Non-Invasive Active Acoustics as Biomarkers of Early Periprosthetic Joint Effusions: A Cadaveric Study

Rahul Kant Goel[1], Quentin Goossens, H. Trask Crane[2], Goktug Ozmen, Omer Inan, Ajay Premkumar
[1]Emory University, [2]Georgia Tech

INTRODUCTION:

Total joint arthroplasty (TJA) has been shown to consistently relieve pain, and improve mobility and quality of life for patients with end-stage degenerative joint disease. Unfortunately, approximately 1-2% of all TJA patients develop a periprosthetic joint infection (PJI) following surgery, a devastating complication with severe health and socioeconomic implications. PJI is responsible for 15% and 25% of all revision hip and knee procedures, respectively. However, there is currently no single reliable test that is both sensitive and specific to early diagnose all types of PJI, especially testing for progression in curing PJI. PJI causes effusions in the joint space, and early detection and frequent monitoring of this effusion can inform orthopaedic surgeons on the potential development of PJI. Currently, there is a lack of available simple and operator independent non-invasive tools to detect small (<60 ml) effusions within the knee joint and characterize these effusions. This information can be used to specify further clinical or laboratory investigations. Vibration analysis is a widely used technique for conducting non-destructive tests on mechanical structures to assess their structural integrity. In this technique, a controlled dynamic response is obtained by applying a stimulating vibration. Recent studies have demonstrated the utility of active vibration analysis as a promising non-invasive and easy to use technique for evaluating the structural integrity of biomechanical systems. This study presents a novel application of non-invasive active vibration analysis, referred to as active acoustics, to detect, monitor, and potentially characterize periprosthetic joint effusions.

METHODS:

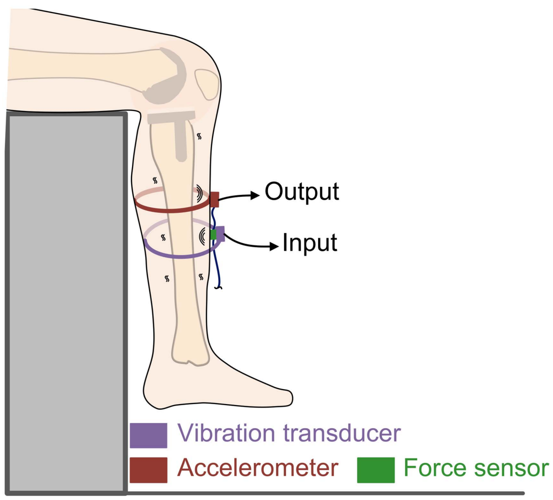
Seven fresh frozen hip-to-toe cadaver specimens were included in this study. The specimens were obtained from individuals having an average age of 80.6 ± 10.2 years and BMI 26.0 ± 4.9 kg/m^2 and the specimens were fully thawed overnight prior to the experiments. All seven specimens had knee replacements: three cruciate retaining total knee arthroplasties (TKA), three posterior stabilizing TKA, and one unicondylar partial knee arthroplasty. Different levels and types of effusion stages were simulated by injecting up to 80 ml with 20 ml increments of saline and methicillin-susceptible Staphylococcus aureus (MSSA, 10^8 CFU/ml) solutions into the joint space. Active acoustics were recorded at each effusion stage, while the specimens were in a supported 45° flexion position. The tibia was excited by a miniature vibration motor that was attached to the skin at the medial surface of the mid-diaphysis. A swept frequency cosine excitation signal with a frequency band between 200 Hz and 5000 Hz and a total duration of 30 s was used to excite the tibia. A force transducer (1022V, Dytran, USA) was placed between the vibration motor and the skin to measure the input force of the vibration motor. The output acceleration was measured using a lightweight accelerometer approximately 2.5 cm proximal to the input. Both sensors and the motor were attached to the skin using double-sided adhesive tape and an elastic band surrounding the lower leg. **Figure 1** shows an overview of the experimental setup. Input / output frequency response functions (FRF) were calculated and the normalized spectral band power (BP) in varying frequency bands were extracted from the FRFs for each effusion step. Pearson's correlation coefficients (r) were calculated between the BP and the injected volume. A two-sample *t*-test was used to compare means of normally distributed samples at different injection levels, otherwise a Wilcoxon rank sum test was used.

RESULTS:

A total of 35 effusion stages were measured over all specimens, two data points were excluded due to insufficient measurement quality. The BP in the 1255 ± 228 Hz spectral band showed to be highly correlated (Pearson's r = 0.83) with the injected volume over all specimens as shown in **Figure 2**. Within specimen Pearson's r varied between 0.80 and 1.00. The BP corresponding to 20 ml and 40 ml injected volume showed to be significantly higher than the baseline (0 ml) (p = 0.030 and p = 0.001, respectively). The BP showed to be on average lower for purely bacteria solution compared to purely saline solution, however this difference was not significant.

DISCUSSION AND CONCLUSION:

The high correlation between BP and injected fluid volumes demonstrates the potential utility of wearable and non-invasive active joint acoustics to quantify extremely small (20 ml) effusions in patients with total knee arthroplasties. The use of active acoustics to discriminate bacteria and saline effusions demonstrates promise but requires more data to be confirmed. The presented approach demonstrates the feasibility of developing future wearable effusion monitoring systems to timely inform orthopaedic surgeons on the presence and potentially the characterization of small periprosthetic effusions.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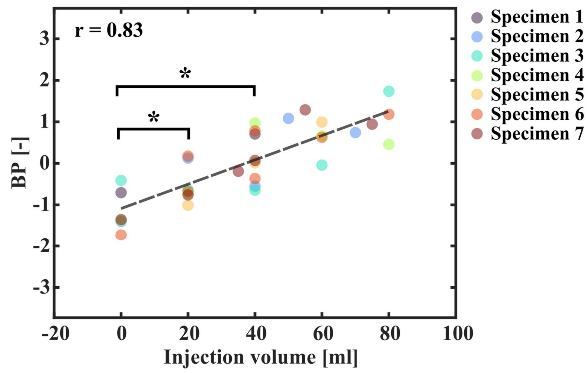
r = 0.83
*
*
BP [-]
Injection volume [ml]
-20
0
20
40
60
80
100
3
2
1
0
-1
-2
-3
Specimen 1
Specimen 2
Specimen 3
Specimen 4
Specimen 5
Specimen 6
Specimen 7