Cementation of a Dual-Mobility Acetabular Component into a Well-Fixed Metal Shell during Revision Total Hip Arthroplasty: A Biomechanical Validation

Julien Wegrzyn,1,2 Andrew R. Thoreson,1 Olivier Guyen,2 David G. Lewallen,3 Kai-Nan An1

1Biomechanics Laboratory, Mayo Clinic, Rochester, Minnesota, 2Department of Orthopedic Surgery—Pavillon T, Hôpital Edouard Herriot, Lyon, France, 3Department of Orthopedic Surgery, Mayo Clinic, Rochester, Minnesota

ABSTRACT: Cementation of polyethylene (PE) liners into well-fixed metal shells has become a popular option during revision total hip arthroplasty (THA) particularly for older and frail patients. Although dramatic results were reported with dual-mobility acetabular components to manage hip instability during revision THA, no study evaluated the fixation strength of the cementation of dual-mobility components into well-fixed metal shells. Eight dual-mobility and eight all-PE components were cemented into a metal shell with a uniform 2- to 3-mm cement mantle. The cemented fixation strength was evaluated using lever-out and torsion testing. The interface at which failure occurred was determined. Lever-out testing showed that dual-mobility components failed at significantly higher maximum moment than the all-PE components. No direct comparison could be performed with torsion testing due to early failure of the all-PE component itself before failure of the cement fixation. However, the maximum moments measured were dramatically higher than the in vivo frictional moments classically reported in THA. In addition, failure was always observed at the metal shell/cement interface whenever it did occur. In conclusion, a dual-mobility acetabular component cemented into a well-fixed metal shell could constitute a biomechanically acceptable alternative to acetabular shell removal or PE liner cementation while simultaneously preventing instability of the THA revision. Clinical studies are warranted. © 2012 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 9999:1–7, 2013

Keywords: revision total hip arthroplasty; dual-mobility acetabular component; cement; fixation strength; instability

Despite continuous improvements in surgical technique and implant design, the rate of revision total hip arthroplasty (THA) did not decrease over the past few decades.1 Furthermore, with increased life expectancy of THA patients and a trend toward surgical indication at younger ages, demand for THA revisions is projected to double by 2026, and case complexity is likely to increase dramatically.2 Instability constitutes the major indication for THA revision, is the most common reason for failure after revision, and represents the most common reason for isolated acetabular revision and modular component exchange.1,3 Modular component exchange has been proposed in an attempt to manage THA instability while minimizing potential morbidity due to extensive bone loss, intra-operative bleeding, and prolonged operative time accompanying formal revision procedures, particularly for older and frail patients.4,5 Beside instability management, modular component exchange could be required in cases of wear or mechanical failure of the liner. However, liner replacement may be impossible or impractical due to damaged locking mechanisms compromising liner fixation, incompatibility of the available components, non-modularity of the metal shell, or sub-optimal positioning of the acetabular component requiring re-orientation. Previous biomechanical and short-term follow-up clinical studies reported the cementation of polyethylene (PE) liners into well-fixed metal shells is a useful procedure to minimize THA revision morbidity in those indications.6–16 This technique, referred to as the double-socket technique, provided fixation strength higher than the standard locking mechanism and allowed a slight reorientation of the acetabular component.6–16 However, even if the indication of this technique is limited to well-positioned acetabular components within acceptable limits, and in the presence of a preserved abductor mechanism, dislocation may occur after 22–55% of these procedures, especially when the indication for revision is instability.4,6 Therefore, cementation of a constrained triplolar acetabular component into a well-fixed metal shell has been advocated for patients with THA instability history for treating and/or preventing dislocation recurrence.6,17 While previous studies of constrained triplar liners reported mechanical failure rates up to 42.1% at 10-year follow-up,18,19 the overall survival rate of dual-mobility acetabular components has been reported to be as high as 96% at 15-year follow-up with a restoration of hip stability in more than 95% of operated patients.20–23

Despite these encouraging clinical results, no study has reported the cementation of dual-mobility acetabular components into well-fixed metal shells during revision THA. Therefore, we assessed lever-out and torsional strength of the cemented fixation of a stainless steel dual-mobility shell into a well-fixed metal shell to validate the use of this technique in routine surgical practice. We hypothesized that cementing a dual-mobility component is a relevant option providing fixation strength as high as the cementation of a standard all-PE component.
MATERIALS AND METHODS

