BIOSIMULANT ARTIFACT WITH EMBEDDED CALCIUM ALGINATE BEAD SENSOR FOR ROBOT IMPACT SAFETY TESTING

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ABSTRACT
This paper presents the design of a disposable biosimulant human tissue artifact system for robot safety testing. It is used to provide a visual indication of potentially severe injuries caused in the case of a robot impact with a human. The fabrication method is described including the design and fabrication of the calcium alginate bead and the embedding procedure of the beads into the biosimulant artifact. The artifact system is tested with a Dynamic Impact Testing and Calibration Instrument (DITCI) from the National Institute of Standards and Technology (NIST). The design is useful for the preparation of new robot safety standards.

INTRODUCTION

The movement of manufacturing to countries featuring labor with low hourly wages over the last fifteen years has motivated the development of a new generation of industrial robots that can work side-by-side with human workers [1]. This has created a new technology of Human-Collaboration-Robotics (HCR), which combines the intelligence and dexterity of humans with the strength, repeatability, and endurance of industrial robots [2]. Since most robots are powerful moving machines, the safety of workers working around these robots has become a top priority for safety standards development. We are using biological simulant (biosimulant) materials for the fabrication of inexpensive, disposable HCR safety testing artifacts. These testing artifacts will make possible the measurement of forces, pressure, and strain when humans and robots come into contact as well as of the magnitude of injuries caused by robot static and impact pressure. The Dynamic Impact Testing and Calibration Instrument (DITCI) is a simple instrument shown in Figure 1, with a significant data collection and analysis capability that is used for the testing and calibration of biosimulant human tissue artifacts [3, 4].

Various research groups have used human subjects to collect data on pain induced by the clamping force, pressure, and maximum impact force of the HCRs [5, 6, 7, 8]. Although the results of these tests are hard to reproduce and can vary even among subjects of similar characteristics, they can be very useful for the preparation of safety testing standards. Unfortunately, human safety testing is not an option for HCR industrial applications every time there is a change of a tool or control program, so the use of a biosimulant artifact system is expected to be a good alternative.

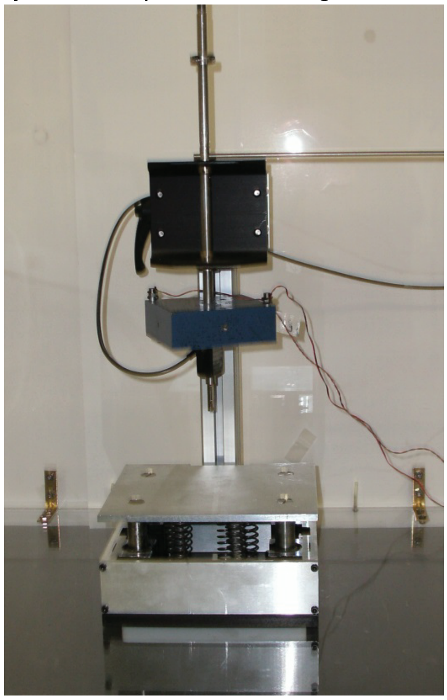


FIGURE 1. Impact testing set up.

Much work has been done in the design of pressure sensors. Sander et al. [9] designed a monolithic capacitive sensor. Someya et al. [10] designed a flexible pressure sensor matrix for the application of artificial skin. A number of Micro-electro-mechanical Systems (MEMS) designs are proposed for pressure sensors [11, 12, 13, 14]. However, the cost of these pressure sensors is high. Based on a chemical fabrication method, we could build a cheap and disposable measurement system. Daly and Knorr [15] proposed the fabrication of a chitosan alginate capsule. Huguet and Dellacherie [16] described the fabrication of calcium alginate beads coated with chitosan.

In this paper, we present a chemical based fabrication procedure for a disposable human artifact embedded with calcium alginate bead for robot impact safety testing. The rest of the paper is organized as follows: We firstly present the design methodology of the artifact system. Secondly, the fabrication method of the calcium alginate bead is followed by a description of the procedure for embedding the beads into the human tissue artifact. Finally, the biosimulant artifact system is mounted on the DITCI for an impact testing.

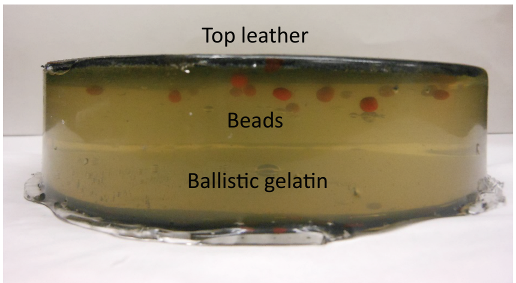
DESIGN OF BIOSIMULANT ARTIFACT WITH EMBEDDED BEAD

In this section, we describe the design of the biosimulant artifact system. As shown in Figure 2, the sensor system consists of three parts: top leather, soft tissue, and embedded sensor. The top leather is a piece of artificial skin of disk shape. Soft tissue is made of ballistic gelatin. The embedded sensor is a calcium alginate-based bead design. The combination of top leather and ballistic gelatin is called the biosimulant artifact [3].

