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# Influence of the deviated center of rotation on facet joint degeneration after cervical disc replacement – an in vivo study with a minimum of 10-year follow-up

Kai Yan[1], Zhan Shi[1], Da He[1], Bo Liu[1], Bin Xiao[1], Qilong Wang[1] and Wei Tian[1*]

## Abstract

**Background** Short term results of the change of center of rotation (COR) after Bryan cervical disc replacement (CDR) have been reported. However, there is a lack of long-term studies focusing on the COR and its influences on facet joint degeneration.

**Objective** To evaluate the long-term clinical and radiographic results of Bryan CDR, and to explore the influence of deviated COR on facet joint degeneration at index level.

**Methods** It is a retrospective follow up study conducted in China. Eighty-three consecutive patients who received single-level Bryan CDR were retrospectively reviewed. Clinical evaluation included Japanese Orthopaedic Association (JOA) score, Neck Disability Index (NDI), and Odom's scale. Radiographic evaluation underwent before surgery, at early follow-up (3 months) and last follow-up (10 years). The radiographic parameters included range of motion (ROM), location of COR presented by the coordinates (COR-x, COR-y), and facet joint degeneration score. Correlation analysis was conducted between changes of COR and facet joint degeneration score.

**Results** Fifty-nine patients were included, with an average age of 44.6 ± 7.4 years. The mean follow-up time was 135.7 ± 12.4 (120–155) months. JOA score, NDI and Odom's scale showed significant improvements at last follow-up. The ROM was well preserved through follow-up. 33 patients (55.9%) showed deterioration of facet joint degeneration at index level. The increment of facet joint degeneration score at index level was strongly correlated with the change of COR-x ($r = 0.758$, $P < 0.001$), and weakly correlated with the change of COR-y ($r$=-0.473, $P < 0.001$). The deviation of COR was significantly greater in Group Degeneration than that in Group Non-degeneration (14.8 ± 10.5% vs. -2.6 ± 8.1% for COR-x, and − 6.4 ± 7.5% vs. 0.8 ± 8.3% for COR-y).

**Conclusions** Bryan CDR with minimum of 10-year follow-up achieved favorable clinical outcome and good maintenance of ROM. Deviated COR could be an important risk factor for facet joint degeneration.

**Keywords** Bryan cervical disc replacement, Range of motion, Center of rotation, Facet joint degeneration, Long-term follow-up

*Correspondence:
Wei Tian
tianwei202@yeah.net

[1]Department of Spine Surgery, Beijing Jishuitan Hospital, Capital Medical University, No. 31, Xinjiekou East St, Xicheng District, Beijing 100035, China

## Introduction

Over the recent 20 years, cervical disc replacement (CDR) has been established as a viable treatment option for symptomatic cervical degenerative disc disease (CDDD). Many clinical studies have demonstrated CDR to be an alternative technique to the gold standard anterior cervical discectomy and fusion (ACDF) with similar clinical outcomes and better preservation of segmental motion and lower rate of adjacent segment degeneration [1–11].

The goal of CDR is to restore physiologic mechanics at the index segment and the ideal prosthesis should accomplish this goal by restoring physiologic quantity and quality of motion. In fact, although the CDR procedure can preserve the range of motion (ROM) well, it can't fully mimic the physiologic quality of motion of cervical spine. The altered mode of motion will theoretically increase the stress on facet joints of the index level [12]. Many in vitro biomechanical studies have demonstrated that facet forces increase significantly after Bryan CDR, Prodisc-C CDR, Mobi-C CDR and Prestige LP CDR [13–19], and the maximal stress was at the lower tip of inferior facet cartilage in extension [15, 19]. However, there is a lack of long-term clinical studies focusing on the facet joint degeneration after CDR, and its relationship with the altered mode of motion (deviated center of rotation). Thus, the aim of this in vivo long-term follow-up study was to evaluate the long-term clinical outcome, the facet joint degeneration at index level, the deviation of center of rotation (COR) after Bryan CDR and its influence on facet joint degeneration.

## Materials and methods

### Patient Population

Between January 2008 and December 2012, 83 consecutive patients who underwent 1-level CDR for CDDD using Bryan artificial disc (Medtronic Sofamor Danek USA, Inc) in our institution were retrospectively reviewed. All patients had signed written informed consents for agreement of follow-up and the possibility of using their clinical and radiographic data.