Eight dual-mobility acetabular components (Saturne®, Amplitude, Valence, France) and eight PE acetabular components (Luna®, Amplitude) were cemented into eight pairs of titanium metal shells (Equateur®, Amplitude) for each of two mechanical testing conditions (Figs. 1 and 2). A 60-mm outer diameter of the metal shell is the minimal diameter we recommend to use with the “double-socket” technique. Insertion of 48-mm outer diameter all-PE and dual-mobility components into 60-mm outer diameter metal shells allowed therefore a cement mantle thickness of 2–3 mm. In addition, the smaller outer diameter of the dual mobility component allowing an acceptable thickness of PE for the mobile PE liner is 48 mm with the tested implant. The all-PE cup was machined from ultra-high molecular weight polyethylene (UHMWPE). The outer surface is designed for cementation with concentric circumferential grooves to interdigitate with the cement. The design of the dual-mobility component is cast from M30NW stainless steel with an outer surface specifically designed for cementation with a peripheral rim and concentric circumferential grooves for cement interdigitation (Fig. 1). To simulate a well-fixed metal shell, titanium shells were securely potted into a mounting fixture using Wood’s metal (Fig. 2). Each construct was assembled to represent the intra-operative conditions of a standard THA revision procedure. A high-speed rotary carbide burr was used to cut a cruciform and circumferential pattern having two concentric grooves 1 mm deep and 2 mm wide into the metal shell inner surface (Fig. 2). This technique has been described in the “double-socket” technique to increase cement interdigitation and fixation strength, particularly when the shell has a smooth inner surface without holes. The cementation technique was performed to mimic the surgeon’s experience intra-operatively. Before cementing, the shell inner surface was carefully cleaned with moist gauze. Standard PMMA bone cement without antibiotics was prepared according to the manufacturer’s instructions (Hygienic®, Colte`ne, Inc., Cuyahoga Falls, OH). After 3.5 min of manual mixing at controlled-room temperature (18–20°C) and humidity (40–50%), a doughy texture was obtained. Then, the cement was thickly applied into the shell. The all-PE or dual-mobility acetabular components were placed into the shell using manual pressure and centralization to ensure a 2–3 mm uniform cement mantle with special attention to avoid a “bottoming out” of the component against the shell (Fig. 3). A 2–3 mm cement mantle provides greater fixation strength than a standard locking liner. Cement was allowed to cure at ≥6 hr before testing.

The fixation strength of the metal shell/cement or cement/acetabular component interface was evaluated with torsion and lever-out testing using a servohydraulic testing machine (858 Mini Bionix II®, MTS Systems, Eden Prairie, MN) until failure occurred at an interface.

Lever-Out Testing

For the dual-mobility components, a lever-arm made from a 100 mm long threaded rod was screwed into a plate welded to the inner surface of the cup. Wood’s metal was poured into the cup, and the construct was secured with a washer contacting the cup rim and captured between two nuts (Fig. 4A). For the all-PE components, a similar lever-arm was screwed into the center of the bearing surface, secured with Wood’s metal, and a nut was screwed onto a retaining washer fixed to the cup with four screws (Fig. 4B). Load was applied to the lever-arm at a controlled-displacement rate of 1 mm/s until failure. Load was monitored with a 2,224 N capacity load cell (Lebow Products, Troy, MI).

Torsion Testing

The mounting fixture was secured to an x–y platform allowing free horizontal motion. To engage the acetabular components, 7 mm deep equatorial slots were machined into the components without damaging the outer surface. A torsion blade connected to the actuator was inserted into the slots (Fig. 5A,B) and rotated at a rate of 1°/s until failure. Load...
was monitored with a 226 N.m capacity load cell (Lebow Products). The maximum lever-out and torsion moments were determined. All constructs were examined to determine the interface at which failure occurred (shell/cement or cement/acetabular component). Occurrence of an audible crack at failure was recorded. Data are presented as mean ± SD (range). Comparisons between maximum torsion and lever-out moments were performed using the Mann–Whitney U test with significance set at $p < 0.05$.

RESULTS

Lever-Out Testing

The mean maximum lever-out moment was significantly higher ($p < 0.001$) for the dual-mobility component (104 ± 8 N.m; range: 94–119 N.m) than for the all-PE component (66 ± 10 N.m; range: 48–80 N.m). Failure always occurred at the metal shell/cement interface with an audible crack, while the cement/acetabular component interface was always preserved (Fig. 6).

