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A Longitudinal Study of the Six Degrees of Freedom Cervical Spine Range of Motion During Dynamic Flexion/Extension and Rotation After Single-Level Anterior Arthrodesis

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Abstract

Study Design—A longitudinal study using biplane radiography to measure in vivo intervertebral range of motion (ROM) during dynamic flexion/extension and rotation.

Objective—To longitudinally compare intervertebral maximal ROM and midrange motion in asymptomatic control subjects and single-level arthrodesis patients.

Summary of Background Data—In vitro studies consistently report that adjacent segment maximal ROM increases superior and inferior to cervical arthrodesis. Previous in vivo results have been conflicting, indicating that maximal ROM may or may not increase superior and/or inferior to the arthrodesis. There are no previous reports of midrange motion in arthrodesis patients and similar-aged controls.

Methods—Eight single-level (C5/C6) anterior arthrodesis patients (tested 7 ± 1 months and 28 ± 6 months post-surgery) and six asymptomatic control subjects (tested twice, 58 ± 6 months apart) performed dynamic full ROM flexion/extension and axial rotation while biplane radiographs were collected at 30 images/s. A previously validated tracking process determined three-dimensional vertebral position from each pair of radiographs with sub-millimeter accuracy. The intervertebral maximal ROM and midrange motion in flexion/extension, rotation, lateral bending, and anterior-posterior translation were compared between test dates and between groups.

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Results—Adjacent segment maximal ROM did not increase over time during flexion/extension or rotation movements. Adjacent segment maximal rotational ROM was not significantly greater in arthrodesis patients than in corresponding motion segments of similar-aged controls. C4/C5 adjacent segment rotation during the midrange of head motion and maximal anterior-posterior translation were significantly greater in arthrodesis patients than in the corresponding motion segment in controls on the second test date.

Conclusions—C5/C6 arthrodesis appears to significantly affect midrange, but not end-range, adjacent segment motions. The effects of arthrodesis on adjacent segment motion may be best evaluated by longitudinal studies that compare maximal and midrange adjacent segment motion to corresponding motion segments of similar-aged controls to determine if the adjacent segment motion is truly excessive.

Keywords

adjacent segment; fusion; kinematics; ACDF; in vivo; biplane radiography; X-ray; activities of daily living; midrange

Introduction

Controversy exists as to the etiology of adjacent segment pathology following anterior arthrodesis¹. The disease may progress due to the underlying spondylosis^{2–5}, the arthrodesis may lead to increased motion in adjacent vertebrae, resulting in overload and instability^{6–10}, or surgical factors, such as placement of the fusion plate^{11,12}, graft type¹³, and postoperative cervical spine alignment^{14,15} may affect adjacent segment mechanics and degeneration. The current study tests the second of these theories, that arthrodesis leads to increased adjacent segment motion.

In vitro studies have consistently indicated that adjacent segment range of motion increases superior and inferior to cervical arthrodesis^{2,16,17}. In contrast, in vivo results have been inconsistent, indicating that ROM may^{18–20} or may not^{21,22} increase superior to the arthrodesis, and may^{20,21} or may not¹⁸ increase inferior to the arthrodesis.

Intervertebral range of motion (ROM) is commonly determined in vivo using two-dimensional lateral radiographs, typically acquired at static full-flexion and full-extension positions^{7,23–25}. These measurements have inherent limitations, including the high measurement variability associated with manual digitization^{23,24,26,27}, the absence of dynamic loading, and the inability to assess motion out of the film plane. In order to improve our understanding of cervical spine kinematics, it has been suggested that three-dimensional (3D) measurements^{7,28–32} be acquired during in vivo dynamic loading conditions^{7,33–35}. An additional limitation of previous research has been the failure to assess the effects of arthrodesis on midrange kinematics, which make up the vast majority of activities of daily living^{36,37}. These limitations are addressed in the present study by collecting synchronized biplane radiographs (to obtain 3D measurements) at 30 images per second during dynamic, functional loading and by using an automated tracking process to determine continuous 3D intervertebral kinematics with sub-millimeter accuracy.