### Inclusion and exclusion criteria

The inclusion criteria involved: (1) diagnosis of 1-level symptomatic CDDD, presented with either myelopathy, radiculopathy, or myeloradiculopathy; (2) age: 18–60 years; (3) ineffective conservative management for more than 6 weeks; (4) complete clinical and radiographic follow-up; and (5) a preoperative ROM at the index level > 3°. The exclusion criteria involved: (1) multi-level symptomatic CDDD, (2) ossification of posterior longitudinal ligament, (3) tumor or infection, (4) previous cervical spine surgery, (5) instability (translation > 3 mm and/or > 11 degrees of angular changes between adjacent segments), (6) severe index level facet degeneration, (7) inflammatory spondyloarthropathies (rheumatoid arthritis, ankylosing spondylitis), and (8) high level (grade III or IV) heterotopic ossification [20] at the last follow-up.

### Clinical evaluation

Japanese Orthopaedic Association (JOA) score [21] was used for assessment of the severity and functionary status of myelopathy, Neck Disability Index (NDI) [22] for neck pain/disability, Visual Analog Scale (VAS) for arm pain, and Odom's scale [23] for overall efficacy. JOA score and NDI were determined preoperatively and postoperatively at last follow-up, and the Odom's scale was assessed at last follow-up.

### Radiographic evaluation

Radiographic evaluation included plain X-ray and computed tomography (CT). Lateral neutral and flexion-extension cervical radiographs before surgery, at early (3-month) follow-up and at last follow-up were collected, and for the CT before surgery and at final follow-up. The ROM of the index level and overall cervical spine (C2-7) were measured on lateral flexion-extension radiographs according to the Cobb method [24]. COR was identified on lateral flexion-extension radiographs and its coordinates (COR-x, COR-y) were calculated by the method shown in Fig. 1, and this methodology had been validated in the literature [25–28, 39]. The severity of facet joint degeneration was identified quantitatively by CT using modified Walraevens' method [29]. The facet joint degeneration score (ranging from 0 to 5) consists of four variables (Fig. 2): (1) hypertrophy of facet joint (grading from 0 to 2), (2) osteophyte (grading from 0 to 1), (3) irregularity of articular surface (grading from 0 to 1), and (4) joint space narrowing (grading from 0 to 1).

The included patients were divided into two groups according to with or without deterioration of facet joint degeneration at index level. Cases with at least 1 score of increment of the facet joint degeneration score at last follow-up compared with preoperative status were defined as Group Degeneration. Cases with no increment of the facet joint degeneration score were defined as Group Non-degeneration. The change of COR-x and COR-y were compared between these two groups.

### Statistical analysis

Statistical analysis was performed with IBM SPSS Statistics 20.0 (SPSS, Chicago, IL, USA). Normality of continuous variable data was assessed by Shapiro–Wilk test. The continuous variable data is presented as mean ± standard deviation. The ordinal data or continuous data which does not comply with normal distribution is presented as median (interquartile range). Paired t-test was used to assess changes of continuous data