Torsion Testing

The mean maximum torsion moment for the dual-mobility component was 128 ± 24 N.m (range: 81–157 N.m). Failure always occurred at the metal shell/cement interface with an audible crack, while the cement/dual-mobility component interface was always preserved. For the all-PE component, no failure of the cement fixation was obtained up to a torsion moment of 200 Nm, which was the safe mechanical limit of the load cell. PE deformation and shearing occurred as the applied loading increased, leading to disengagement of the torsion cross without failure of the cement mantle. Therefore, no direct comparison between the torsion strength of the cemented dual-mobility versus an all-PE acetabular component could be performed.

DISCUSSION

Dual-mobility acetabular components are effective in the treatment and prevention of instability following THA, particularly in patients at high risk for dislocation, with fewer mechanical complications and lower loosening rates than with constrained tripolar acetabular components.18,20,21,23–28 Despite these encouraging results, no study evaluated the fixation strength of
a dual-mobility acetabular component cemented into a well-fixed metal shell compared to a standard all-PE acetabular component. Our results were in agreement with previous studies on cemented fixation strength of PE liners and demonstrated that cementation of a dual-mobility component provided even greater fixation strength, particularly during lever-out testing (Table 1).7,8,10–12,14 Interestingly, failure consistently occurred at the metal shell/cement interface whereas the cement/acetabular component interface was always preserved. This finding contrasts with previous studies in which failure usually occurred at the cement/PE liner interface.7,10–12,14 However, in these studies, PE liners had a smooth outer surface requiring hand-texturing to maximize cement interdigitation, and cementation was performed into multiholed and/or scored metal shells.7,10–12,14 In our study, the cementation was performed into a smooth inner surface titanium metal shell with no screw holes.10,12 In this case, shell roughening with a spider-web pattern using a high-speed rotary tool is recommended as it increases fixation strength by as much as 20%.12,16 In addition, both acetabular components were specifically designed for cement fixation with grooves oriented to oppose both torsion and lever loading. This may explain the absence of dissociation at the cement/acetabular component interface. This observation is supported by previous studies demonstrating that textured and trunion liners offer improved strength over intra-operatively hand-modified liners.10,14 However, surgeons should be aware of the potential for metallic debris resulting from shell roughening. To prevent this potential, we advocate dispensing wet gauze around the acetabulum and shell during the procedure. Toughening of the metal-shell inner surface must then be performed with continuous irrigation and suction to avoid debris egress to the surrounding tissues. When roughening is complete, the gauze should be carefully folded and removed and then pulsed irrigation should be performed with saline solution to clean the joint space.

Despite dissociation at the shell/cement interface, the maximum moments in our study were dramatically higher than in vivo frictional moments reported in THA.29 Using a biaxial hip joint simulator, Davidson et al.29 evaluated the frictional torque produced by 32-mm diameter CoCr or alumina ceramic femoral heads articulating against a UHMWPE liner. At a 5,000 N walking load and using water as lubricant, the frictional torque was 0.94 Nm with CoCr and 0.46 Nm with ceramic.29 These values are considerably lower than even the lowest failure torque that we measured.
with dual-mobility components. Therefore, the cemented fixation strength of dual-mobility component should provide a stable and safe fixation.

Our study has several limitations. These ex vivo testing methods did not exactly reproduce the in vivo failure mechanisms. Neither lever-out nor direct torsion loading is truly physiologic, but both are relatively easy methods to assess the construct fixation strength. In addition, the influence of cyclic loading was not assessed. Further study with cyclic loading could provide data on the effect of fatigue on failure and temporal weakening of the shell/cement or cement/acetabular component interfaces. Moreover, our study did not simulate in vivo conditions such as wetness or temperature that could contribute to cement degradation or adherence.

To minimize this risk of dislocation related to the double-socket technique, use of a larger femoral head, constrained tripolar liner, and dual-mobility acetabular component has been recommended.5,30 However, the inner diameter of the shell limits the PE liner size and head diameter. The liner must be undersized when cemented into a well-fixed shell to provide a uniform cement mantle ensuring the greatest construct strength.7,10 Therefore, a liner with a thin PE wall would have to be used to accept heads >28 mm diameter in some cases. Such liners could be at higher risk of fatigue failure and fracture.31,32 In this regard, cementation of all-metal acetabular components has been proposed to use large-diameter heads.33 However, serious complications emerged with metal-on-metal THA, and there is increasing awareness of potential for early failure.34

The dual-mobility acetabular component (Saturne®) consists of a M30NW stainless steel outer shell with a highly polished inner surface articulated with a mobile intermediate UHMWPE component capturing the femoral head using a snap-fit type mechanism (Fig. 1).21 This principle creates two articulations: a low friction inner bearing between the head and the UHMWPE component, and an outer bearing between the UHMWPE and the shell resulting in an ultra-large effective head (UHMWPE “femoral head” ≥40 mm). This concept explains the dramatic effect on THA

