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Neurosurg Clin N Am 16 (2005) 589–594

NEUROSURGERY
CLINICS
OF NORTH AMERICA

Cervical Spine Arthroplasty Biomechanics

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In the last few years, interest in so-called ''motion-sparing'' or ''motion-preserving'' spinal technologies has dramatically risen. In many cases, the goal of motion preservation has been to design instrumentation or effective strategies that target the diseased intervertebral disc. These devices range from repair of local defects, such as annular tears, to complete replacement of the disc. This survey article focuses solely on the latter and attempts to give the reader a general overview as to the goals of cervical disc replacement, the current state of knowledge concerning how these devices have been evaluated, and a commentary on future work that should be performed to characterize these devices better. These issues are described from a biomechanical perspective, which is a challenging task, given the limited knowledge that currently exists. This is mainly attributable to the fact that although the literature (especially from Europe) is replete with early follow-up studies [1–4], case reports [5,6], survey articles [7–10], and materials consideration with regard to disc arthroplasty designs [11–13], the number of peer-reviewed publications on the biomechanical aspects of cervical disc replacement is quite small in comparison.

Motivation and design goals of cervical arthroplasty

Cervical radiculopathy refers to pain or motor dysfunction that is caused by mechanical deformation and/or inflammation of the nerve roots in the cervical spine. The cause of radiculopathy can be discogenic. When conservative management fails to alleviate the pain and neurologic deficits caused by disc herniation, the patient is given the option of surgical decompression of the affected nerves and spinal cord. Cervical decompression is most often accomplished via partial or complete removal of the diseased disc, providing immediate relief of pressure to the spinal cord and associated nerve roots, and most cervical discectomies are augmented by the insertion of a bone graft and introduction of a plate that spans the adjacent vertebral levels to promote a solid fusion between adjacent vertebrae (commonly referred to as anterior cervical discectomy and fusion [ACDF]). Although ACDF has proven to be a successful procedure [14], fusion of a relatively mobile spinal segment is not an ideal reconstruction and can potentially lead to deleterious long-term iatrogenic effects. For example, various clinical and biomechanical studies have postulated that fusion produces heightened stresses on the discs above and below the fusion, which is commonly manifested as accelerated degeneration of the adjacent motion segment [15–17]. The clinical result is adjacent segment instability, which requires additional operative intervention [18].

The main aims or goals of disc replacement were largely conceived because of the shortcomings associated with fusion. The primary focus of a cervical intervertebral disc arthroplasty device is to restore or maintain cervical disc motion after an anterior cervical discectomy. The prosthesis is designed to act as an intervertebral body spacer that maintains disc space height and spinal

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1042-3680/05/$ - see front matter
doi:10.1016/j.nec.2005.07.002

decompression while theoretically reducing the likelihood of accelerated degeneration in adjacent discs through the preservation of normal disc kinematics at the affected disc level. In addition, it should impart stability to the affected area that approximates what is normally seen in the native spine. Finally, and this point is often overlooked, if the disc arthroplasty fails (eg, leads to painful pseudoarthrosis), the implantation of a disc arthroplasty device should not preclude or significantly complicate a subsequent fusion procedure.

Given that the main aim of the cervical disc device is to maintain motion, it is important to review the ranges of "normal" or "physiologic" motion that are typically present at the lower cervical (C4–C7) spine levels. The most often cited spinal kinematic data come from the classic text of White and Panjabi [19], wherein they describe ranges of combined flexion-extension, one-side lateral bending, and one-side axial rotation that have been reported by various authors. The authors also offer representative values that fall in the middle of these ranges. Table 1 summarizes these data. It is clear that all three motion planes exhibit a relatively high degree of mobility at all three lower cervical levels. Another factor that further complicates trying to define explicitly a stated motion target for the various arthroplasty designs is that there exists a large disparity in the amount of motion afforded at each level across the general population. This finding is evidenced by the large possible ranges of sagittal, transverse, and frontal plane possible ranges of motion given in Table 1. Nevertheless, the goal of most disc arthroplasty designs is to attempt to approximate the normal spinal kinematics as much as possible. The guiding rationale behind these designs is that preservation of motion, even if it is less than what one would expect if the disc were healthy, still results in a better long-term outcome than if only a relatively minute amount (in the limit, fusion) is left after an operative procedure.