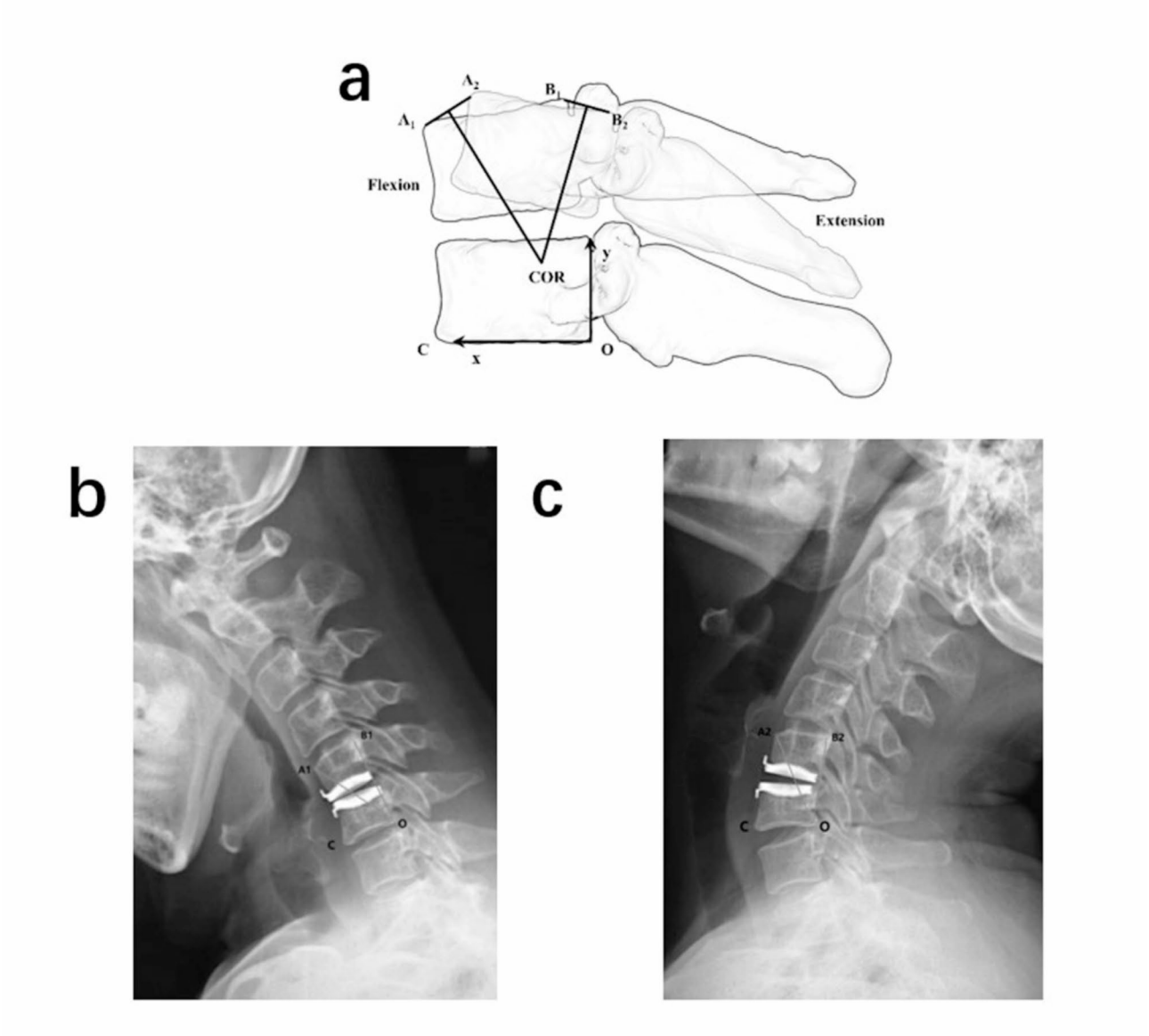


**Fig. 1** Schematic diagram showing how to determine the location of COR. **a** Make two points of the cranial vertebra in flexion (point A1 and point B1) and in extension (point A2 and point B2). The location of COR is the intersection of perpendicular bisectors of line A1A2 and B1B2 which is expressed as the coordinates (COR-x, COR-y) in an orthogonal plane coordinate system. The coordinates COR-x and COR-y are normalized as percentage (%) of the inferior endplate length and posterior height of the caudal vertebra body separately **b-c** Actual measurement of the COR in flexion and extension radiographs. The posterior inferior corner of the caudal vertebra (point O) is set as origin of coordinates, and the inferior endplate (line OC) is set as x-axis. Analytical geometry method is used to calculate the coordinates of COR after measuring the coordinates of points A1, A2, B1 and B2

with normal distribution. Wilcoxon signed-rank test was used for paired ordinal data or continuous data which does not comply with normal distribution. Spearman's rank correlation analysis was used to assess correlation between two variables. Student t-test was used to compare means of continuous data with normal distribution between groups. A two-tailed p value $<0.05$ was considered significant. All measurements were performed by two independent spine surgeons following standardized criteria. The reliability of grading the facet joint degeneration score and determining the location of COR was evaluated by intra-class correlation coefficient (ICC). The ICC was graded as follows: excellent for ICC $>0.75$, good for 0.61–0.75, fair for 0.41–0.60, and poor for 0.0–0.40.

