Biomechanics and Mechanobiology of Osteochondral Graft Insertion: Cartilage Damage is Associated with Delivered Energy and Reduced by a Waisted Graft Geometry

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Introduction:
One of the most effective treatments for articular cartilage defects is the surgical placement of an osteochondral graft (OCG). However, impact of the articular cartilage (AC) of an OCG during insertion can cause chondrocyte death and matrix damage. While the peak impact force increases as the OCG advances into osteochondral recipient site (OCR), the effects of the graft-host interference fit on OCG insertion biomechanics and mechanobiological consequences are unclear. While a modified OCG geometry has been suggested, its effects on insertion biomechanics is unknown. The hypotheses of the present study were (1) an increasing tightness of graft-host interference fit leads to higher insertion energy and resultant AC damage, and (2) a simple modification of OCG to provide a waisted geometry can maintain structural stability while reducing insertion energy and resultant cartilage damage.

Methods:
Samples and Study Groups: A total of 41 OCG and 26 OCR were isolated fresh (within 1 day) from the knee joints of 6 adult bovines. The OCG were initially prepared to a “standard” cylindrical geometry with radius, \(a_{OCG}\), 2.40 mm, full-thickness AC, and subchondral bone height of 5.0 mm (Fig. 1A). Some “standard” OCG were “modified” (Fig. 1B) to reduce the bone radius by \(\sim 0.1\)mm in the central 3mm region, leaving the proximal and distal 1mm regions at radius \(a_{OCG}\). The OCR were osteochondral tissue blocks (200 mm\(^2\) base x 20 mm height), the center of which was drilled (Fig. 1C) to a depth \(>6.5\) mm with radius, \(a_{OCR}\), of 2.40, 2.35, or 2.30 mm, creating OCG-OCR interference fits, \(\Delta R=a_{OCG}−a_{OCR}\), of 0.00 mm (loose), 0.05 mm (moderate), or 0.10 mm (tight). To test the effect of interference fit and OCG modification, the following groups were analyzed (each, \(n=6-7\)): standard OCG into OCR with interference fit that was (1) loose, (2) moderate, or (3) tight; and (4) modified OCG into OCR with tight fit.

Biomechanics: Analysis was facilitated by insertion with an instrumented drop tower apparatus. Impacts were delivered through a rigid surgical tamp, with measurement of load, tamp displacement, and axial OCG advancement. A mass was dropped from increasing heights to advance OCG by applying successive taps (i) with increasing applied impact energy, \(W^{PE}[i]\), such that \(W^{PE}[i] = 16.0\times 1.5^{i-1}\) mJ. When the AC surfaces of the OCG and OCR were flush, the insertion was complete and the final tap was designated as \(#N\). For each tap \(#i\), peak axial force, \(F_p[i]\), impulse, \(I[i]\), and time of peak force, \(T[i]\), were determined from force profiles; displacement of the AC, \(u_{ac}[OCG][i]\), was taken as peak axial displacement of the tamp, \(u_{amp}[i]\), less the OCG advancement distance during each tap, \(u_{adv}[i]\), as determined from video imaging, allowing estimation of the associated peak cartilage compressive strain, \(\varepsilon[i]\). Also, for
each tap, the insertion energy delivered by the tamp to the sample, \( W_{\text{Tamp}[i]} \), was quantified by integrating the measured force, \( F(t) \), over axial displacement of the tamp, \( u_{\text{Tamp}[t]} \), and the portion of \( W_{\text{Tamp}[i]} \) delivered to the articular cartilage, \( W_{\text{AC,OCG}[i]} \), and to other sources resisting advancement, \( W_{\text{Adv}[i]} \), including the OCG-OCR bone interface, were estimated according to \( u_{\text{Adv}[i]} \) and \( u_{\text{pTamp}[i]} \). Through tap \#n, the cumulative OCG advancement distance, \( u_{\text{Adv}[m]} \), and cumulative insertion energy, \( W_{\text{Tamp}[m]} \), were calculated as the sums of \( u_{\text{Adv}[i]} \) and \( W_{\text{Tamp}[i]} \), respectively. The total energy delivered to the AC of an OCG, \( W_{\text{Insert}}{\text{AC,OCG}} \), was calculated as the sum of \( W_{\text{AC,OCG}[i]} \) over all \( N \) taps.