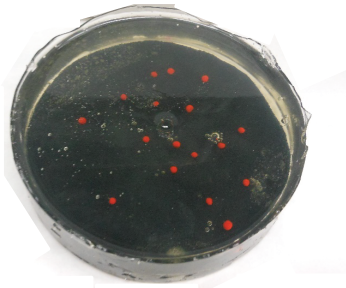
The biosimulant artifact simulates human skin and muscle, and simulates the stress distribution when the impact force is applied on the top surface of the skin. The deformation of the ballistic gelatin caused by the dynamic impact force results in the stress distributed on the bead sensors. Thus, the embedded bead sensors will deform corresponding to the deformation of the ballistic gelatin. When the red beads over-deform, they will be destroyed when the impact force causes a certain pressure threshold to be exceeded. Due to the low fabrication costs, the artifact may be disposed of after testing.

FABRICATION OF CALCIUM ALGINATE BEAD

In this section, we present the fabrication of the calcium alginate bead. The main chemical reaction is based on the mixing of a solution of sodium alginate and calcium chloride. As shown in Figure 3, there are two solutions: base and bath. The base solution is used to drop into the bath solution. Here, the base solution is sodium alginate and the bath solution is calcium chloride.



(a) Side view of the artifact with imbedded bead sensors



(b) Bottom view of the biosimulant artifact system

FIGURE 2. Biosimulant artifact and embedded sensor.

The base solution consists of sodium citrate, deionized (DI) water, latex, and sodium alginate. The chemicals used in the fabrication are shown in Table 1. Firstly, sodium citrate is dissolved in the DI water to obtain a transparent solution. The sodium citrate is used to remove the calcium ions which will otherwise react with the sodium alginate. Then, red latex enamel is added into the solution. By stirring with a steel stick, we can obtain a red solution without the calcium ion. Finally, we add sodium alginate. Stirring the sodium alginate solution continues until the sodium alginate powder is fully dissolved. This takes approximately 15 minutes. The bath solution is obtained by dropping calcium chloride into DI water. The materials used in fabrication of the artifacts are food-grade, making them easy to procure and use. Sodium citrate, sodium alginate, and calcium chloride are purchased from Modernist Pantry [1]. The latex

[1]Certain commercial materials, equipment, and instru-

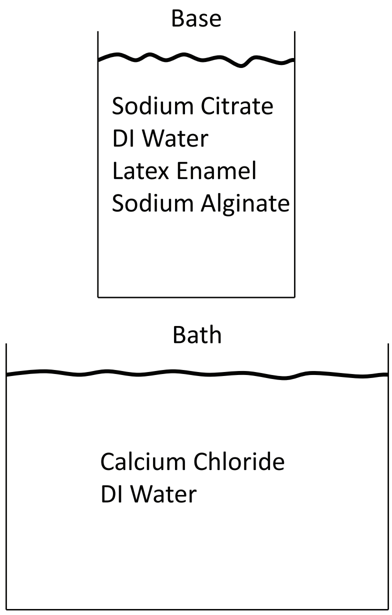


FIGURE 3. Preparation of the base and bath.

enamel of gloss cherry is from Valspar.

As shown in Figure 4, the base is dropped into the bath with a pipette. The viscosity of the base should be higher than the one of the bath so that the drop of the base maintains the original shape of the beads instead of dispersing. If the viscosity is not high enough, xanthan gum could be added to the base to make the solution stickier.

The pipette is positioned at a height shown in Figure 4 to ensure the drop can maintain its shape when it contacts the surface of the bath solution. We can continue dropping several drops, but each drop needs to be kept at some distance from the rest so that they do not stick to each other. The beads are kept in the bath for 2 minutes. In this step, the sodium alginate in the base attracts the calcium chloride in the bath. This reaction creates one layer of calcium alginate as shown in Figure 4. The calcium alginate is a kind of membrane which surrounds the inside liquid sodium alginate. After we take out the beads from the bath and soak them in the DI water, we manually stir the water for about 2 minutes to clean the remaining calcium chloride on the outside surface of the membrane. In this step, if the beads are kept over 30 minutes in the DI water, the size of the beads will increase because the calcium alginate membrane is porous and the DI water is absorbed by the beads.

Finally, we take the beads out of the DI water. Instead of drying the beads, we keep them wet and store in the refrigerator. The extra calcium ions in the outside membrane will keep reacting with the inside liquid sodium alginate. After about 12 hours, the bead turns to be a uniform ball, which contains water like a sponge.