## Results

### General information

Eighty-three patients were initially reviewed, and a total of 59 patients (35 men and 24 women) were included at last, with a mean age of 44.6±7.4 (26–56) years old at operation time. The surgery levels included C3/4 (1 patient), C4/5 (13 patients), C5/6 (38 patients) and C6/7

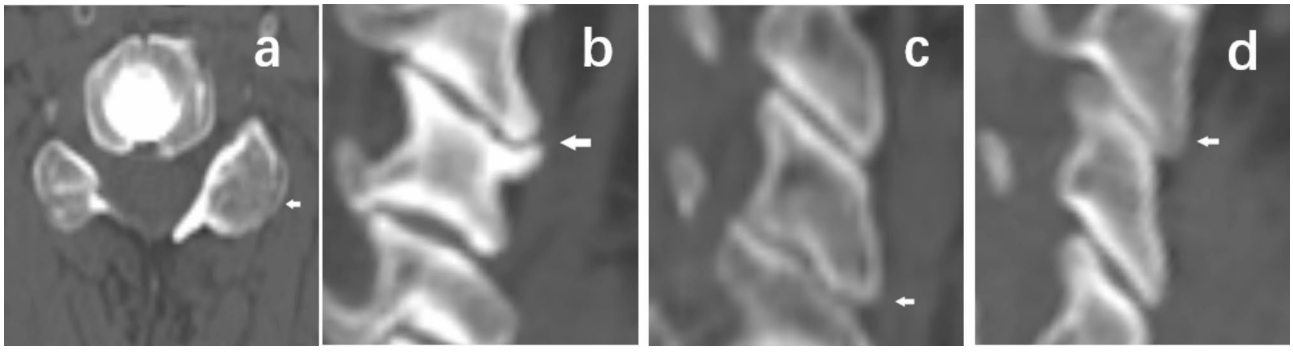


**Fig. 2** Evaluation of facet joint degeneration by CT scan, with the white arrow pointing the degenerated facet joint. **a** Hypertrophy of facet joint, 1 point when hypertrophy is present on one side of the articular surface, and 2 points when it is on both sides. **b** Osteophytes, 1 point when osteophytes are present. **c** Irregularity of articular surface, 1 point when the articular surface is irregular. **d** Narrowing of joint space, 1 point when the joint space is narrowed

**Table 1** Baseline characteristics

| Variable | Value |
|---|---|
| Number of patients | 59 |
| Gender (female/male) | 24/35 |
| Age (years) | 44.6 ± 7.4 |
| Index level | |
| C3/4 | 1 (1.7%) |
| C4/5 | 13 (22.0%) |
| C5/6 | 38 (64.4%) |
| C6/7 | 7 (11.9%) |
| Follow-up time (months) | 135.7 ± 12.4 |

**Table 2** Clinical outcomes

| Variable | Preoperative | Last Follow-up | *P* value* |
|---|---|---|---|
| JOA score | 13.5 (12–15) | 16.5 (15–17) | < 0.001 |
| NDI | 26.0 (22–32) | 12.0 (10–18) | < 0.001 |
| VAS | 7.0 (6–8) | 0.5 (0–1) | < 0.001 |
| Odom's scale | | | |
| Excellent | | 30 (50.8%) | |
| Good | | 24 (40.7%) | |
| Fair | | 5 (8.5%) | |
| Poor | | 0 | |

The values are given as median (interquartile range), or number (percentage)

*Wilcoxon signed-rank test

JOA score, Japanese Orthopaedic Association score

NDI, neck disability index

VAS, Visual Analog Scale

(7 patients). The mean follow-up time was 135.7 ± 12.4 (120–155) months (Table 1).

### Clinical and surgical outcome

All the patients showed good relief of radiculopathy and/or myelopathy. The JOA score increased from 13.5 (interquartile 12–15) before operation to 16.5 (interquartile 15–17) at last follow-up ($p<0.001$). The NDI improved from 26.0 (interquartile 22–32) before operation to 12.0 (interquartile 10–18) at last follow-up ($P<0.001$). The VAS improved from 7.0 (interquartile 6–8) before operation to 0.5 (interquartile 0–1) at last follow-up ($P<0.001$). In terms of Odom's Scale, 91.5% of the patients reported good or excellent outcome (Table 2). Two patients presented self-limiting dysphagia postoperatively. There was no other complications such as esophagus injury, infection, hematoma, migration or subsidence of prosthesis, or revision surgery up to the over 10 years' follow-up.

### Range of motions

The range of motion (ROM) at index level decreased from 10.6 ± 4.0° preoperatively to 9.4 ± 4.0° at early follow-up ($p=0.042$), and maintained to the last follow-up (9.4 ± 4.0° vs. 9.6 ± 5.2°, $p=0.722$). The global (C2-7) ROM maintained from 46.9 ± 15.3° preoperatively to 45.4 ± 13.3°at early follow-up ($p=0.473$), and was well preserved (47.3 ± 13.2° ) to the last follow-up ($p=0.410$).

