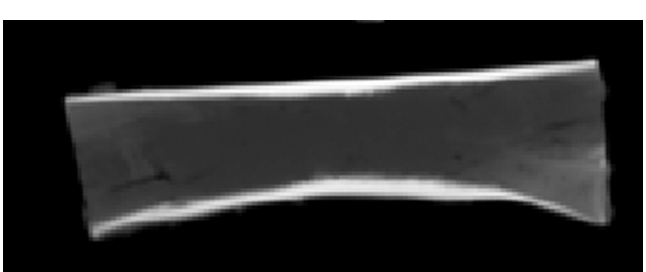

Fig. 1. CT image of bone.