<table>
<thead>
<tr>
<th>Authors</th>
<th>Type of Construct</th>
<th>Interface of Failure</th>
<th>Lever-Out (N.m)</th>
<th>Torsion (N.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bonner et al.7</td>
<td>Various designs of all-PE liner cemented into a metal shell with or without screw holes</td>
<td>All-PE liner/cement</td>
<td>17.10–88.35</td>
<td>—</td>
</tr>
<tr>
<td>Haft et al.10</td>
<td>Various designs of all-PE liner cemented into a metal shell with or without surface scoring and/or screw holes</td>
<td>All-PE liner/cement</td>
<td>23–146</td>
<td>6.1–65.7</td>
</tr>
<tr>
<td>Hofmann et al.11</td>
<td>Roughened or smooth all-PE liners cemented into a metal shell with screw and dome holes using two different cements</td>
<td>All-PE liner/cement</td>
<td>a</td>
<td>117 (mean value for roughened and smooth all-PE liners)</td>
</tr>
<tr>
<td>Mauerhan et al.14</td>
<td>Trunion or roughened all-PE liners cemented into a metal shell with screw and dome holes</td>
<td>All-PE liner/cement</td>
<td>50.7 ± 2.8 (roughened all-PE liners); 51.7 ± 3.7 (trunion all-PE liners)</td>
<td>—</td>
</tr>
<tr>
<td>Ebramzadeh et al.33</td>
<td>All-metal acetabular cup (CoCr alloy) cemented into three different sizes of metal shell with screw and dome holes to vary cement mantle thickness</td>
<td>Cement/metal shell</td>
<td>—</td>
<td>43–57</td>
</tr>
<tr>
<td>Wegryn et al. (current study)</td>
<td>M30NW dual-mobility vs. all-PE acetabular components cemented into a roughened smooth metal shell without screw and dome hole</td>
<td>Cement/metal shell</td>
<td>103.55 ± 8.27 (dual-mobility cups); 66.00 ± 9.52 (all-PE cups)</td>
<td>127.94 ± 23.87 (dual-mobility cups); &gt;200 (all-PE cups)</td>
</tr>
</tbody>
</table>

aMean failure load during lever-out testing for roughened and smooth all-PE liners was 1,377 N. No lever arm information was reported to calculate lever-out torque.
range of motion before impingement in positions at risk of dislocation with a PE volumetric wear similar to a conventional metal-on-PE bearing using a 22.2-mm femoral head.24,30 In contrast, reduced range of motion was described with constrained tripod liners leading to early impingement and increased load transmission to the multiple interfaces including the cement/implant interface.18,19 Therefore, concerns have been raised with constrained liners (increased wear, early loosening, and mechanical failures).18,19 In addition, most constrained liners require hand-made texturing of the smooth PE outer surface to improve cement interdigitation and avoid rapid failure due to liner dissociations.7,10,17 However, the effect of PE texturing on liner weakening and fatigue strength remains unknown.7,10,15 Therefore, when cemented into a well-fixed shell, high risk of device-related mechanical failure with constrained liners was reported at short- to mid-term follow-up.18,25 Previous series also raised concerns regarding PE component loosening and migration at short-term follow-up with the cementation of rigid shells directly into the bony acetabulum.35–37 However, similar to the low dissociation rate reported with all-PE cup cementation into acetabular reinforcement devices (Burch–Schneider cage or Kerboull cross-plate), recent studies on cementation of dual-mobility components reported survival rate up to 99.3% at 8 years post-operatively using acetabular component loosening for aseptic loosening as the endpoint and a restoration of hip stability in 96% of the recurrent dislocating hips.26,37,38–40 Contrarily to other conventional shells, the results reported with dual-mobility components could be related to the fact that most of the motion occurs within the inner bearing surface, avoiding overloading of the dual-mobility component/cement or the acetabulum/cement interface.24,26,30 Another benefit is the absence of retaining rings. Therefore, pull-out forces do not occur on different interfaces of the construct explaining the better result in terms of implant fixation and mechanical survival particularly when cementation is required.19,25

Our results demonstrated that cementation of a dual-mobility acetabular component into a well-fixed metal shell is a biomechanically acceptable alternative to acetabular shell removal or cementation of conventional or constrained PE liners. The dual-mobility component could also prevent instability while assuring stable cemented fixation during revision THA. These promising results are strong rationale for further research in clinical studies of long-term viability of such cemented fixation. Moreover, in those conventional acetabular component revisions using a highly porous trabecular metal shell, the cemented fixation strength of a dual-mobility acetabular component should be improved further due to the high coefficient of friction and volumetric porosity of highly porous structures providing benefits in terms of construct stability.41,42

ACKNOWLEDGMENTS
The authors thank Lawrence Berglund and Alexander Hooke for assistance in study design. We thank Amplitude (Valence, France) for providing the implants used in testing.

