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Evaluation of bone surrogates for indirect and direct ballistic fractures

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ABSTRACT

The mechanism of injury for fractures to long bones has been studied for both direct ballistic loading as well as indirect. However, the majority of these studies have been conducted on both post-mortem human subjects (PMHS) and animal surrogates which have constraints in terms of storage, preparation and testing. The identification of a validated bone surrogate for use in forensic, medical and engineering testing would provide the ability to investigate ballistic loading without these constraints. Two specific bone surrogates, Sawbones and Synbone, were evaluated in comparison to PMHS for both direct and indirect ballistic loading. For the direct loading, the mean velocity to produce fracture was 121 ± 19 m/s for the PMHS, which was statistically different from the Sawbones (140 ± 7 m/s) and Synbone (146 ± 3 m/s). The average distance to fracture in the indirect loading was .70 cm for the PMHS. The Synbone had a statistically similar average distance to fracture (.61 cm, $p = 0.54$) however the Sawbones average distance to fracture was statistically different (.41 cm, $p < 0.05$). Fractures patterns were found to be comparable to the PMHS for tests conducted with Synbones, however the input parameters were slightly varied to produce similar results. The fractures patterns with the Sawbones were not found to be as comparable to the PMHS. An ideal bone surrogate for ballistic testing was not identified and future work is warranted.

1. Introduction

One of the most common ballistic injuries seen in wartime or civilian life is a fracture [1,2,4,15]. For wartime injuries, about 20% of wounded in action may have fractures. Long bone fractures, because bone heals slowly, account for a greater number of potential lost work-days and longer hospital stays when compared to injuries of soft tissue only [1,4,15]. Understanding what factors have contributed to fracture formation has led to a better understanding of both treatment of ballistic injuries as well as developing preventative measures.

The pathophysiology of fractures caused by ballistic loading in long bones has been studied in the past [3,5–9,11–14,16,18]. These studies are important in order to isolate variables involved with the production of the fracture. These fractures can be produced by either direct loading of the bullet [7–9] or indirectly due to the proximity of the passage of the bullet and temporary cavity formation [3,13,17]. By using both strain gage technology and high-speed video, the temporal relationship between the passage of a bullet and occurrence of long bone fracture has been determined [17].

The previous work to identify parameters that could predict the risk of fracture utilized post-mortem human subjects (PMHS) and animal surrogates. However, working with these types of specimens can be difficult in ballistic settings due to several issues including storage, prep and testing constraints. While an effective simulant for soft tissue ballistic injury has been developed, an optimal bone simulant for use in scientific testing has not been established [4]. Because of the difficulty in handling specimen tissue, advances to produce high quality bone simulants has been important in several other fields as well.

Recently, Pacific Sawbones (Vashon Island WA) has marketed a line of high quality composite femurs and tibiae that have similar material properties to human bone. Comparison has been made between the bone and composite materials utilizing material testing machines with a high degree of similarity in both material properties and failure. Such composite bone has not been previously compared to human tissue in a ballistic model.

Synbone (Malans, Switzerland) has also produced a bone simulant designed from polyurethane foam that consists of a "cancellous" inner core and a harder outer shell simulating cortical bone. A ballistic model is available, although there is limited data

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supporting its biofidelity. Positive comparisons were identified in terms of retained kinetic energy, bone fragmentation and wound channeling with direct impacts [10,14], however it was noted that this validation was in comparison to swine and not human bone.

Currently there is not a long bone model for ballistic fracture testing that has been validated against PMHS. The purpose of this study is to evaluate two (2) commonly used bone simulants and compare them to PMHS tested under the same circumstances in the same lab for both direct and indirect ballistic loading. The outcomes measured include the risk of fracture, injury biomechanics and overall material response in comparing these two (2) bone simulants: Sawbones and Synbone.

2. Materials and methods

A total of 36 total femurs from post-mortem human specimens (18 pairs) were used for comparison in the current study. Nine (9) pairs were tested using an indirect loading method and nine (9) were used for direct impacts. Concurrence of exemption was obtained from the Wayne State University Human Investigation Committee prior to initiation of the study. All personnel were trained in the proper handling techniques and followed ethnical guidelines previously established.

Bone surrogates were procured from two different manufacturers for testing: Sawbones® and SYNBONE®. Twenty-five (25) biomechanical composite (4th generation) femurs were obtained from Sawbones®. These surrogates were reported to have similar strength properties as real bone. They were composite with both a cortical and cancellous layer. Fifteen (15) were used for indirect ballistic loading with the remaining ten (10) used for direct impacts.

In addition, twenty-four (24) synthetic bone simulants were obtained from SYNBONE® (Malans, Switzerland). These polyurethane bone simulants (model PRO107) were hollow bone forms with an outer diameter of 30 mm and a wall thickness of 7 mm. Fourteen (14) were used for direct and ten (10) for indirect ballistic loading.

