Design & Development of Novel Filtration Device for the Removal of Immunogenic Wear Debris in Artificial Joints

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Clinical Problem

Arthritis is the most common cause of disability, and osteoarthritis (OA) is the most common form within the United States, affecting the life of over 27 million Americans each year. Osteoarthritis or degenerative joint disease is the most common form of arthritis, and occurs when the cartilage within a joint wears away. The absence of cartilage allows the bones of the joint to come in physical contact and cause pain. This burden of osteoarthritis results in 623,000 joint replacements each year, 11.1 million outpatient visits, and $13.2 billion spent on job-related OA. With the aging baby-boomer population and obesity on the rise, the prevalence, health impact and economic consequences of OA are expected to increase dramatically.[1] Of these 27 million Americans, 10 million of them suffer from OA of the knee.[2]

Total Knee Replacement (TKR)

Over the past century, total joint arthroplasty has improved dramatically, from a risky experimental procedure to an everyday surgery with initial success rates of over 90%. Artificial joints give arthritis-sufferers, trauma victims, and many other patients a new lease on life and a restored degree of independence. In 2008, 1.3 million first-time (primary) total joint replacements were performed in the United States. Artificial knees and hips are the most mature devices in this field; in 2008, 307,000 primary artificial hips and 608,000 primary artificial knees were implanted.[3]

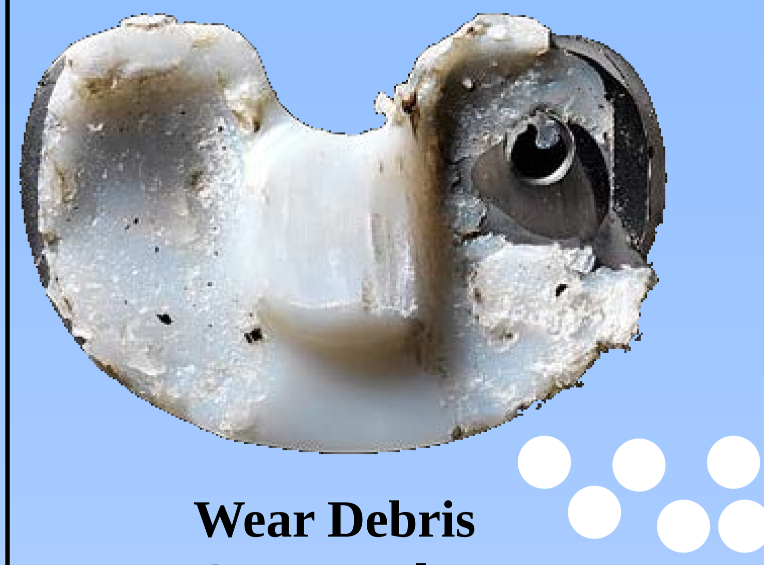
This surgery involves replacing the native joint with an artificial interface (Figure 1) that alleviates the pain of osteoarthritis while providing returned mobility for the patient. The most common interface within these joints is metal-on-plastic (Cobalt Chrome (Co-Cr) on ultra-high-molecular-weight polyethylene (UHMWPE); however, alternative interfaces include combinations of plastics, metals, and ceramics.

Figure 1: Total Knee Replacement

Wear & Revision Surgery

With the rigorous loading and environmental conditions to which artificial knee implants are subjected, they suffer from a progressive wear phenomenon that eventually leads to a variety of failures and revision surgery, a procedure where the artificial joint is replaced. In 2008, there were over 40,000 knee revisions in the U.S.[3] For the patient, a revision surgery means a longer stay, another grueling recovery period, and more time away from work and loved ones. Revision surgery is also financially painful. The American Academy of Orthopedic Surgeons estimates that knee and hip revisions cost Medicare and private insurance companies about $3 billion each year.[4]

How does Total Knee Replacement Fail?