TABLE 1. Chemicals of sodium alginate bead.

Chemical	Quantity (g)	Testing (g)
Sodium citrate	0.1	0.15
DI water	10	10.25
Latex enamel	2	2
Sodium alginate	0.08	0.08
Calcium chloride	0.2	0.2
DI water	20	20.6

FABRICATION OF BIOSIMULANT ARTIFACT AND EMBEDDING PROCEDURE OF BEAD

Our current artifact consists of a disk of biosimulant skin and the soft tissue shown in Figure 2. In nature, human skin consists of a thin outer layer called the epidermis, a thick inner layer called the dermis, and subcutaneous fat. The skin is the first layer of defense against impact injuries, which have been studied by medical professionals and forensic researchers. Because cadavers are expensive and difficult to maintain, forensic researchers have been searching for biosimulant materials with mechanical properties similar to those of human skin [17]. There are a few suppliers of this type of material. For all of our artifact test samples, we used chromed tanned cowhide, Full Cowhide Side, Upholstery or Garment Leather Black [18]. Its thickness is about 1.1 mm and it well simulates the human skin of the mechanical property.

Water solutions containing 10 % to 30 % mass of gelatin have been studied extensively and are considered to be good human muscle tissue biosimulants [19]. Here are the most important conclusions relevant to our work. For non-penetrating injuries, a water solution containing 20 % mass of gelatin gives a better representation of muscle tissue impact response [20], since the muscle tissue is compressed. For penetrating injuries, a water solution containing 10 % mass of gelatin is more appropriate [21], since the muscle tissue is teared. Distilled water should be used for the gelatin solutions to avoid contami-

ments are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

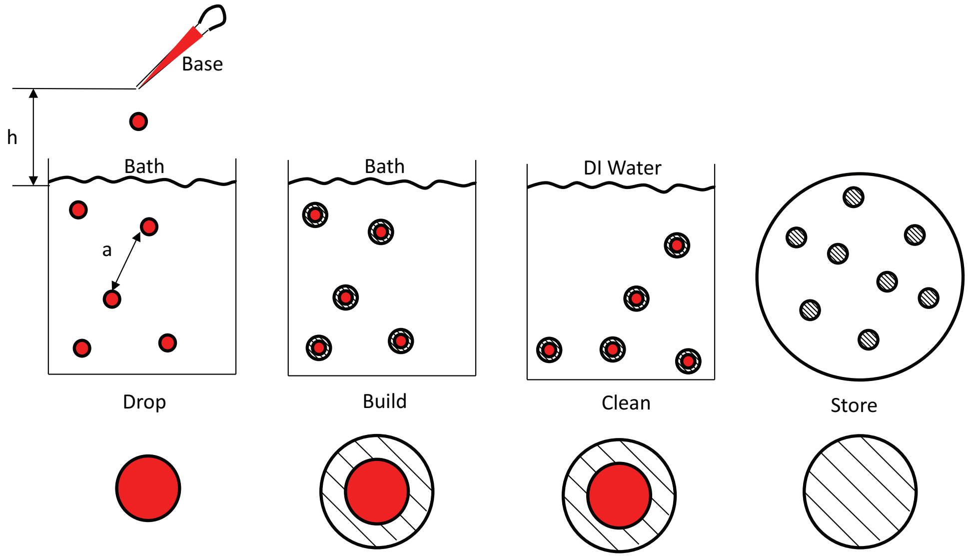


FIGURE 4. Fabrication of the calcium alginate beads.

nants and acidity variations [22]. For all of our test artifact preparations, we used a distilled water solution containing 10% mass gelatin powder supplied by Vyse Professional Grade Ballistic & Ordnance Gelatin [23].

As shown in Figure 5, the solution is poured on top of the skin-biosimulant in an aluminum or glass mold. The glass mold produced artifacts of excellent transparency, and are preferred over the metal molds. The gelatin forms a strong bond with the back side of the skin biosimulant and is observed never to delaminate during impact tests.

After pouring the first layer of ballistic gelatin, we drop the beads into the liquid gelatin. The beads will float due to their light weight. In order to seal the beads, the liquid gelatin need to be cured. The curing process could be accelerated by placing the gelatin in the refrigerator. When the first layer of the gelatin is partially cured, we pour the liquid gelatin for the second layer. Once the second layer of gelatin is fully cured, the embedding procedure is completed. The most important thing in embedding is the temperature control of the first and second layer of gelatin. The first layer of gelatin needs to be cool enough in order to seal the beads. The temperature of the poured liquid gelatin for the second layer needs to be around 30 degree Celsius. If the temperature is too high, the gelatin will heat up the contact surface of the first layer of gelatin. This results in releasing the sealed beads, which will float to the top surface of the second layer of gelatin. If the temperature is too low, the bonding of the first and second layer will be not strong enough to remain bonded throughout the impact testing.