**Cartilage Damage:** For impacted and also freshly-isolated samples (n=15), the proportion of viable surface chondrocytes, \( V_{\text{AC,OCG}} \), was determined by isolation of the AC, incubation of the AC in medium with 10% FBS for 24hr, staining the AC with Live-Dead™, fluorescence imaging of cells at the AC surface, and image processing to calculate the ratio of live cells/total cells. Also, total crack length in the cartilage surface, \( L_{\text{Crack}} \), was quantified by fixing, staining with India Ink, imaging, and image processing.

**Structural Integrity of OCG-OCR Repair:** The repairs were evaluated for structural integrity by micro-computed tomography (\( \mu \)CT, at 9 \( \mu \)m) of typical samples of each experimental group. Image cross-sections through the proximal, middle, and distal portions of the graft-host interface, and also through vertical axes, were evaluated for integrity of the OCG and of the OCR, and also for OCG-OCR apposition.

**Statistics:** The effects of \( \Delta R \) as well as standard versus modified OCG graft geometry (with a tight fit, \( \Delta R=0.10 \) mm) on biomechanical and mechanobiological variables were assessed by one-way ANOVA with Tukey post-hoc test and a planned comparison. The relationship between \( L_{\text{Crack}} \) and \( W_{\text{Insert}}{\text{AC,OCG}} \) was tested by linear regression. Data are shown as mean±SD.

**Results:**
An increasingly tight OCG-OCR interference fit led to more taps for insertion (higher \( N \)) as well as higher \( F_{p}[i] \) and \( u_{p,\text{OCG}[i]} \), lower \( T[i] \), \( u_{\text{pTamp}[i]} \) and \( u_{\text{adv}[i]} \), and shifted total energy of insertion, \( W_{\text{Tamp}[i]} \) (increased in the AC, \( W_{\text{AC,OCG}[i]} \), and reduced elsewhere, \( W_{\text{Adv}[i]} \)) (Fig. 2A and Table 1). The net effects were that during OCG advancement, \( u_{\text{Adv}[m]} \), there was increasing cumulative energy delivery, \( W_{\text{Tamp}[m]} \) (right shift in Fig. 2B), and total energy delivery to cartilage, \( W_{\text{Insert}}{\text{AC,OCG}} \) (Fig. 2C). The biological consequence of a tight interference fit was more cartilage tissue damage, with lower chondrocyte viability (\( V_{\text{AC,OCG}} \), Fig. 1D) and a tendency for higher \( L_{\text{Crack}} \).

By comparison, when the modified OCG was inserted into the OCR with a tight interference fit, the biomechanical insertion parameters were altered significantly, with most parameters being similar to those for a moderate interference fit OCR (Fig. 2A-C and Table 1), and with consequently less AC damage in terms of \( V_{\text{AC,OCG}} \) (Fig. 1D) and \( L_{\text{Crack}} \).

Under all of the test conditions, an increase in \( W_{\text{Insert}}{\text{AC,OCG}} \) [mJ] was strongly associated with an increase in \( L_{\text{Crack}} \) [mm] \( (L_{\text{Crack}}=0.01*W_{\text{Insert}}{\text{AC,OCG}}-0.83, R^2=0.93) \). \( \mu \)CT confirmed structural interference between the OCR bone and both the proximal and distal 1mm bone segments of the OCG, with the central regions being slightly separated for the modified OCG.

**Discussion:**
This is the first comprehensive biomechanical analysis of impact insertion of OCG and evaluation of OCG-OCR interference fit. The association of cartilage damage with energy delivered to cartilage is consistent with fracture mechanics energy principles. The modified OCG geometry appears to maintain structural integrity, but needs to be tested in vivo for functional stability and biological efficacy.

