Electromechanical characterization of novel composite structures for spine implants

Perea RD, Friis EA
University of Kansas, Mechanical Engineering, Lawrence, KS

Statement of Purpose: Many different electrical stimulation methods are currently used to enhance bone growth in spine fusion. In this study, the feasibility of a novel electrical stimulation method using piezoelectric materials embedded into metallic cellular solid structures is presented. This new methodology will present direct electrical stimulation in the area implanted while suppressing the use of external electric power supplies and then compared to previous reported bone electrical stimulators [1]. Over the last 30 years, limited work has been done to study the use of piezoelectric materials to enhance bone growth [2], but little work has been tailored to the development of ductile materials suitable for application in lumbar spine fusion. Metal-piezoceramic cellular composites with different geometric dimensions were handcrafted and characterized electro-mechanically. Finite elements analysis (FEA) was used to validate the experimental results, design optimal structures, and understand the influence of manufacturing parameters.

Methods Ductile honeycomb cellular solids with inverted segments were manufactured using 302 stainless steel and lead zirconate titanate (PZT-5A) piezoplates (n=5). Structures with two different relative densities were created by varying the thickness of the metal struts. 302 SS strips were cut and bent to 60 degrees and piezoplates were embedded and bonded in the middle surfaces with conductive epoxy (Figure 1). The structures were placed into a servo hydraulic MTS system (Mini Bionic 858, MTS, Eden Prairie, MN) with insulating interfaces to avoid electrical charge dissipation and short circuiting. Structures were subjected to 10 sine wave cycles of axial compression at two different frequencies (1Hz and 2Hz) up to strain levels of 0.01, 0.02 and 0.04. Axial force, axial displacement, alternated voltage, direct voltage and direct current were recorded. An electronic circuit was built to rectify the alternated signal. Direct current was calculated by Ohm's law using a known resistor value (475kΩ). FEA with quadrilateral 2D plane–strain elements was utilized to verify the stress distribution at interaction points between the piezoelectric plates and the metallic cellular solids at different bonding states.

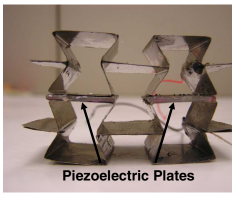

Figure 1. Inverted honeycomb structure

Results: Representative electrical output for a structure up to 0.01 strain is presented in Figure 2. The electrical signals presented a significant peak-to-peak voltage of 600mV. DC voltages were around 80mV with dc currents of 0.3μA, respectively. High voltage drops in electronic components explained the decrease in magnitude between dc and ac voltages, which will directly affect dc current. Higher relative density structures generated higher currents due to greater load transfer, as confirmed by FEA. However, there was significant variation in electrical outputs in all structures, primarily due to manufacturing limitations. FEA analysis demonstrated that even small variance in manufacturing assembly could lead to uneven loading transfer to the piezoelectric plates, thereby significantly reducing and varying electrical output. FEA showed that the compressive stresses were located primarily at the edges and demonstrated the sensitivity of appropriate interface bonding, which explains the variability in experimental results as confirmed by microscopic analysis. These results suggest an improvement of the design to maximize electrical output of the structure.

The direct electrical currents found were smaller than the range reported in literature as effective in stimulating osteogenesis (0.75–20 μA) [3,4]. Superior manufacturing techniques and adequate electronic components with smaller voltage drops could be used in these ductile structures. Higher levels of direct electrical current generated would then be within the range required for osteogenesis.

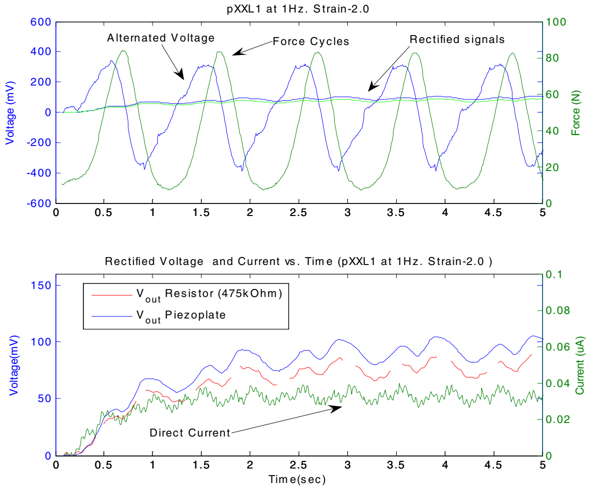

Figure 2. Representative electrical signals.

Conclusions: This study demonstrated proof of concept that metal-ceramic structures can be designed to successfully convert the mechanical energy into electrical energy at levels appropriate for stimulating osteogenesis. Adequate electronic components, better manufacturing processes, and more efficient structure geometries could lead to a promising new generation of spine fusion devices that could withstand mechanical loading and simultaneously provide self-generated electrical stimulation that is proven to enhance osteogenesis.

References:

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