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Biomechanics of osteochondral impact with cushioning and graft Insertion: Cartilage damage is correlated with delivered energy

Alvin W. Su [a], Yunchan Chen [b], Yao Dong [b], Dustin H. Wailes [b], Van W. Wong [b], Albert C. Chen [b], Shengqiang Cai [a,c], William D. Bugbee [e,f], Robert L. Sah [a,b,d,e,*]

[a] *Materials Science and Engineering Graduate Program, University of California, San Diego, La Jolla, CA, USA*
[b] *Department of Bioengineering, University of California, San Diego, La Jolla, CA, USA*
[c] *Department of Mechanical and Aerospace Engineering, University of California, San Diego, La Jolla, CA, USA*
[d] *Department of Orthopaedic Surgery, University of California, San Diego, La Jolla, CA, USA*
[e] *Center for Musculoskeletal Research, Institute of Engineering in Medicine, University of California, San Diego, La Jolla, CA, USA*
[f] *Department of Orthopaedic Surgery, Scripps Clinic, La Jolla, CA, USA*

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ABSTRACT

Articular cartilage is susceptible to impact injury. Impact may occur during events ranging from trauma to surgical insertion of an OsteoChondral Graft (OCG) into an OsteoChondral Recipient site (OCR). To evaluate energy density as a mediator of cartilage damage, a specialized drop tower apparatus was used to impact adult bovine samples while measuring contact force, cartilage surface displacement, and OCG advancement. When a single impact was applied to an isolated (non-inserted) OCG, force and surface displacement each rose monotonically and then declined. In each of five sequential impacts of increasing magnitude, applied to insert an OCG into an OCR, force rose rapidly to an initial peak, with minimal OCG advancement, and then to a second prolonged peak, with distinctive oscillations. Energy delivered to cartilage was confirmed to be higher with larger drop height and mass, and found to be lower with an interposed cushion or OCG insertion into an OCR. For both single and multiple impacts, the total energy density delivered to the articular cartilage correlated to damage, quantified as total crack length. The corresponding fracture toughness of the articular cartilage was 12.0 mJ/mm^2. Thus, the biomechanics of OCG insertion exhibits distinctive features compared to OCG impact without insertion, with energy delivery to the articular cartilage being a factor highly correlated with damage.

1. Introduction

Articular cartilage is susceptible to impact injury, such as that occurring in traumatic events or surgical procedures like osteochondral graft (OCG) insertion. Such injury may lead to post-traumatic osteoarthritis (Anderson et al., 2011). Understanding the mechanobiological factors that cause such damage to the cartilage may aid in prevention or treatment. Two key features of cartilage damage due to impact are fissure formation (Ewers et al., 2001; Jeffrey et al., 1995; Repo and Finlay, 1977) and chondrocyte death (Loening et al., 2000; Repo and Finlay, 1977; Szczodry et al., 2009; Torzilli et al., 1999).

Various mechanical factors during impact have been suggested as causative of cartilage damage. Cartilage matrix damage and chondrocyte death have been associated with impact force (Kang et al., 2010; Patil et al., 2008; Whiteside et al., 2005), contact stress (Repo and Finlay, 1977; Torzilli et al., 1999), compressive stress rate (Ewers et al., 2001; Milentijevic and Torzilli, 2005), compressive strain (Repo and Finlay, 1977; Torzilli et al., 2006), compressive strain rate (Quinn et al., 2001), and total impact energy (Burgin and Aspden, 2008; Finlay and Repo, 1979; Szczodry et al., 2009). Studies of OCG insertion into OCR from human cadavers *ex vivo* (Borazjani et al., 2006; Patil et al., 2008), in animals *in vivo* (Pallante et al., 2012), and in models *in vitro* (Pylawka et al., 2007; Whiteside et al., 2005) have focused on applied energy, force, impulse, and the number of taps required for insertion. However, the biomechanics of energy transmission and dissipation during OCG impact insertion, and its relation to articular cartilage damage, are unclear.