Many designs have been advocated as replacements for cervical intervertebral discs (Fig. 1). Most of these implants consist of metallic or polymeric components. Some, by the nature of their geometric design, limit the amount of possible motion in certain planes or do not provide for coincident translation during rotation (often referred to as constrained or semiconstrained). Other devices rely on the perispinal soft tissue architecture and the inherent compression across the disc space (commonly called unconstrained prostheses) to provide support and restrict the end limits of motion and translation. The design rationale for many of these implants is to try not only to replicate the kinematics of the cervical spine but to mimic the physiologic center of rotation. Thus, based largely on the geometry of the articulating surfaces, the center of rotation is fixed within the body of the implant or in the adjacent inferior or superior vertebral body. As is outlined elsewhere in this article, these design differences have had little impact on the overall acute kinematics and kinetics, and their effect on the load profile of the spine has yet to be elucidated or has not been reported.

Peer-reviewed biomechanics literature

Given the aforementioned design rationale and the increasing interest in spine arthroplasty, it is not surprising that the actual kinetic and biomechanical effects that cervical disc arthroplasty imparts on the spine have started to become more widely reported. Almost all the biomechanical studies have used cadaveric models and compared the ranges of motion of the intact spine and after implantation of the device. These studies have

Table 1

	Combined flexion-extension		Unilateral Lateral Bending		Unilateral Axial Rotation	
Disc level	Possible range	Representative value	Possible range	Representative value	Possible range	Representative value
C4-C5	13–29	20	0–16	11	1–12	7
C5-C6	13–29	20	0–16	8	2–12	7
C6-C7	6–26	17	0–17	7	2–10	6

Data illustrating the native or normal range of motion that is present at each level in the lower cervical spine in combined flexion-extension, unilateral lateral bending, and unilateral axial rotation. The data indicate that the possible ranges are quite large, reflecting the significant variability across the population.

Data from White AA, Panjabi MM. Clinical biomechanics of the spine. 2nd edition. Philadelphia: Lippincott; 1990.

Device	*Prestige*	*Bryan*	*Prodisc-C*	*CerviCore*	*PCM*
Image					
Articulating Materials	Metal - Metal	Metal - UHMWPE	Metal-UHMWPE	Metal-Metal	Metal - UHMWPE
Theoretical Center of Rotation Location	Superior Vertebra	Within Implant	Inferior Vertebra	Superior and Inferior Vertebra	Inferior Vertebra
Initial Fixation	Screws	Milled Bone	Keels	Screws and Spikes	Ridges

Fig. 1. Tabulated data demonstrate the range of design factors of some current cervical intervertebral disc arthroplasty devices. (Courtesy of Medtronic Sofamor Danek, Inc, Cervitech, Synthes Spine, with permission.)

been performed to evaluate a number of different cervical arthroplasty disc designs that are, for the most part, widely available in Europe and undergoing investigational US Food and Drug Administration (FDA) clinical trial series in the United States. The following gives a brief summary of the various studies that have been reported in peer-reviewed journals.