REFERENCES
Dear Author,

During the copyediting of your paper, the following queries arose. Please respond to these by annotating your proofs with the necessary changes/additions.

- If you intend to annotate your proof electronically, please refer to the E-annotation guidelines.
- If you intend to annotate your proof by means of hard-copy mark-up, please refer to the proof mark-up symbols guidelines. If manually writing corrections on your proof and returning it as a scanned pdf via email, do not write too close to the edge of the paper. Please remember that illegible mark-ups may delay publication.

Whether you opt for hard-copy or electronic annotation of your proofs, we recommend that you provide additional clarification of answers to queries by entering your answers on the query sheet, in addition to the text mark-up.

<table>
<thead>
<tr>
<th>Query No.</th>
<th>Query</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>AQ1</td>
<td>Please provide volume number.</td>
<td></td>
</tr>
<tr>
<td>AQ2</td>
<td>Please provide volume number.</td>
<td></td>
</tr>
</tbody>
</table>
INSTRUCTIONS FOR CHECKING PAGE PROOFS

A PDF page proof of your article is provided with these instructions. Its purpose is for you to:

- Proofread your article.
- Answer any queries (which, if present, are in a query list at the end of the article).
- Check the content and positioning of tables and figures.

It is important that you check this proof very carefully and answer all the queries. Please note that only essential corrections can be made at this stage. Also note that changes you make to your article that do not comply with the style of the Journal and those that are grammatically incorrect will not be incorporated.

**Proofreading instructions**

Read over your article carefully, and check that:

- There are no errors in the article (including data, equations and references).
- Author and address details are accurate.
- Content and positioning of tables and figures is correct (note that some photographs in the file may appear blurry, as figures in the PDF are low resolution).
- Special characters such as figure legend symbols and Greek letters have not corrupted.
- Any previously submitted amendments have been incorporated correctly.

**Queries**

- Any queries are listed on the last page of the proof, with a corresponding number in the margin next to the relevant text.
- Please ensure all queries are answered in full.

**Return of approval to publish**

- Add corrections or answers to any queries using e-Annotation. The instructions for using e-Annotation tools are on the following pages.
- Retain a copy of your corrections for your records.
- Email the Production Editor your approval to publish your article (either with or without amendment) and any corrections required. The Production Editor's contact details are given in the covering email.
- Prompt notification of your approval to publish your article is very much appreciated.
- Please contact the Production Editor if you have any queries.
USING e-ANNOTATION TOOLS FOR ELECTRONIC PROOF CORRECTION

Required software to e-Annotate PDFs: Adobe Acrobat Professional or Adobe Reader (version 8.0 or above). (Note that this document uses screenshots from Adobe Reader X)
The latest version of Acrobat Reader can be downloaded for free at: http://get.adobe.com/reader/

Once you have Acrobat Reader open on your computer, click on the Comment tab at the right of the toolbar:

This will open up a panel down the right side of the document. The majority of tools you will use for annotating your proof will be in the Annotations section, pictured opposite. We’ve picked out some of these tools below:

1. **Replace (Ins) Tool** – for replacing text.
   - Strikes a line through text and opens up a text box where replacement text can be entered.
   **How to use it**
   - Highlight a word or sentence.
   - Click on the Replace (Ins) icon in the Annotations section.
   - Type the replacement text into the blue box that appears.

2. **Strikethrough (Del) Tool** – for deleting text.
   - Strikes a red line through text that is to be deleted.
   **How to use it**
   - Highlight a word or sentence.
   - Click on the Strikethrough (Del) icon in the Annotations section.

3. **Add note to text Tool** – for highlighting a section to be changed to bold or italic.
   - Highlights text in yellow and opens up a text box where comments can be entered.
   **How to use it**
   - Highlight the relevant section of text.
   - Click on the Add note to text icon in the Annotations section.
   - Type instruction on what should be changed regarding the text into the yellow box that appears.