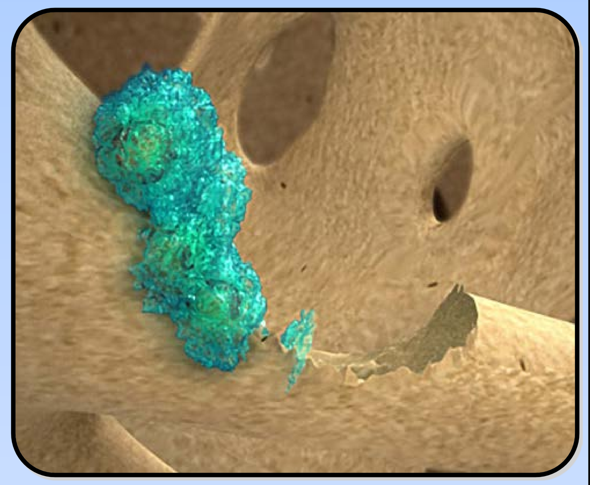


Figure 2: Immune Response Mediated Failure

As the artificial knee wears down, it releases submicron particles. It is estimated that with each step of gait, ½ million particles are released into the joint space. 90% of particles < 1 μm & 0.1 – 1 μm particles have been shown to the most biologically active.[5] When these immunogenic wear particles collide with soft tissue, they illicit a macrophage response which results in a downstream cascade of signaling (pro-inflammatory cytokines: TNF-α, IL-1, IL-6) that upregulates osteoclast activity and ultimately, bone resorption and implant loosening.