### Center of Rotation (COR)

The inter-rater and intra-rater reliability for determining location of COR were excellent, with ICC 0.89 and 0.91. The location of COR was expressed as the coordinates (COR-x, COR-y). The COR-x increased from 42.1 ± 9.5% preoperatively to 49.2 ± 14.0% at early follow-up ($p<0.001$), and maintained to the last follow-up with 47.0 ± 14.4% ($p=0.203$). Meanwhile, the COR-y decreased significantly after surgery from 70.7 ± 12.8% to 67.5 ± 13.9% ($p=0.005$), and retained to 66.7 ± 12.9% at last follow-up ($p=0.196$). The data showed that the initial COR of the flexion-extension motion at disc level was located in the posterior superior quadrant of the caudal vertebral body, and shifted anteriorly and inferiorly after implantation of Bryan artificial disc.

### Facet joint degeneration at index level

The inter-rater and intra-rater reliability for grading the facet joint degeneration score were excellent, with ICC 0.76 and 0.84. The facet joint degeneration score at index level increased from 1 (interquartile 1–2) preoperatively to 2 (interquartile 1–3) at last follow-up ($P<0.001$). Twenty-six patients (Group Non-degeneration) showed

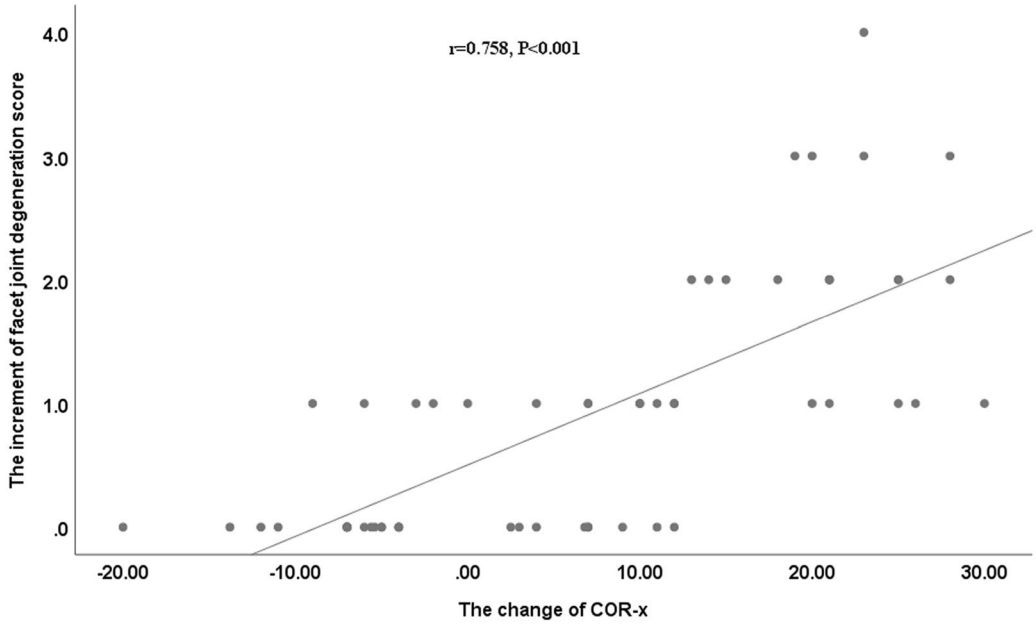


**Fig. 3** Scatterplot indicating correlation between the increment of facet joint degeneration score and the change of COR-x