All specimens were prepped with a single strain gage rosette (model 031RB, Vishay Micro-Measurements, Shelton, CT) attached to the medial aspect of the mid-diaphyseal region using M-Bond 200 (Vishay Micro-Measurements, Shelton, CT). Rectangular molds measuring 13 cm × 13 cm × 24.1 cm were prepped to receive both the instrumented surrogate and a mixture of 10% ballistics gelatin. The instrumented bones were position with the anterior aspect located 2 cm deep behind the front surface of the mold (Fig. 1). The gelatin was then solidified by placing the mold in an environmental chamber at 4 °C for a period of 24 h.

A MotionXtra HG-100 K camera (Redlake, Tucson, AZ) was used to collect high-speed video of the testing at a rate of 10,000 frames per second. The strain gage data was collected at a rate of 20,000 Hz using a TDAS Pro (Diversified Technologies, Seal Beach, CA).

For the indirect ballistic loading, a 5.56 mm armor-piercing round with tungsten carbide penetrator core (M995) was fired using a universal receiver with a rifled barrel with a 20 in. barrel and 1:9 twist. The prepared targets were placed with the face of the gelatin two (2) meters from the muzzle of the barrel. The rounds were targeted to impact the gelatin at approximately .8 cm based on previous testing [3].

For the direct ballistic impact, the velocity was significantly lower. Given the inability to produce consistent velocities by downloading the rounds, the bullets were pulled and fired through a modified paintball gun. This modification included the development of a sabot-based firing system to propel the bullets.

Each specimen/surrogate was radiographed after testing. The gelatin was then removed in 2 cm coronal slices and the shot placement was verified. The specimens/surrogates were then stripped of the gelatin and a board certified trauma surgeon evaluated the injuries. All fractures were noted and characterized. Strain data from the rosettes was post-processed to determine the principal strains (ε_1, ε_2) and maximum shear strain (γ_{max}).

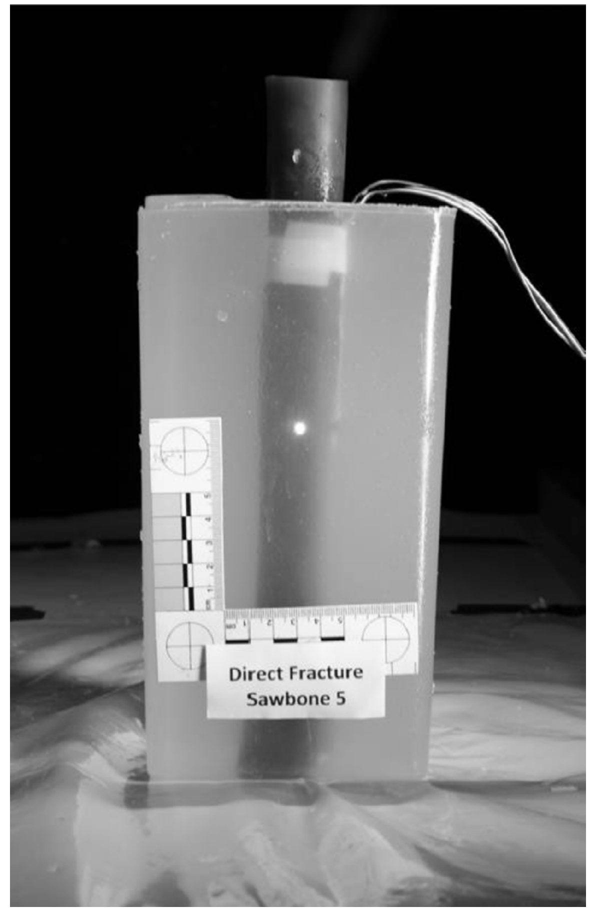

Fig. 1. Sawbone embedded in 10% gelatin block.

3. Results

3.1. Indirect fracture – Synbone

A total of fourteen (14) indirect ballistic loading tests were conducted using the Synbone® surrogates (Table 1). The average velocity was 133.7 ± 14.9 m/s. Four out of the fourteen surrogates fractured. The fracture types included three transverse and one oblique.

The average distance from the permanent track to the bone was measured post-test was .743 ± .327 cm and .610 ± .074 cm for the non-fracture and fracture cases respectively. Logistic regression analysis was performed using the fracture outcome as the dependent variable and shot line distance as the independent variable. This analysis demonstrated that distance from edge of the bone was not a significant predictor for the Synbones® (χ^2 = .918, p = .338).

Strain data from the rosette was further analyzed to determine their predictive ability for the resulting fracture. The average principal strain for the fracture cases was 8998 ± 1970 $\mu\varepsilon$ whereas the non-fracture cases resulted in principal strains of 4107 ± 1602 $\mu\varepsilon$. The principal strain 1 (ε_1) was found to be a significant predictor of fracture using logistic regression analysis (χ^2 = 12.21, $p < 0.00$).

3.2. Indirect fracture – Sawbones

A total of fifteen (15) tests were conducted using the Sawbones surrogates (Table 2). However, six (6) impacted the bone, therefore