With cartilage impact and OCG insertion, articular cartilage damage may be associated with the energy density transmitted to the cartilage. Energy density has been analyzed as energy nor-

* Corresponding author at: University of California-San Diego, Department of Bioengineering, 9500 Gilman Drive, Mail Code 0412, La Jolla, CA 92093-0412, USA.
E-mail address: rsah@ucsd.edu (R.L. Sah).

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malized either to articular cartilage surface contact area (Heiner et al., 2013; Martin et al., 2009) or to cartilage volume (Burgin and Aspden, 2008; Finlay and Repo, 1979). However, during OCG insertion into an OCR, energy can be absorbed by structures other than the articular cartilage, particularly the interacting bone between the OCG and OCR.

To elucidate OCG insertion biomechanics and the possible role of delivered energy in causing cartilage damage, two experiments were performed with a specially instrumented drop-tower apparatus. (1) Isolated OCGs were impacted at two energy levels, with or without an interposed cushion to provide a series compliance, somewhat like an OCR, to modulate the delivered energy. (2) OCGs were inserted into OCRs by five sequential impacts of increasing energy. Impact of isolated OCGs tests an approach to assess energy delivered to cartilage, modulated by cushion or drop height, while approximating the situation where an impact is insufficient to cause OCG advancement. Impact insertion of OCGs into OCRs tests mechanical mechanisms of energy storage or dissipation, diverting energy from the cartilage. Both test if lessened cartilage strain energy reduces cartilage damage.

2. Methods

2.1. Study design

In two experiments, the effects of OCG impact (Fig. 1) on a number of biomechanical variables (Table 1) were quantified, based on measurement of axial load, $F(t)$, and cartilage surface displacement, $u^{AC}(t)$, along with optical visualization of the samples inbetween the impact and insertion events. Subsequently, biological damage to articular cartilage was assessed, primarily, as total crack length, L_{crack}.

Experiment 1. During OCG impact, the effects of total applied (potential) energy density, W_S^{PE}, and cushioning on biomechanical variables as well as damage to the OCG articular cartilage were analyzed for four groups, each with n = 6 samples, (1) W_S^{PE} = 7.6 mJ/mm^2, without cushioning, (2) W_S^{PE} = 7.6 mJ/mm^2 with cushioning, (3) W_S^{PE} = 22.9 mJ/mm^2, without cushioning, and (4) W_S^{PE} = 22.9 mJ/mm^2, with cushioning. The two levels of W_S^{PE} were chosen, based on pilot studies, to cause mild and severe cartilage damage, respectively. The cushioning was provided by a 3.2 mm thick, 12 mm diameter disc of 40-Durometer silicone-rubber, placed atop the loading tamp. The cushion was chosen so that its structural stiffness, 190 N/mm, was similar to the stiffness of the OCG under the tested impact conditions, with the expectation of diverting approximately half of the applied energy from the OCG to the cushion. Damage was assessed, secondarily, as articular cartilage area, $A^{AC}(t_{24hr+})$.

Experiment 2. During sequential OCG impact, the effects of insertion on biomechanical variables as well as damage to articular cartilage were analyzed with two study groups, each with n = 3 samples, (1) non-insertion impact of an isolated OCG (similar to Experiment 1), and (2) insertion of an OCG into an OCR, as well as for a non-loaded control group for viability analysis (n = 6). Five levels of W_S^{PE}, 0.9, 1.3, 2.0, 3.0, and 4.5 mJ/mm^2 (increasing by a factor of ∼1.5) were applied sequentially to the OCG, based on preliminary studies (and confirmed in the present study) indicating that such an impact sequence was sufficient to advance the OCG into the OCR incrementally, while leaving the OCG slightly proud after the 5th (last) tap. Damage was assessed, secondarily, as viability of chondrocytes at the cartilage surface, V^{AC}.