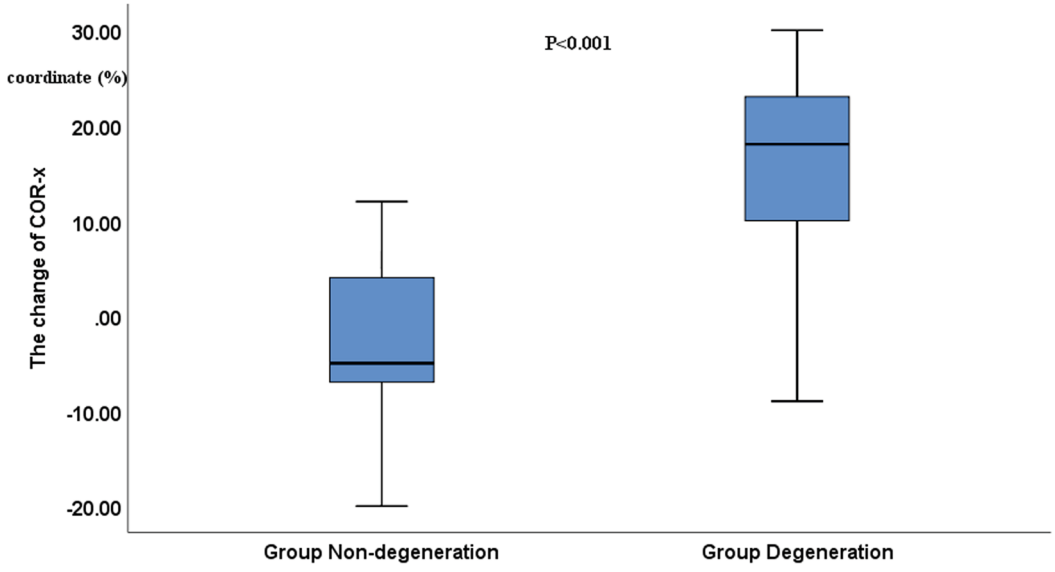


**Fig. 4** Boxplot showing the difference of the change of COR-x between two groups

no deterioration of facet joint degeneration during follow-up, and the other 33 patients (Group Degeneration) showed deterioration of facet joint degeneration with at least 1 score of increment of the degeneration score (18 patients with 1 score of increment, 10 patients with 2 scores of increment, 4 patients with 3 scores of increment, 1 patient with 4 scores of increment). Using Spearman's rank correlation analysis method, the increment of facet joint degeneration score at index level was strongly correlated with the change of COR-x ($r$=0.758, $P$<0.001) (Fig. 3), and weakly correlated with the change of COR-y ($r$=-0.473, $P$<0.001). The change of COR-x was significantly greater in Group Degeneration than that in Group Non-degeneration ( 14.8±10.5% vs. -2.6±8.1%, $p$<0.001), indicating that COR shifted more anteriorly in Group Degeneration (Fig. 4). The change of COR-y was greater in Group Degeneration than that in Group Non-degeneration, (-6.4±7.5% vs. 0.8±8.3%, $p$=0.001), indicating

that COR shifted more inferiorly in Group Degeneration (Fig. 5).

## Discussion

The present long-term follow-up study focused on the clinical and radiographic outcomes in 59 patients who underwent Bryan CDR, and highlighted the influence of the deviated COR on facet joint degeneration at the index level.

In the past 20 years, the clinical practice and related studies had proved CDR as an alternative technique to ACDF for CDDD on condition that the decompression was good enough and the patient selection was proper [2, 4, 9, 10, 30, 31]. The ideal indication for CDR should be soft disc herniation causing neurological symptoms or signs with physiologic ROM without instability, kyphosis, scoliosis, infection, osteoporosis, inflammatory disease, or facet arthritis [32]. The present study revealed a significant improvement of the clinical outcome parameters such as JOA score and NDI, and 91.5% of the patients reported excellent or good overall efficacy. Similar observations were verified in a number of studies irrespective of the type of prosthesis used [2, 10, 31, 33].

ROM is a very important radiographic parameter for CDR. The primary advantage of CDR over ACDF is just preservation or restoration of ROM of the index level. Good maintaining of ROM after CDR for long-term follow-up was well reported in the literature. Dejaegher et al. [8] reported that mean ROM of the Bryan prosthesis at 10-year follow-up was 8.59±5.85°, and 81% of the prostheses reached the mobility threshold of 2°. Lavelle et al. [31] reported mean angular motion at index level for Bryan disc was 8.7° at 10-year follow-up. Similar result in this present study, there was a minor decrease of ROM of index level from 10.6° preoperatively to 9.4° at early follow-up, and no significant change was found at last 10-year follow-up. Nowadays low ROM is no more a contraindication for CDR. However, in this study we focused on the COR before and after CDR operation, and COR can only be evaluated when ROM was acceptable. So we excluded the patients with low index level ROM (≤3°). HO is a common complication of CDR that affects ROM of prosthesis. The incidence of grade III/IV HO varies significantly among different devices, with ProDisc-C disc having the highest incidence rate (38%), followed by Prestige-LP (17%), Mobi-C (14%), and with Bryan disc having the lowest incidence rate (4%) [34]. The underlying cause may be the mount of bony structure disruption and bony debris residue different for various prosthesis design. In the initial reviewed 83 patients of the present study, there were 4 cases of high-level HO (3 cases of grade III HO, and 1 case of grade IV HO), with significant decrease of ROM. These 4 cases were excluded due to large errors in measuring location of COR which is an important parameter in the present study.