**Significance:**
The results (1) clarify OCG insertion biomechanics and mechanobiology, and (2) introduce a simple modification of OCG that facilitates insertion with reduced energy while maintaining a structural interference fit.

**Fig. 1.** Schematic of OCG and OCR geometries and insertion, with mechanical variables and parameters. (A) Standard OCG. (B) Modified OCG. (C) Tight-fitting OCR. (D) Advancement of OCG into OCR, starting with flush position (i) and advancing with successive taps (ii-iv) to final flush position (v), with corresponding photographs (vi-x).
Fig. 2. Effects of interference fit (Loose, Moderate, Tight) and OCG geometry (Standard or Modified) on insertion mechanics and chondrocyte viability. (A) Total number of taps, \(N\), (B) Cumulative OCG advancement, \(u_{adv}[m]\), as a function of cumulative insertion energy, \(W_{Temp}[mJ]\), after \(m\) taps. (C) Total energy delivered to AC of OCG, \(W_{insert,AC,OGC}\). (D) Percentage of surface chondrocytes that are viable, \(v_{AC,OGC}\).

Table 1: Comparison of biomechanics for OCG-OCR interference fits that were loose (\(AR = 0.00\)mm), moderate (\(AR = 0.05\)mm) and tight (\(AR = 0.10\)mm) for Standard (S) OCG and for a Modified (M) OCG into a tight fit OCR. Statistical results are indicated as *** p<0.001, ** p<0.01, * p<0.05, and non-significant results presented with a p value.

<table>
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<tr>
<th>OCG type</th>
<th>(AR) (mm)</th>
<th>(#)</th>
<th>(#H)</th>
<th>(W_{Temp}[mJ]) (mJ)</th>
<th>(F_{p}[N]) (N)</th>
<th>(T_{n}[m]) (ms)</th>
<th>(\epsilon_{a}[%])</th>
<th>(\epsilon_{p}[%])</th>
<th>(W_{Temp}[mJ]) (mJ)</th>
<th>(W_{AC,OGC}[mJ]) (mJ)</th>
<th>(W_{Adv}[mJ]) (mJ)</th>
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<tbody>
<tr>
<td>S</td>
<td>0.00</td>
<td>7</td>
<td>3</td>
<td>36</td>
<td>51 ±10</td>
<td>232 ±34</td>
<td>8.0 ±1.7</td>
<td>0.73 ±0.13</td>
<td>0.35 ±0.07</td>
<td>0.21 ±0.03</td>
<td>30.5 ±4.7</td>
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<tr>
<td></td>
<td>0.05</td>
<td>6</td>
<td>3</td>
<td>36</td>
<td>61 ±16</td>
<td>220 ±21</td>
<td>5.3 ±0.8</td>
<td>0.79 ±0.16</td>
<td>0.41 ±0.12</td>
<td>0.22 ±0.07</td>
<td>29.7 ±2.7</td>
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<tr>
<td></td>
<td>0.10</td>
<td>6</td>
<td>3</td>
<td>36</td>
<td>79 ±15</td>
<td>244 ±38</td>
<td>3.8 ±0.9</td>
<td>0.66 ±0.11</td>
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<td>35.4 ±8.6</td>
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<tr>
<td></td>
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<td>7</td>
<td>3</td>
<td>36</td>
<td>72 ±20</td>
<td>259 ±33</td>
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<td>0.47 ±0.23</td>
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<td>36.3 ±12.8</td>
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<tr>
<td>M</td>
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<td>36</td>
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<td>0.70 ±0.63</td>
<td>0.63 ±0.43</td>
<td>0.50 ±0.22</td>
</tr>
</tbody>
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Effect of \(AR\) (p-value): ** 0.45 *** 0.04 ** 0.10 0.05 0.35 0.15 ** 0.05
Effect of OCG type (p-value): 0.95 0.39 0.16 0.35 0.30 0.70 0.63 1.00 0.55 0.43 0.02