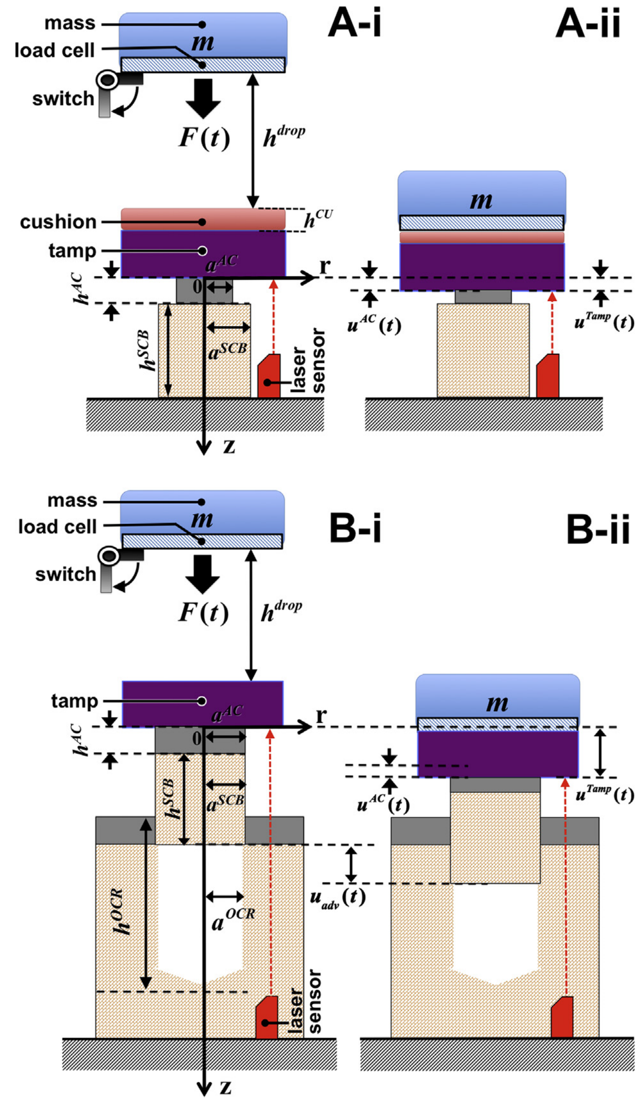

Fig. 1. Schematics of impact load application and sensor measurements using drop tower apparatus. (A) Impact of isolated OsteoChondral Sample, with interposed cushion. (B) Insertion of OsteoChondral Graft into OsteoChondral Recipient site. (i) Mass in raised position. (ii) Mass at time (t) after impact. Optional cushion included in-line between the drop mass and the rigid tamp.

2.2. Detailed experimental methods

2.2.1. OCG and OCR Preparation

A total of 36 OCGs and 3 OCRs were prepared from a total of six adult bovine knees, essentially as described previously (Chen et al., 2001). The OCGs had a subchondral bone radius, a^{SCB}, of 2.40 mm and a subchondral bone thickness, h^{SCB}, of 5.0 mm. The radius of the articular cartilage of the 24 OCGs for *Experiment* 1 was 1.50 mm, and that of the 12 OCGs for Experiment 2 was 2.40 mm. The OCR bone sockets had radius, a^{OCR}, of 2.40 mm and depth from the articular surface, h^{OCR}, of 10 mm. (See Supplement.)

2.2.2. Impact loading and OCG insertion

A drop tower, combining features of previous designs to assess impact mechanics (Burgin and Aspden, 2007; Finlay and Repo, 1978; Jeffrey et al., 1995), was used to apply impact load with known potential energy to the OCGs and obtain measures of biomechanical variables (Fig. 1A). Impact was delivered by dropping a mass, m, from height, h^{drop}, onto a tamp, placed on the articular surface of an OCG, with an in-line piezoelectric load cell

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