The theoretic basis of CDR is to restore the physiologic mechanics at the index level and the ideal prosthesis should not only just restore the ROM, but also mimic the physiologic mode of motion. Movement of a cervical spine segment is actually a combination of translational and angular motion. The combined motion can be reproduced by a pure angular motion on a point denoted as COR [35]. Location of COR is a good parameter to describe the mode of motion and can be found for any two points of a moving vertebra of a motion segment [12]. In the literature, there were limited studies mentioned the COR after Bryan CDR. Pickett et al. [36] reported 20 cases of Bryan CDR with 2-year follow-up, and they

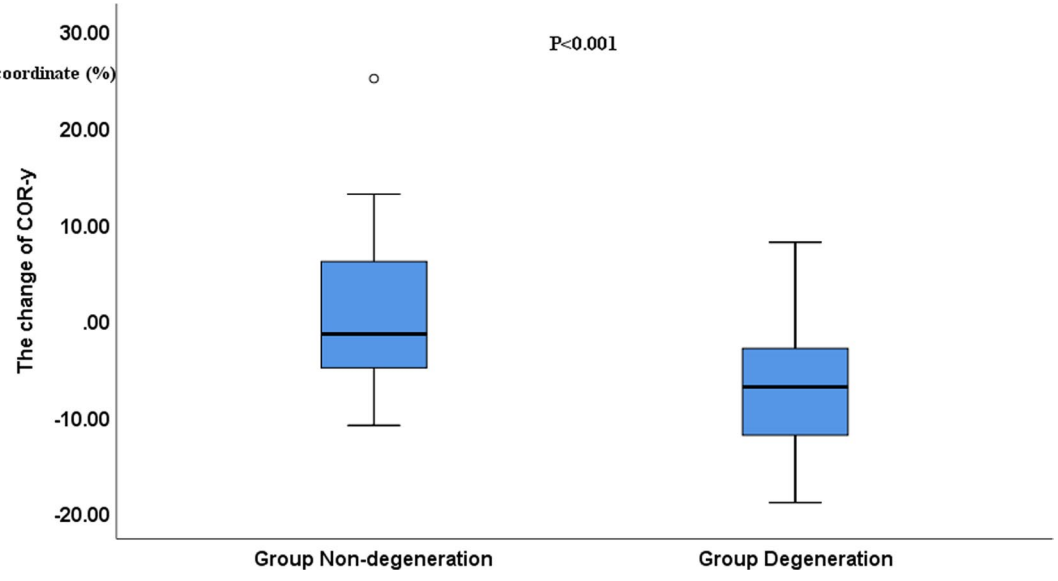


**Fig. 5** Boxplot showing the difference of the change of COR-y between two groups

found that COR coordinates did not change significantly after surgery and COR was most frequently located posterior and inferior to the center of the disc space. Lazaro et al. [37] reported 20 cases of Bryan disc with 6–12 months follow-up, and also found no significant change of COR location. While Powell et al. [38] report 22 cases with 2-year follow-up, and found that COR shifted more posterior (1% endplate width) and cephalad (20% endplate width) after the Bryan CDR. The limitations of the 3 studies above were small number of cases and only short-term follow-up. In the present 10-year follow-up study with 59 cases included, we used analytical geometry method to calculate the coordinates of COR, without requirement of superimposing the inferior vertebra of the index level in the flexion and extension radiographs, also without need of manual drawing perpendicular bisector lines. Therefore, our COR coordinates results may be more accurate and reliable. We found that the COR shifted forward and downward after Bryan CDR, as increased COR-x from a preoperative mean of 42.1±9.5% to 49.2±14.0% postoperatively ($p<0.001$), and decreased COR-y after surgery (70.7±12.8% vs. 67.5±13.9%, $p=0.003$). The possible explanation for this deviation may be the more caudal insertion angulation and/or insufficient insertion depth of the prosthesis during the operation. But this assumption needs further detailed studies to clarify. Theoretically, the postoperative COR should be better to be placed near the physiological position which is near the posterior corner of the inferior vertebra to copy the regular intervertebral motion. If the COR moves, the functioning of the facets changes with friction and thus arthritis comes.

