Superior Lubrication Mechanism in Artificial Hydrogel Cartilage for Joint Prostheses

Teruo Murakami, PhD¹, Nobuo Sakai, PhD², Tetsuo Yamaguchi, PhD¹, Seido Yarimitsu, PhD¹, Kazuhiro Nakashima, PhD¹, Yoshinori Sawae, PhD¹, Atsushi Suzuki, PhD³.

¹Kyushu University, Fukuoka, Japan, ²Kyushu Institute of Technology, Kita-kyushu, Japan, ³Yokohama National University, Yokohama, Japan.

Disclosures:


Introduction:

In most of joint prostheses composed of ultra-high molecular weight polyethylene (UHMWPE) and metal or ceramic as bearing material, efficacious treatments such as crosslinking, addition of vitamin E and the grafting of phospholipid polymer for UHMWPE improved the wear resistance and durability. However, wear problems have not yet been completely solved under severe conditions in various daily activities. In contrast, in healthy natural synovial joints possessing articular cartilage as biphasic bearing material with surface lubricity, minimal wear with extremely low friction has been maintained for a whole life. Therefore, the joint prosthesis with artificial hydrogel cartilage with similar properties to articular cartilage is expected to show superior tribological functions with very low friction and infinitesimal wear if the appropriate lubrication mechanism is actualized [1].

In this study, the effectiveness of biphasic lubrication mechanism in hydrogel through significant load-support by fluid phase accompanied with surface lubricity is evaluated in finite element (FE) analysis.

Methods:

As biocompatible artificial hydrogel cartilage materials, three kinds of poly(vinyl alcohol) (PVA) hydrogels were prepared by the repeated freezing-thawing (FT) method, the cast-drying (CD) method and hybrid method, which are physically crosslinked with hydrogen bonding but different in structure and mechanical properties. To evaluate these time dependent behaviors of load-support partitioning of fluid/solid phases and friction, two-dimensional biphasic FE analysis for cylindrical PVA hydrogel cartilage as 1.5 mm thick soft layer and radius of 5 mm was conducted under continuous loading of 0.2 N/mm by impermeable rigid plate in reciprocating motion in Fig. 1. The hybrid gel was composed of surface zone of CD gel in 0.7 mm thickness and lower FT gel in 0.8 mm thickness. The sliding speed is 4 mm/s for stroke of 8 mm at period of 4 s. A commercial package ABAQUS (6.8-4), which was appropriately evaluated for the biphasic FE analyses, was used in this study. The biphasic tissue was modeled by CPE4RP (four-node bilinear displacement and pore pressure, reduced integration with hour glass control) elements. The mechanical properties such as permeability, Young’s modulus and Poisson’s ratio were estimated by curve fitting to stress relaxation behaviors in compression test (Table1). Friction coefficients for solid-to-solid were estimated from experimental tests; 0.01 for hybrid, 0.05 for CD and 0.2 for FT gels.
Results:
As indicated in Fig.2, it is worth noting that the CD gel shows significant interstitial fluid pressurization compared with hybrid and FT gels at 292 s after start-up. The load partitioning by fluid phase at 292 s are 39.0 % for hybrid, 59.3 % for CD, and 46.7 % for FT gels, respectively. CD gel shows the highest load partitioning by fluid phase. Mises stresses were examined for solid phase in three PVA hydrogels. For FT gel, the highest stress was observed in loading zone. Hybrid and CD gels showed stresses at similar level but in different distribution. It is noticed that the stress at surface for hybrid gel is lower than that in CD gel.

Next, changes in friction for PVA hydrogels in reciprocating motion were estimated as shown in Fig.3. FT gel shows high level friction which gradually increases. CD gel exhibits much lower level but also gradually increases. Hybrid gel maintains the lowest level.

Discussion:
The frictional behaviors of 3 kinds of PVA hydrogels as candidate materials for artificial cartilage were evaluated by the biphasic FE analysis. The effective biphasic lubrication can contribute to low friction level and minimal wear through high load partitioning as suggested by the behaviors of CD gel, but the surface lubricity with low friction can control the rubbing severity as indicated by hybrid gel. These frictional behaviors were confirmed in experiments.

Significance:
In the existing joint prostheses composed of UHMWPE and metal or ceramic component, wear debris-induced osteolysis is still important problem. The development of artificial hydrogel cartilage with super lubricity has great possibility to establish minimum wear and extremely low friction.

Acknowledgments:
This work was supported by JSPS KAKENHI Grant Number 23000011.

References:

Properties of PVA hydrogels

<table>
<thead>
<tr>
<th>PVA hydrogel</th>
<th>Permeability m⁴/Ns</th>
<th>Young’s modulus kPa</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT</td>
<td>$2.0 \times 10^{-13}$</td>
<td>110</td>
<td>0</td>
</tr>
<tr>
<td>CD</td>
<td>$2.4 \times 10^{-12}$</td>
<td>190</td>
<td>0.41</td>
</tr>
</tbody>
</table>
Figure 1 Biphasic finite element model for reciprocating motion for rigid plate against cylindrical PVA hydrogel cartilage specimen.
Figure 2 Interstitial fluid pressure after 292 s (73 cycles)
Figure 3 Changes in friction for 3 kinds of gels in reciprocating tests