Orthopedic Filtration Device

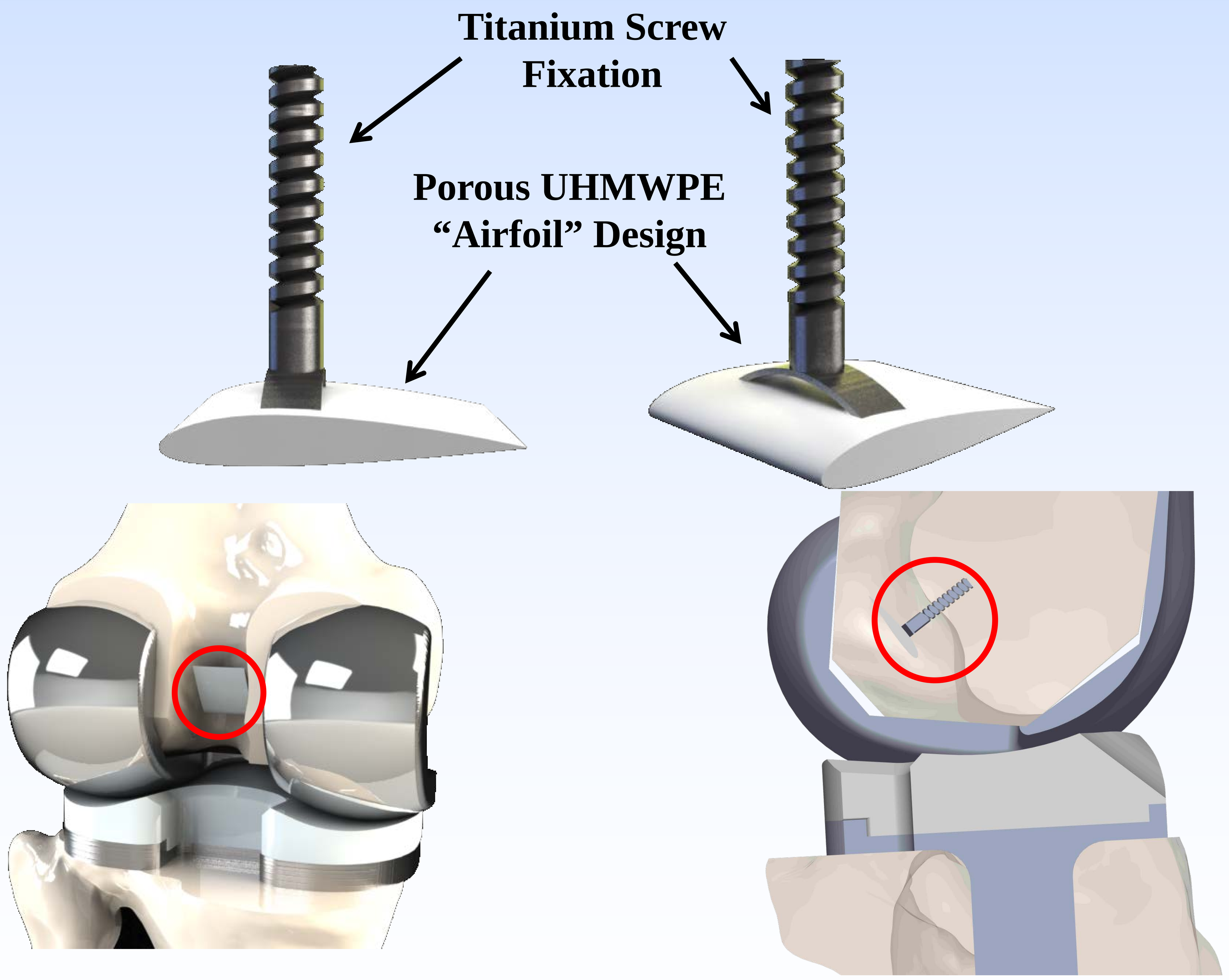


Figure 3: Design and Surgical Implantation

The proposed solution of an orthopedic filtration device would consist of two components: 1) porous UHMWPE filtration unit that is currently used and manufactured for other medical filtration applications as well as cranioplasty and 2) a titanium fixation screw for proper placement of the filter. This device would also utilize an "airfoil" design as to take advantage of the Venturi effect to create a pressure gradient in the transverse direction of the filter. This would help optimize the placement and profile of the device to minimize risk of the device causing problems in functionality of the artificial knee implant.

The work presented has been generously funded by an E-Team Grant from the National Collegiate Inventors and Innovators Alliance.

Bench Testing

Knee Flow Model

In order to simulate to test the basic idea of filtration via porous UHMWPE, a bench knee fluid model was setup using a custom-machined chamber (polycarbonate) along with an Arduino (microcontroller) to control a DC pump to provide an oscillatory flow regimen as is seen in the knee.[6] A sample of bovine serum containing wear debris is taken before an experiment and after an experiment to determine changes of particle concentration. An experiment consists of running the oscillatory flow pump at 1 hz for 1 hour continuously simulating a day's worth of walking.

