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ORIGINAL ARTICLE

Biomechanical analysis of the camelid cervical intervertebral disc

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Summary Chronic low back pain (LBP) is a prevalent global problem, which is often correlated with degenerative disc disease. The development and use of good, relevant animal models of the spine may improve treatment options for this condition. While no animal model is capable of reproducing the exact biology, anatomy, and biomechanics of the human spine, the quality of a particular animal model increases with the number of shared characteristics that are relevant to the human condition. The purpose of this study was to investigate the camelid (specifically, alpaca and llama) cervical spine as a model of the human lumbar spine. Cervical spines were obtained from four alpacas and four llamas and individual segments were used for segmental flexibility/biomechanics and/or morphology/anatomy studies. Qualitative and quantitative data were compared for the alpaca and llama cervical spines, and human lumbar specimens in addition to other published large animal data. Results indicate that a camelid cervical intervertebral disc (IVD) closely approximates the human lumbar disc with regard to size, spinal posture, and biomechanical flexibility. Specifically, compared with the human lumbar disc, the alpaca and llama cervical disc size are approximately 62%, 83%, and 75% with regard to area, depth, and width, respectively, and the disc flexibility is approximately 133%, 173%, and 254%, with regard to range of motion (ROM) in axial-rotation, flexion-extension, and lateral-bending, respectively. These results, combined with the clinical report of disc degeneration in the llama lower cervical spine, suggest that the camelid cervical spine is potentially well suited for use as an animal model in biomechanical studies of the human lumbar spine.

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Introduction

Chronic low back pain (LBP) is a prevalent global problem, which is often correlated with degenerative disc disease. Available treatments for patients with chronic LBP have dismal satisfaction rates, and the development of novel treatments is hampered because we lack a testing model to effectively verify safety and efficacy.

Current *ex vivo* testing methodologies provide exceptionally useful information. For example, numerical analysis studies help analyse nutrient flow and mechanical flexibility; spine simulators may verify the numerical studies or provide benchmark comparison data for future devices; benchtop testing protocols using cadaver specimens increase our confidence in devices prior to FDA approval; and bioreactors allow testing cellular therapies. However, none of these models can demonstrate *in vivo* efficacy of treatments, thus the design/prototype/test cycle common to engineers is limited by the burdensome regulatory process required for human testing. In order to accelerate development of better treatments for LBP, a more readily accessible and characteristically similar model of the human condition is required [1,2].

Animals are an important part of biomedical research of the spine [1—4]. Each animal model has distinct advantages and disadvantages, yet no animal is capable of perfectly replicating the environment of the human spine, nor the degenerative condition of the human intervertebral disc (IVD), which has been linked with LBP. Age-related IVD degeneration is a virtually universal condition for humans yet remains largely absent from most of the animal kingdom. Only a few species are known to spontaneously degenerate: various canine breeds [5], ovine, and some primates (macaque monkeys and baboons) [6—8]. Of this group, only dogs have been reported to experience pain [5]. However, this pathology is limited to certain dog breeds that develop a condition called chondrodystrophy, which is genetically dissimilar from the typical course of disc degeneration observed in humans. Sheep have presented degeneration in their lumbar spine [9,10], but require further validation testing before wide acceptance. Also, while similarities may be drawn between the gravity load on the human spine and the muscle load on the quadruped spine, there remains much to learn about the effects of the differences in the biomechanical loading environment. Ethical concerns pre-emptively reduce our willingness to promote testing on primates [7,8,11—14].

Animal models of the spine have proven exceptionally useful in evaluating IVD mechanics and biomechanical changes due to induced disc degeneration [1,2,15]. However, there are fundamental differences in the biomechanical loading observed in the spine of most quadrupeds as compared with that of humans. Oriented resistance to gravity loading is a fundamental loading condition associated with erect posture and ambulation in humans, and most quadruped spines lack this characteristic, particularly in the lumbar spine. Many species of quadrupeds lack the range of motion (ROM) exhibited by human spines, particularly in axial rotation and flexion. Both humans and quadrupeds exhibit additional compressive loading due to the intermediate and deep muscle loading and prestrain in passive stability elements (i.e., ligaments and fascia) of the spine, which varies by location [1,16], but the human lumbar spine exhibits a characteristic lordotic curvature that is in stark contrast to the kyphotic curvature in the lumbar region of quadrupeds. This difference in curvature contributes to a different loading condition and biomechanical motion profiles [17] for the IVD.

Painful degenerative disc disease was first documented in llamas in 2006 [18], and prompted our interest in investigating biomechanical and anatomical similarities between camelid and human spines, with the aim of determining the appropriateness of using camelids (specifically llamas and alpacas) as preclinical models for spine treatments. We aim to address key characteristics of a good animal model for the human IVD, including biomechanical flexibility testing, and disc morphology (shape and size) [18]. The purpose of this paper is to report on our findings for the camelid cervical IVD in the context of providing an animal model of the human lumbar IVD.

The camelid is skeletally mature by the age of 2 years and typically lives for 15—20 years. The spine consists of seven cervical vertebrae, 12 thoracic, seven lumbar, five sacral, and 11—17 caudal vertebrae. In general, the cervical vertebrae are relatively long compared to their transverse geometry, with the exception of the atlas (C1) and also the C7 vertebra, which is noticeably shorter than the other cervical vertebrae. The cervical vertebrae also have noticeable differences from the human lumbar vertebrae; specifically, the camelid vertebrae have two sets of lateral masses: cephalic and caudal protrusions extend ventrally to protect the blood vessels, trachea, and oesophagus. The vertebrae transverse-sectional geometry is smaller in the mid-transverse section and expands outward near the endplates. The cervical IVDs get larger with the lower segments, which is similar to the human lumbar spine. The facet joints of the camelid spine are similar in size to the human spine; however, the orientation is more vertical, and appears to act as a stabilizing guide during axial-rotation, rather than a hard-stop motion limiter during extension and/or lateral-bending motions, as seen in humans.

Materials and methods

Cervical spines were obtained from four alpacas and four llamas immediately following slaughter for purposes unrelated to this study. The spine specimens were further segmented into individual functional spinal units (FSUs) ranging from C2C3 to C7T1 for various studies, including flexibility/biomechanics, and morphology/anatomy. Each animal was young (2—4 years), but skeletally mature, and healthy with no known spinal disorders. Alpaca and llama test-specimens were obtained from a local, United States Department of Agriculture (USDA)-funded, camelid research center (The Camelid Center, Moroni, UT, USA). The center has a significantly larger population of alpacas as compared to llamas, thus these animals were more readily available and constitute the bulk of our testing specimens, and a limited number of llama specimens were also obtained for comparison based on availability.