The current study is a longitudinal follow-up to a previous report on the six degrees of freedom ROM in the cervical spine of arthrodesis patients and control subjects³⁸. The previous study compared the six degrees of freedom ROM in arthrodesis patients seven months post-surgery to similar-aged asymptomatic controls during head flexion/extension. The present study expands on the previous report by assessing longer-term effects of arthrodesis on the six degree of freedom ROM during flexion/extension and additionally evaluates longitudinal changes in ROM during axial rotation. In addition, intervertebral kinematics were determined during the midrange of motion to assess the effect of arthrodesis on adjacent segment motion during the movement range most commonly encountered during activities of daily living. The overall objective of the current study was to compare changes in intervertebral ROM due to the natural aging process to changes observed after single-level arthrodesis. It was hypothesized that adjacent segment ROM would increase with time after surgery and that adjacent segment ROM would be greater than ROM at the corresponding motion segments in similar-aged asymptomatic controls.

Materials and Methods

Subjects

Following Institutional Review Board (IRB) approval, informed consent to participate in this study was obtained from 8 single-level (C5/C6) anterior arthrodesis patients (1 M, 7 F; average age: 45 ± 9 yrs.; age range: 37–56 yrs. at first test; tested at 7 ± 1 months and 28 ± 6 months post-surgery) and 6 asymptomatic controls of similar age (0 M, 6 F; average age: 47 ± 6 yrs.; age range: 39–57 yrs. at first test; the first test occurred concurrently with the initial arthrodesis patient tests, the second test was 58 ± 6 months later). Patients who were scheduled to undergo, or who had recently undergone, single-level arthrodesis were recruited during clinic visits. Control subjects with similar age and sex distribution to the arthrodesis patients were recruited through an advertisement in an employee newsletter and word of mouth. Pregnant women, individuals previously diagnosed with osteoporosis, and individuals with any other injury or disease that interferes with spine function were excluded.

Data Collection

Subjects were seated within a custom designed biplane X-ray system³⁹ and directed to continuously move their head and neck through their entire range of motion for six dynamic movement trials (3 trials each of flexion/extension and axial rotation). For each dynamic movement trial, participants performed the movement for 5 to 10 continuous full ROM movement cycles. A metronome set at 40 to 44 beats per minute was used to ensure that the participants moved at a continuous, steady pace to complete each full movement cycle in 3 seconds or less. During these continuous movements, participants were verbally encouraged to move through their full ROM. Biplane radiographs were collected simultaneously at 30 images per second for 3 seconds (X-ray parameters: 70 KV, 160 mA, 2.5 ms X-ray pulses, source-to-subject distance 140 cm) to capture at least one full movement cycle of the continuous motion. Data were collected in this way for each dynamic movement trial, with a brief rest period between trials. Participants were asked after the first trial of each type of dynamic movement if the movement was painful or uncomfortable. Reflective markers were

placed on the head and torso to determine global head ROM during each movement trial using a conventional optical motion analysis system (Vicon MX, Centennial, CO). Biplane radiographs were also collected for 0.1 s static neutral trials prior to the three dynamic flexion/extension movement trials and prior to the three rotation movement trials. High-resolution CT scans ($0.29 \times 0.29 \times 1.25$ mm voxels) of the cervical spine (C2–C7) were also acquired from each participant (GE Lightspeed 16; GE Healthcare, Waukesha, WI).

The effective radiation dose (i.e. the sum of all tissue-weighted doses) for each dynamic motion trial was estimated to be 0.16 mSv (determined using PCXMC simulation software, STUK, Helsinki, Finland). In comparison, the effective dose of a cervical spine CT scan has been reported to be between 3.0 mSv and 4.36 mSv^{40,41}.