4. **Add sticky note Tool** – for making notes at specific points in the text.
   - Marks a point in the proof where a comment needs to be highlighted.
   **How to use it**
   - Click on the Add sticky note icon in the Annotations section.
   - Click at the point in the proof where the comment should be inserted.
   - Type the comment into the yellow box that appears.
### 5. Attach File Tool – for inserting large amounts of text or replacement figures.

- **How to use it**
  - Click on the Attach File icon in the Annotations section.
  - Click on the proof to where you’d like the attached file to be linked.
  - Select the file to be attached from your computer or network.
  - Select the colour and type of icon that will appear in the proof. Click OK.

### 6. Add stamp Tool – for approving a proof if no corrections are required.

- **How to use it**
  - Click on the Add stamp icon in the Annotations section.
  - Select the stamp you want to use. (The Approved stamp is usually available directly in the menu that appears).
  - Click on the proof where you’d like the stamp to appear. (Where a proof is to be approved as it is, this would normally be on the first page).

### 7. Drawing Markups Tools – for drawing shapes, lines and freeform annotations on proofs and commenting on these marks.

- **How to use it**
  - Click on one of the shapes in the Drawing Markups section.
  - Click on the proof at the relevant point and draw the selected shape with the cursor.
  - To add a comment to the drawn shape, move the cursor over the shape until an arrowhead appears.
  - Double click on the shape and type any text in the red box that appears.

For further information on how to annotate proofs, click on the Help menu to reveal a list of further options:
ELECTRONIC PROOF CHECKLIST, Journal of Orthopaedic Research

***IMMEDIATE RESPONSE REQUIRED***
Please follow these instructions to avoid delay of publication.

☐ READ PROOFS CAREFULLY
   • This will be your only chance to review these proofs.
   • Please note that the volume and page numbers shown on the proofs are for position only.

☐ ANSWER ALL QUERIES ON PROOFS (Queries for you to answer are attached as the last page of your proof.)
   • Mark all corrections, including query answers, directly on the proofs, within the text. Note that excessive author alterations may ultimately result in delay of publication and extra costs may be charged to you.

☐ CHECK FIGURES AND TABLES CAREFULLY
   • Check size, numbering, and orientation of figures.
   • All images in the PDF are downsampled (reduced to lower resolution and file size) to facilitate Internet delivery. These images will appear at higher resolution and sharpness in the printed article.
   • Review figure legends to ensure that they are complete.
   • Check all tables. Review layout, title, and footnotes.

☐ COMPLETE REPRINT ORDER FORM BY CLICKING ON THE LINK SHOWN ON THE REPRINT ORDER PAGE
   • If no reprints are desired, please ignore this reprints page.

RETURN ☐ PROOFS AND SIGNED COPYRIGHT TRANSFER AGREEMENT VIA EMAIL ONLY:
SEE INSTRUCTION PAGE FOR SOFT PROOFING E-PROOFS*

1: RETURN CTA WITHIN 48 HOURS OF RECEIPT VIA SCANNED PDF FILE TO jorprod@wiley.com
2: RETURN PROOF CORRECTIONS WITHIN 48 HOURS USING ADOBE ACROBAT NOTES TO jorprod@wiley.com

*If you do not have access to Adobe Acrobat Notes tool, please
   either (a) mark the proofs with black pen and scan into a pdf to send as an email attachment, or
   (b) send your corrections by marking up your original manuscript in a Word document file.

QUESTIONS?

Lillian Solondz, Senior Production Editor
Phone: 201-748-6183
E-mail: jorprod@wiley.com
Refer to journal acronym and DOI number (i.e., JOR 21466).
COLOR REPRODUCTION IN YOUR ARTICLE

Color figures were included with the final manuscript files that we received for your article. Because of the high cost of color printing, we can only print figures in color if authors cover the expense.

Please indicate if you would like your figures to be printed in color or black and white. Color images will be reproduced online in Wiley Online Library at no charge, whether or not you opt for color printing.

Failure to return this form will result in the publication of your figures in black and white.