Maintenance of ROM with altered mode of motion would alter the facet joint loading at index level, which could lead to long-term facet joint degeneration theoretically. In the literature, many in vitro biomechanical studies had focused on this point [12–19]. Wo et al. [14] reported the facet joint force increased by 167.95% in extension loading after Prestige LP CDR. Chang et al. [15] reported that facet joint force at index level increased by 95.4% under an extension load after ProDisc-C CDR, and 25.1% for Prestige CDR. Choi et al. [13] reported that the facet forces increased by 13% and 183.9% under extension with Bryan CDR and ProDisc-C CDR, respectively. Gandhi et al. [17] reported increased facet contact force by 71% for Bryan CDR, and 75% for Prestige LP under extension. Mo et al. [19] reported maximal facet stress on extension for Mobi-C CDR (2.8 MPa) compared with healthy disc (1.2 MPa) and Bryan CDR (1.8Mpa). The different prostheses mentioned above represented different types of CDR designing. ProDisc-C is ball-in-socket design with fixed rotation center on the inferior endplate; Prestige LP is ball-in-socket design with reverse rotation center on the superior endplate; Mobi-C is ball-in-socket design with mobile rotation center on the inferior endplate; Bryan is dual articulation design with mobile rotation center between the endplates. However, facet joint arthrosis takes a long time to appear, and the biomechanical conclusions above need long-term clinical data to verify. Up to now, there is a lack of long-term clinical studies focusing on the facet joint degeneration after CDR in the literature. In this present 10-year follow-up study, we found that 55.9% of the Bryan CDR patients showed deterioration of the facet joint degeneration at the index level. Our long-term clinical data strengthened the findings of biomechanical studies. On the other hand, the natural COR of the cervical segment, is correlated with the location and orientation of the facet joints relative to the disc. Therefore, in the presence of mismatch between the prosthesis COR and the natural COR of a given cervical segment, the facet joints may experience abnormal loads, and the facet capsules could experience abnormal strains, disturbing the normal load-sharing characteristic of the cervical 3-joint complex. In the present study, we found a strong correlation ($r=0.758$, $P<0.001$) between deviation of COR and facet joint degeneration at index level. In the subgroup analysis, the deviation of COR was significantly greater in Group Degeneration than that in Group Non-degeneration (14.8±10.5% vs. -2.6±8.1% for COR-x, and −6.4±7.5% vs. 0.8±8.3% for COR-y).

Different design of the prosthesis will affect the position of COR differently. There is still no prosthesis that can fully mimic the natural cervical disc with physiologic ROM and COR. The Bryan prosthesis is the most approximate one although still not perfect. The installation should avoid the caudal insertion angulation or the insufficient insertion depth of the prosthesis during the operation to get a more posterior and cranial position of COR which is more physiologic.

There are some limitations in the study. Firstly, the follow-up rate is not high enough, among the initial reviewed 83 patients, 4 cases were excluded due to grade III/IV HO and 20 patients (24.1%) were lost to follow up (8 patients refused to accept CT scan at final follow-up, and 12 patients changed contact information and failed to complete the final follow-up). Secondly, we used flexion-extension radiographs to calculate the average COR, and this may not fully capture the motion path. The instantaneous center of rotation does not remain stationary during motion.

## Conclusion

Bryan CDR with minimum of 10-year follow-up achieved favorable clinical outcome and good maintenance of ROM. Deviated COR could be an important risk factor for facet joint degeneration. For CDR surgery, more attention should be paid to preoperative selection of

prosthesis and intraoperative technique to obtain a more natural COR.

**Abbreviations**

| | |
|---|---|
| CDR | Cervical disc replacement |
| CDDD | Cervical degenerative disc disease |
| ROM | Range of motion |
| COR | Center of rotation |
| HO | Heterotopic ossification |
| JOA | Japanese Orthopaedic Association |
| NDI | Neck Disability Index |
| CT | Computed tomography |

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Not applicable.

**Author contributions**
WT and KY conceived the study. KY and ZS collected the data, performed the data analysis and drafted the first version of the manuscript. ZS and QLW analyzed the data. HD provided the critical comments to design the study. LB provided additional advice. BX contributed to the literature review. All authors read and approved the final manuscript.

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**Data availability**
The data generated and/or analyzed during this study are available from the corresponding author on reasonable request.

## Declarations

**Ethics approval and consent to participate**
All study participants provided informed consent, and the study design was approved by Beijing Jishuitan Hospital Institutional Review Board and written informed consent was obtained from all participants. All the authors agreed to be assigned. All procedures were in accordance with the principles of the Declaration of Helsinki.

**Consent for publication**
Not applicable.

**Competing interests**
The authors declare no competing interests.

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