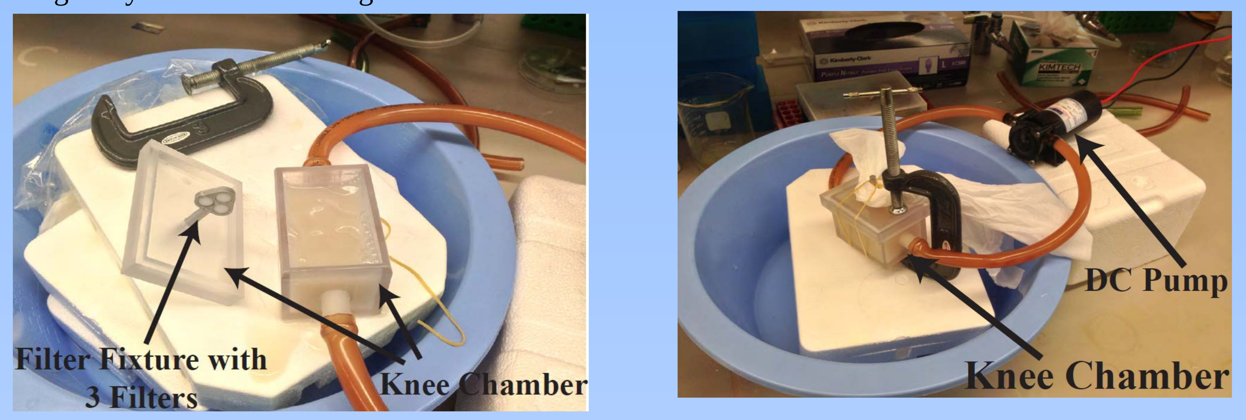


Figure 4: Bench Knee Flow Model

Custom MATLAB Particle Quantification Algorithm

Due to the small size of the wear particles, the most common method of counting or quantifying wear particle concentrations in synovial fluid has involved digesting out the albumin (HCL for these experiments), filtering the digested solution, and SEM imaging and counting the particles. However, due to the nonhomologous nature of wear debris in shape, size, and intensity, counting these particles manually can provide high variation in absolute counts. Even with sophisticated commercial algorithms, there has been difficulty in obtaining accurate absolute counts. In this case, since our experiments are looking for a change in particle concentration, we developed a custom MATLAB based algorithm to count these particles and conduct analysis to assess efficacy of the filter in removing these immunogenic wear debris.

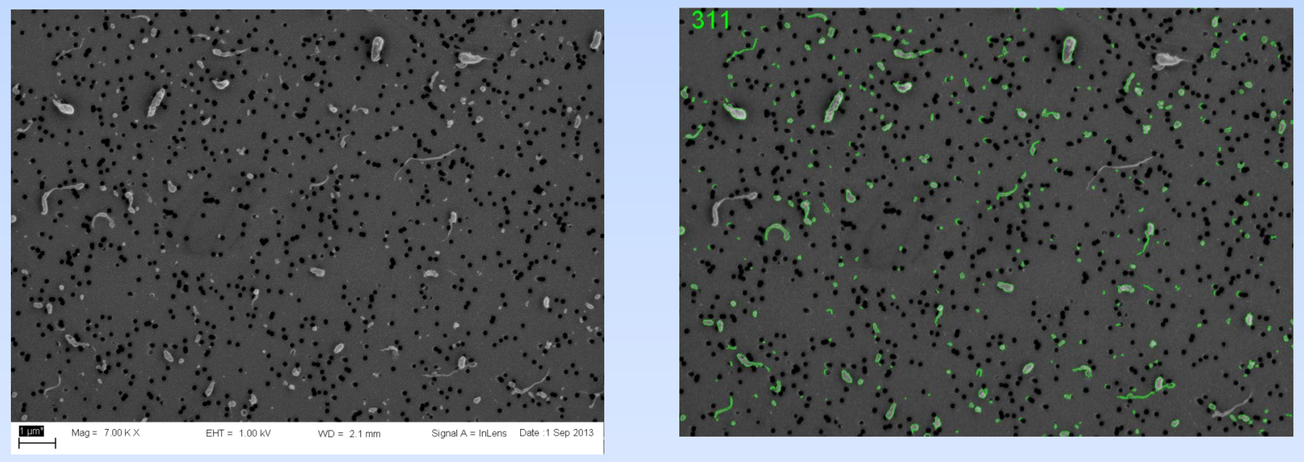


Figure 5: MATLAB Algorithm

(left) SEM imaging of particles on filter. (right) Output of algorithm demonstrating its ability to accurately identify and count particles.

Preliminary Results

Initial results, while showing high variability, confirm that the porous UHMWPE filter is able to collect particles with an initial 10% reduction of particles from the synovial fluid. The algorithm outputs the following data including the absolute particle distribution, the percentage particle distribution, as well as absolute and fraction reductions of particles for given particle sizes. The ability for the algorithm to organize the data in this way helps assess the efficacy of the filter for different particle sizes.