Two different groups have reported on the biomechanical effects of implanting the Prodisc-C (Synthes Spine Solutions, West Chester, Pennsylvania) device in the cervical intervertebral space. The Prodisc-C is a semiconstrained device that uses an ultrahigh-molecular-weight polyethylene (UHMWPE) ball that articulates with a metal socket. The purported advantage of semiconstrained devices is that they resist allowing excessive motion, thus imparting an inherent stability to the intervertebral space. Many argue that these types of devices effectively fix the center of rotation, which is commonly thought to change as one moves through the ranges of motion of the different rotational planes. Puttlitz and colleagues [20] used pure moment loading, with and without a compressive follower load, to investigate how the implantation of the Prodisc-C changed, if at all, the kinetics of the spine. They looked at primary motions (flexion-extension, lateral bending, and axial rotation) and the coupled motion (motion in a plane that is secondary to the plane of loading) behavior of the spine. The data indicate that flexion-extension and axial rotation motion were not significantly altered after implantation of the device (Fig. 2). There was a significant difference in lateral bending motion without a compressive load; however, there was no difference in lateral bending motion before and after disc arthroplasty when a compressive load was applied (which probably more closely approximates the physiologic loading regimen). In addition, there were no significant differences in coupled motion at the affected level or at the levels above or below the level of implantation. DiAngelo and coworkers [21] also investigated the motion-sparing ability of the Prodisc-C implant. Using a displacement control protocol [22], they reported that there were no significant differences between the intact and implanted conditions for flexion, extension, and right or left lateral bending (Table 2). Taken together, these two studies seem to indicate that motion obtained with the Prodisc-C device, at least in the immediately postoperative period, simulates the native motion of the spine.

The Prestige Cervical Disc (Medtronic Sofamor Danek, Memphis, Tennessee) is a metal-on-metal ball and socket design with a trough in the anterior-posterior direction that allows for some translation in this direction during flexion and extension [23]. DiAngelo and colleagues [24] have also used a displacement protocol to investigate the kinematics of the Prestige device. They reported no significant differences in motion at the level of implantation before and after the device was installed. In addition, the motions at the superior adjacent and subadjacent levels were not significantly different as a result of implantation of the device.

The Porous Coated Motion (PCM; Cervitech, Rockaway, New Jersey) device is a cobalt chrome-on-UHMWPE device that allows some translational motion. The device is available in two variants: a ''low-profile'' version for cases in which the posterior longitudinal ligament (PLL) is spared and a ''fixed'' adaptation for when the

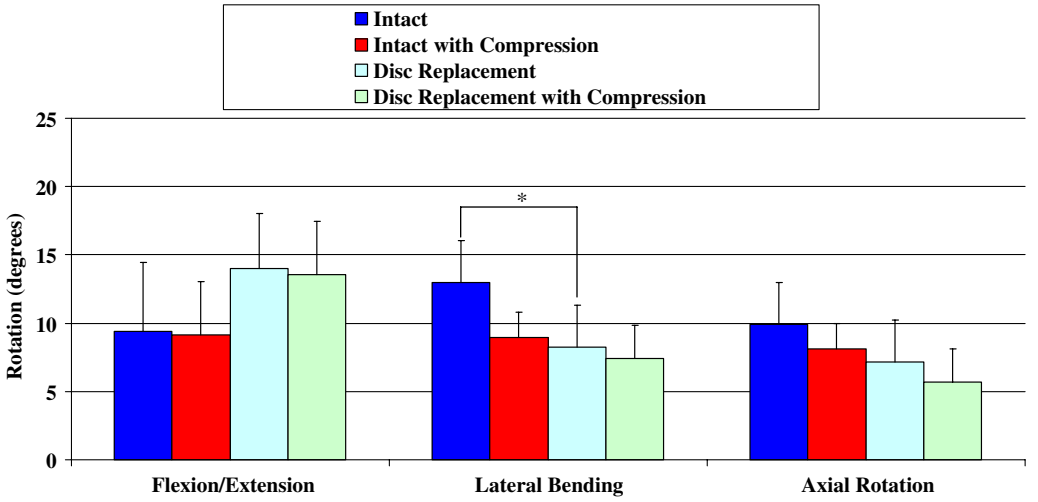

Fig. 2. Kinetic analysis of the Prodisc-C prosthesis. The data indicate that implantation of the device replicates the intact condition, especially when a compressive follower load is applied. The only significant difference ($P < .05$, designated by *) detected in this study was between the intact condition and after disc replacement in lateral bending. This difference was not evident when the follower load was applied. (*From* Puttlitz CM, Rousseau MA, Xu Z, et al. Intervertebral disc replacement maintains cervical spine kinetics. Spine 2004;29(24):2809–14; with permission.)

