Towards a Bionic Spine: Kinodynamic Holistic Spine Modeling and Development of Novel Implants for Spinal Restoration

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Diseases of the spine are a leading cause of disability worldwide, and the global prevalence is growing due to an aging population. Low back and neck pain are one of the leading causes of years lived in disability in most countries and age groups globally [1]. Compression of neural elements and instability of spine can result from degeneration, trauma, deformity, tumors, infections or hematoma [2,5]. Spinal fusion is performed to decompress neural elements, restore stability, and relieve pain [2,3]. Fusion is usually accomplished with implanted fixation devices, which alter the normal range of motion of the spine resulting in higher stress on the adjacent vertebrae. As a result, long-term complications include accelerated degeneration, failure of the fusion or hardware and chronic pain [4].

For many spine diseases, there are no current alternatives to fusion, which relies on decades-old fixation and arthrodesis technology (Figure 1A). This stands in contrast to advances in robotics, medical imaging, computational design, and materials science that present an unprecedented opportunity to make revolutionary advances in the restoration of the human spine for pain-free dynamic movement.

The overarching vision of this multi-disciplinary effort is to fundamentally transform the treatment of human spine disorders using bionic devices (see Figure 1B) that requires the innovative application of robotics to produce devices that are not only biocompatible but also operate in physiological harmony and facilitate normal biomechanics within the human body. In the long-term, the key engineering systems we seek to build to realize this vision are: (1) a spine disorder diagnostics and treatment planning platform that integrates medical imaging and captures the kinematics and dynamics of the spine based on the actual geometry and physiological properties of spine components; (2) a system for the design and manufacture of implantable bionic devices that leverages the kinodynamic model and integrates topological design and 3D printing of multifunctional biocompatible materials; (3) a function and integration assessment tool for evaluating the effectiveness of the bionic spine and for longitudinal study for life-span modeling and prediction.

Within the context of this long-term vision, the *research objectives* of this seed-grant proposal are to: (A) Develop a kinodynamic model and computer simulation of the lumbar region of the spine (lower back) that incorporates the geometry of the so-called *three-joint complex* [6] which is a basic building block of the spine (B) Develop algorithms and techniques for topology optimization-based computational design of two types of implantable devices, namely, one that can mimic the role of a single vertebra and one that can mimic the role of the facet capsule and constrain the motion between adjacent vertebrae (C) Perform preliminary feasibility studies on multifunctional biocompatible materials that can be used for manufacturing the bionic devices with desirable mechanobiological properties. The merging of robotics inspired technologies with spine restoration would represent the first major effort to develop endoskeleton bionic devices that can co-exist within the human body for the restoration of spine functions including protection of the nervous system, structural support, and dynamic motion.