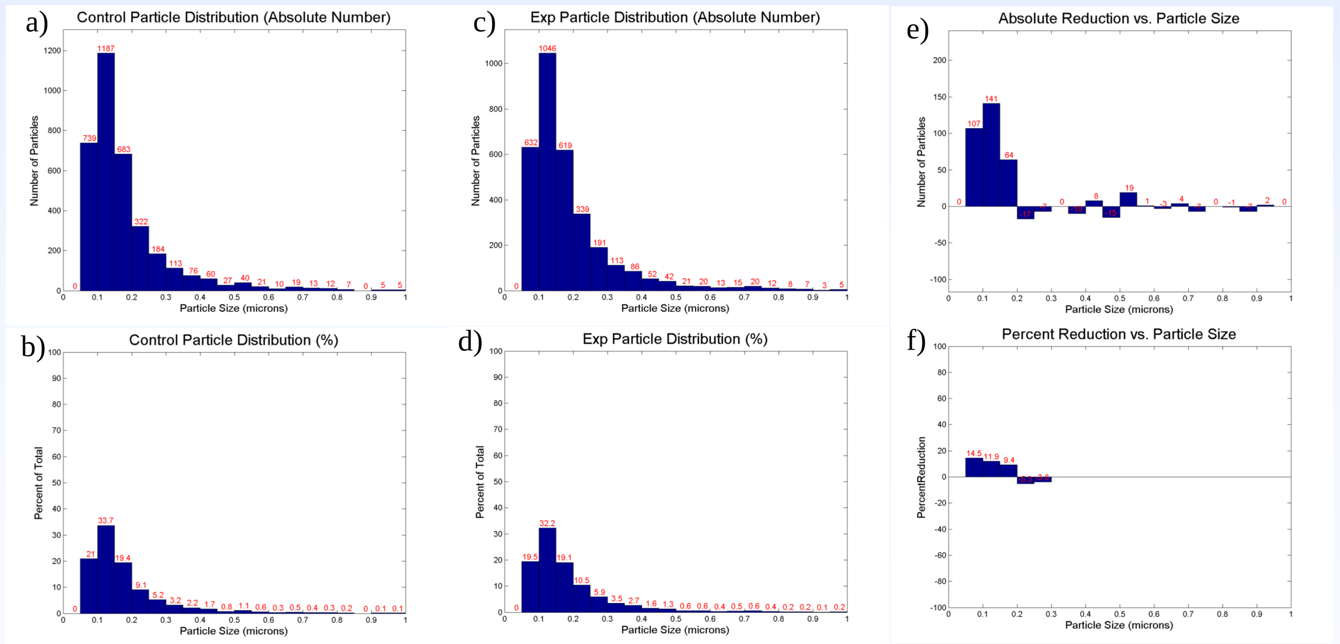


Figure 6: Preliminary Results

a) Control (Before Experiment) Absolute Particle Distribution b) Control Percentage Particle Distribution c) Experimental (After Experiment) Absolute Particle Distribution d) Experimental Percentage Particle Distribution e) Absolute Reduction of Particles f) Percentage Reduction of Particles

References

[1] Busija, L., Bridgett, L., Williams, S. R. M., Osborne, R. H., Buchbinder, R., March, L., & Fransen, M. (2010). Osteoarthritis. *Best practice & research. Clinical rheumatology*, *24*(6), 757-68. doi:10.1016/j.berh.2010.11.001
[2] Zhang, Y., Nevitt, M., Niu, J., Lewis, C., Torner, J., Guermazi, A., Roemer, F., et al. (2011). Fluctuation of knee pain and changes in bone marrow lesions, effusions, and synovitis on magnetic resonance imaging. *Arthritis and rheumatism*, *63*(3), 691-9. doi:10.1002/art.30148
[3] U.S. Orthopedic Joint Replacement Market. (2007).*Frost & Sullivan*. Retrieved November 20, 2008, from http://www.frost.com/c/10024/sublib/display-report.do?ctxixpLink=FcmCtx3&searchQuery=US+artificial+joint&bdata=aHR0cHM6Ly93d3cuZnJvc3QuY29tL
[4] Patient Demographics: Information about Orthopedic Patients and Conditions. (2008).*American Academy of Orthopedic Surgeons*. Retrieved September 2, 2008, from http://www.aaos.org/Research/stats/patientstats.asp
[5] London, N. J., Miller, L. E., & Block, J. E. (2011). Clinical and economic consequences of the treatment gap in knee osteoarthritis management. *Medical hypotheses*, *76*(6), 887-892
[6] Pedowitz, R. A., Gershuni, D. H., Crenshaw, A. G., Petras, S. L., Danzig, L. A., & Hargens, A. R. (1989). Intraarticular pressure during continuous passive motion of the human knee. *Journal of Orthopaedic Research*, *7*(4), 530-537.