PLL is resected. McAfee and coworkers [25] have reported on a cervical cadaveric study that used a pure moment loading methodology to test the kinetic response of both devices after implantation. The data indicate that the low-profile and fixed PCM variants are capable of restoring the acute motion profiles of the intact spine.

The previous studies are characteristic of the data that have been reported from biomechanical investigations of the cervical spine. Other studies have started to use methodologies that try to discern the long-term performance of the devices, however. These tests were originally developed for total joint replacement (eg, hip, knee) and try to study other issues, such as wear debris generation and osseointegration for long-term fixation. Anderson and colleagues [26] reported on a series of high-cycle wear debris tests that they performed on the Bryan Cervical Disc (Medtronic Sofamor Danek). The Bryan device contains two titanium end plates with a polyurethane core that allows for completely unconstrained motion. The wear testing was performed in bovine serum at 37°C and involved applying 130 N of compression coupled with repeated loading of 4.9° of flexion-extension and 3.8° of axial rotation. The data indicate that there was a minimal height loss (0.75%) after 10 million cycles. Three test

Table 2

		Recorded moment	
Rotational plane	Applied global rotation (°)	Intact condition (N-m)	Bristol prosthesis (N-m)
Flexion	22.5 ± 0.6	0.57 ± 0.25	0.47 ± 0.28
Extension	23.0 ± 0.2	1.22 ± 1.30	0.23 ± 0.22
Right lateral bending	13.5 ± 0.3	0.55 ± 0.51	0.56 ± 0.49
Left lateral bending	11.5 ± 0.2	0.74 ± 0.40	0.59 ± 0.37

Kinematic evaluation of the Bristol cervical prosthesis. Using a displacement control protocol, the investigators applied a predetermined amount of global rotation and recorded the subsequent moment needed to affect this rotation. There were no significant differences in the moment recording between the intact condition and the disc arthroplasty device.

Data from DiAngelo DJ, Roberston JT, Metcalf NH, et al. Biomechanical testing of an artificial cervical joint and an anterior cervical plate. J Spinal Disord Tech 2003;16(4):314–23.

assemblies were allowed to run beyond these fatigue limits to 37.7, 39.7, and 40 million cycles. Data such as these provide important insight into the long-term survivorship of these implants.

Summary

The advent of cervical intervertebral disc replacement represents an exciting new frontier in the treatment of myelopathy and discogenic pain. The ability to retain motion at the treated level, minimally affecting the motion patterns at adjacent spinal levels, may represent an important step in reducing the incidence of adjacent segment disease. Nevertheless, there is still a good deal of biomechanical data that needs to be determined before these arthroplasty devices should be widely accepted and implanted. Specifically, as has been detailed previously, although many of the disc arthroplasty implants are capable of maintaining acute motion within the three anatomic planes of movement, couple movements between these planes (ie, axial rotation coupled with lateral bending) have not been thoroughly investigated. To achieve this goal, researchers must first develop testing protocols that involve multibody and multiaxis control systems as well as advance the state of complexity of current biomechanical testing systems to permit displacement, force, or hybrid (displacement with force feedback) control strategies.

There also exists a significant vacuum of knowledge concerning how spinal loading is altered with these devices. We would caution the reader that just because the current motion data suggest that physiologic kinematics and kinetics are maintained, this in no way implies that spinal loading is similarly restored. The native disc tissue is composed of a highly hydrated nucleus surrounded by a fiber-reinforced annulus. The mechanical behavior of these tissues is highly nonlinear and involves the use of fluid flow and hydrostatic support to counterbalance stresses that are seen during the activities of daily living. The currently available arthroplasty disc designs in no way resemble the native disc from a geometric or material property standpoint. Intuitively, from an engineering perspective, one would expect the load transmission profile in the cervical spine to be altered after implantation of these devices. Future studies using computational methods (eg, finite element technique) to investigate and predict cervical spine load transmission should greatly enhance the available knowledge base and facilitate the design of the next generation of disc arthroplasty designs.

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