As shown in Figure 5, we take out the artifact system from the mold after the ballistic gelatin is fully cured. The height of the artifact corresponds to the thickness of human tissue. In this paper, the height of the used artifact was 5 cm (4”) because it simulates the soft tissue of the human abdomen. The beads need to be sealed in the gelatin because they are porous and contain water. If the beads dry out, their behavior becomes rubber-like.

IMPACT TESTING

In this section, we demonstrate the artifact system in the robot impact testing device, shown in Figure 1. The fabrication parameters of the sample bead are shown in Table 1. The tool attached to the weight drops on the artifact. This simulates the impact on the human abdomen.

As shown in Figure 6, the tool hits the leather first, and then deforms the gelatin and the embedded red bead. Here, we use a tool with a cross section of 5 mm $\times$ 6 mm. The force sensor fixed on the tool records a maximum value of 118 N. Thus, the corresponding pressure is 3.93 N/mm^2, which is higher than the the maximum allowable transient pressure, 2.86 N/mm^2[24]. No tearing is observed. This means that the tool has gen-

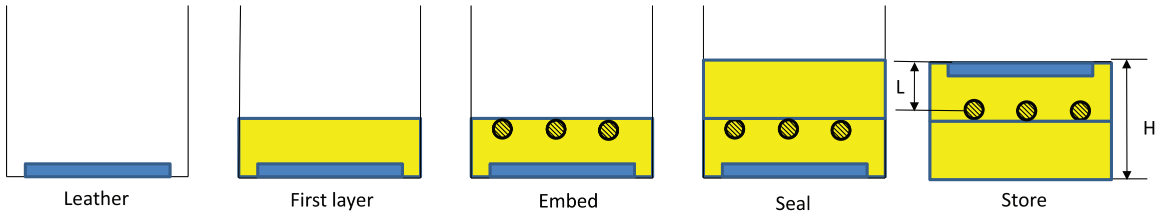


FIGURE 5. Embedding procedure of the beads into the biosimulant artifact.

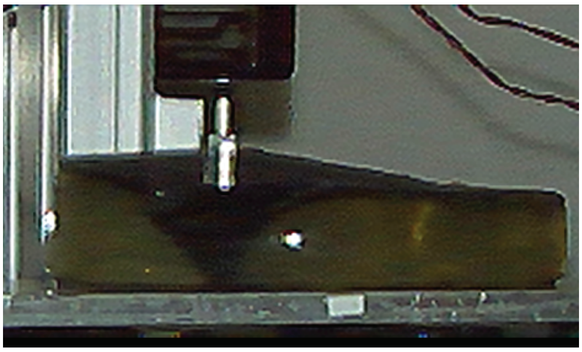


FIGURE 6. Impact testing of bead sensor embedded artifact system.

erated a serious abdominal injury. Figure 7 (a) shows the original embedded bead sensor. Figure 7 (b) shows the destroyed bead after the impact testing.

After we section the ballistic gelatin, we can see the destroyed bead sensor in Figure 7 (c).

CONCLUSION

In this paper, a design of a disposable low-cost biosimulant human tissue artifact system is proposed. It is used for the measurement of the injuries caused by a robot impact force. The fabrication and embedding procedure of calcium alginate bead senors are described. In the impact testing, the bead is destroyed and shows a clear sign that the tool hit the artifact severely. This design can be used in the preparation of artifact safety test standards.

ACKNOWLEDGMENT

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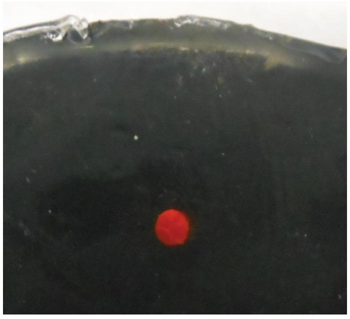
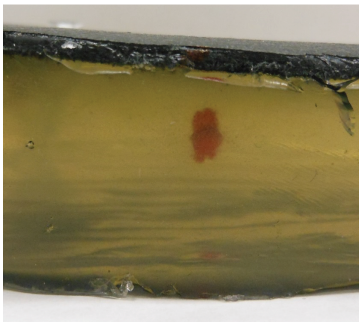
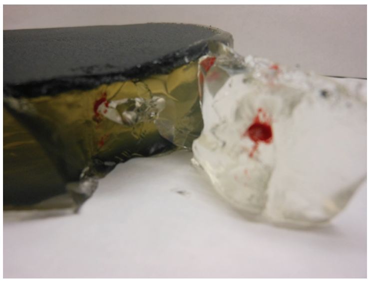


(a) Before impact testing



(b) After impact testing



(c) The destroyed sensor

FIGURE 7. Impact testing results of the sensor system.

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