<table>
<thead>
<tr>
<th>JOURNAL</th>
<th>JOURNAL OF ORTHOPAEDIC RESEARCH</th>
<th>VOLUME</th>
<th>ISSUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITLE OF MANUSCRIPT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MS. NO.</td>
<td>NO. OF COLOR PAGES</td>
<td>AUTHOR(S)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No. Color Pages</th>
<th>Color Charges</th>
<th>No. Color Pages</th>
<th>Color Charges</th>
<th>No. Color Pages</th>
<th>Color Charges</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>400</td>
<td>5</td>
<td>2000</td>
<td>9</td>
<td>3600</td>
</tr>
<tr>
<td>2</td>
<td>800</td>
<td>6</td>
<td>2400</td>
<td>10</td>
<td>4000</td>
</tr>
<tr>
<td>3</td>
<td>1200</td>
<td>7</td>
<td>2800</td>
<td>11</td>
<td>4400</td>
</tr>
<tr>
<td>4</td>
<td>1600</td>
<td>8</td>
<td>3200</td>
<td>12</td>
<td>4800</td>
</tr>
</tbody>
</table>

***Please contact the Production Editor for a quote if you have more than 12 pages of color***

- [ ] Please print my figures in black and white
- [ ] Please print my figures in color

BILL TO:  
Name ___________________________  
Institution ___________________  
Address ________________________  
Order No. ___________________________
Phone ___________________________  
Fax ____________________________  
E-mail ___________________________
COPYRIGHT TRANSFER AGREEMENT

Date: ________________

To: ________________

Re: Manuscript entitled ____________________________________________ (the "Contribution") for publication in JOURNAL OF ORTHOPAEDIC RESEARCH ___________________________ (the "Journal") published by Wiley Periodicals, Inc. ("Wiley") for the Orthopaedic Research Society.

Dear Contributor(s):

Thank you for submitting your Contribution for publication. In order to expedite the publishing process and enable Wiley to disseminate your work to the fullest extent, we need to have this Copyright Transfer Agreement signed and returned to us as soon as possible. If the Contribution is not accepted for publication this Agreement shall be null and void.

A. COPYRIGHT

1. The Contributor assigns to Wiley, during the full term of copyright and any extensions or renewals of that term, all copyright in and to the Contribution, including but not limited to the right to publish, republish, transmit, sell, distribute and otherwise use the Contribution and the material contained therein in electronic and print editions of the Journal and in derivative works throughout the world, in all languages and in all media of expression now known or later developed, and to license or permit others to do so.

2. Reproduction, posting, transmission or other distribution or use of the Contribution or any material contained therein, in any medium as permitted hereunder, requires a citation to the Journal and an appropriate credit to Wiley as Publisher, suitable in form and content as follows: (Title of Article, Author, Journal Title and Volume/Issue Copyright [year] Wiley Periodicals, Inc. or copyright owner as specified in the Journal.)

B. RETAINED RIGHTS

Notwithstanding the above, the Contributor or, if applicable, the Contributor's Employer, retains all proprietary rights other than copyright, such as patent rights, in any process, procedure or article of manufacture described in the Contribution, and the right to make oral presentations of material from the Contribution.

C. OTHER RIGHTS OF CONTRIBUTOR

Wiley grants back to the Contributor the following:

1. The right to share with colleagues print or electronic "preprints" of the unpublished Contribution, in form and content as accepted by Wiley for publication in the Journal. Such preprints may be posted as electronic files on the Contributor's own website for personal or professional use, or on the Contributor's internal university or corporate networks/intranet, or secure external website at the Contributor's institution, but not for commercial sale or for any systematic external distribution by a third party (e.g., a listserv or database connected to a public access server). Prior to publication, the Contributor must include the following notice on the preprint: "This is a preprint of an article accepted for publication in [Journal title] copyright (year) (copyright owner as specified in the Journal)". After publication of the Contribution by Wiley, the preprint notice should be amended to read as follows: "This is a preprint of an article published in [include the complete citation information for the final version of the Contribution as published in the print edition of the Journal]", and should provide an electronic link to the Journal's WWW site, located at the following Wiley URL: http://www.interscience.Wiley.com/. The Contributor agrees not to update the preprint or replace it with the published version of the Contribution.
2. The right, without charge, to photocopy or to transmit online or to download, print out and distribute to a colleague a copy of the published Contribution in whole or in part, for the Contributor’s personal or professional use, for the advancement of scholarly or scientific research or study, or for corporate informational purposes in accordance with Paragraph D.2 below.

3. The right to republish, without charge, in print format, all or part of the material from the published Contribution in a book written or edited by the Contributor.

4. The right to use selected figures and tables, and selected text (up to 250 words, exclusive of the abstract) from the Contribution, for the Contributor's own teaching purposes, or for incorporation within another work by the Contributor that is made part of an edited work published (in print or electronic format) by a third party, or for presentation in electronic format on an internal computer network or external website of the Contributor or the Contributor's employer.

5. The right to include the Contribution in a compilation for classroom use (course packs) to be distributed to students at the Contributor’s institution free of charge or to be stored in electronic format in datarooms for access by students at the Contributor’s institution as part of their course work (sometimes called “electronic reserve rooms”) and for in-house training programs at the Contributor’s employer.

D. CONTRIBUTIONS OWNED BY EMPLOYER

1. If the Contribution was written by the Contributor in the course of the Contributor's employment (as a "work-made-for-hire" in the course of employment), the Contribution is owned by the company/employer which must sign this Agreement (in addition to the Contributor’s signature), in the space provided below. In such case, the company/employer hereby assigns to Wiley, during the full term of copyright, all copyright in and to the Contribution for the full term of copyright throughout the world as specified in paragraph A above.

2. In addition to the rights specified as retained in paragraph B above and the rights granted back to the Contributor pursuant to paragraph C above, Wiley hereby grants back, without charge, to such company/employer, its subsidiaries and divisions, the right to make copies of and distribute the published Contribution internally in print format or electronically on the Company's internal network. Upon payment of the Publisher's reprint fee, the institution may distribute (but not resell) print copies of the published Contribution externally. Although copies so made shall not be available for individual re-sale, they may be included by the company/employer as part of an information package included with software or other products offered for sale or license. Posting of the published Contribution by the institution on a public access website may only be done with Wiley's written permission, and payment of any applicable fee(s).

E. GOVERNMENT CONTRACTS

In the case of a Contribution prepared under U.S. Government contract or grant, the U.S. Government may reproduce, without charge, all or portions of the Contribution and may authorize others to do so, for official U.S. Government purposes only, if the U.S. Government contract or grant so requires. (U.S. Government Employees: see note at end).

F. COPYRIGHT NOTICE

The Contributor and the company/employer agree that any and all copies of the Contribution or any part thereof distributed or posted by them in print or electronic format as permitted herein will include the notice of copyright as stipulated in the Journal and a full citation to the Journal as published by Wiley.

G. CONTRIBUTOR'S REPRESENTATIONS

The Contributor represents that the Contribution is the Contributor's original work. If the Contribution was prepared jointly, the Contributor agrees to inform the co-Contributors of the terms of this Agreement and to obtain their signature to this Agreement or their written permission to sign on their behalf. The Contribution is submitted only to this Journal and has not been published before, except for "preprints" as permitted above. (If excerpts from copyrighted works owned by third parties are included, the Contributor will obtain written permission from the copyright owners for all uses as set forth in Wiley's permissions form or in the Journal's Instructions for Contributors, and show credit to the sources in the Contribution.) The Contributor also warrants that the Contribution contains no libelous or unlawful statements, does not infringe on the rights or privacy of others, or contain material or instructions that might cause harm or injury.
CHECK ONE:

[____]Contributor-owned work

Contributor's signature

Date

Type or print name and title

Co-contributor's signature

Date

Type or print name and title

ATTACH ADDITIONAL SIGNATURE PAGE AS NECESSARY

[____]Company/Institution-owned work

(made-for-hire in the course of employment)

Company or Institution (Employer-for-Hire)

Date

Authorized signature of Employer

Date

[____]U.S. Government work

Note to U.S. Government Employees

A Contribution prepared by a U.S. federal government employee as part of the employee's official duties, or which is an official U.S. Government publication is called a "U.S. Government work," and is in the public domain in the United States. In such case, the employee may cross out Paragraph A.1 but must sign and return this Agreement. If the Contribution was not prepared as part of the employee's duties or is not an official U.S. Government publication, it is not a U.S. Government work.

[____]U.K. Government work (Crown Copyright)

Note to U.K. Government Employees

The rights in a Contribution prepared by an employee of a U.K. government department, agency or other Crown body as part of his/her official duties, or which is an official government publication, belong to the Crown. In such case, the Publisher will forward the relevant form to the Employee for signature.
Additional reprint and journal issue purchases

Should you wish to purchase additional copies of your article, please click on the link and follow the instructions provided: https://caesar.sheridan.com/reprints/redirect.php?pub=10089&acro=JOR

Corresponding authors are invited to inform their co-authors of the reprint options available.

Please note that regardless of the form in which they are acquired, reprints should not be resold, nor further disseminated in electronic form, nor deployed in part or in whole in any marketing, promotional or educational contexts without authorization from Wiley. Permissions requests should be directed to mailto: permissionsus@wiley.com

For information about ‘Pay-Per-View and Article Select’ click on the following link: http://wileyonlinelibrary.com/ppv