Data Processing

Bone tissue was segmented from the CT volume using a combination of commercial software (Mimics software, Materialise, Leuven, Belgium) and manual segmentation⁴². A three-dimensional (3D) model of each vertebra was generated from the segmented bone tissue⁴³. Markers were interactively placed on the 3D bone models to define orthogonal bone-specific anatomic coordinate systems, with the X-axis directed right to left, the Y-axis directed inferior to superior, and the Z-axis directed posterior to anterior⁴⁴.

A previously validated tracking process determined 3D vertebral position from each pair of radiographs with sub-millimeter accuracy⁴⁵ for all static and dynamic trials for the C3 through C7 vertebrae (Figure 1). Details describing the volumetric model-based tracking process, including hardware and software specifications, calibration and distortion correction procedures, and computational algorithms have been described previously^{45–48}. Tracked bone movement data were filtered at 1.7 Hz and 1.5 Hz for the flexion/extension and rotation trials, respectively, using a fourth-order, low-pass Butterworth filter with the filter frequency determined using residual analysis⁴⁹. Reflective marker data were smoothed at 20 Hz for all trials. A total of 103 dynamic full ROM movement trials were tracked and included in the present analysis.

The six degrees of freedom kinematics (3 translations, 3 rotations) at each cervical motion segment from C3 to C7, normalized to the average of the static neutral trials, were calculated for each participant following established standards for reporting spine kinematics^{50,51}. The maximum and minimum values of each of the six kinematic curves were determined for each dynamic movement trial (Figure 2). The maximum and minimum translation and rotation values over all trials for a single subject were used to determine the ROM at each respective motion segment. An additional measurement, termed the “clinical anterior-posterior range of motion” was calculated. This anterior-posterior (AP) ROM was calculated for each motion segment as the AP distance between points on the inferior-posterior edge of the superior vertebral body and the superior-posterior edge of the inferior vertebral body. This measurement corresponds to a commonly used method to determine AP translation in the clinic¹⁸. Additionally, the intervertebral ROM that occurred during the midrange of head motion (defined as $\pm 20^\circ$ of head flexion/extension or head rotation from the neutral orientation) was determined for each dynamic movement trial. Previous research indicates that the vast majority of activities of daily living occur within this limited ROM^{36,52,53}.

Statistical Analysis

The outcome variables analyzed for the flexion/extension movement trials were the flexion/extension component of global head ROM, the flexion/extension component of intervertebral ROM, and the clinical anterior-posterior translation at each motion segment. The outcome variables analyzed for the rotation movement trials were the rotation component of global head ROM, and the rotation and lateral bend components of intervertebral ROM at each motion segment. Although statistical analysis was not performed on the other ROM components, the means and standard deviations are available in the supplemental digital content (Tables 1s, 2s and 3s).

The Shapiro-Wilk test of normality was used to determine if the ROM data were normally distributed at each motion segment. In cases of normally distributed data, paired t-tests were used to identify changes within subjects over time and independent-samples t-tests were used to identify differences between groups (control vs. arthrodesis) at the first and second test dates. In cases of non-normally distributed data, the Wilcoxon Signed Rank and the Mann-Whitney tests were used to test for differences within subjects and between groups, respectively.

Results

Static Orientation

The static orientation of the sub-axial cervical spine (C3–C7) was characterized by high inter-subject variability, and no differences were observed over time in asymptomatic controls (all $p = 0.147$) or in arthrodesis patients (all $p = 0.153$) (Table 1). Static orientation was not significantly different between groups on either test date (all $p = 0.278$) (Table 1).

Flexion/Extension Movement

Head flexion/extension ROM during the flexion/extension movement was not significantly different between test sessions in the control group ($102^\circ \pm 14^\circ$ vs. $98^\circ \pm 6^\circ$; $p = 0.505$) or in the arthrodesis group ($84^\circ \pm 15^\circ$ vs. $88^\circ \pm 15^\circ$; $p = 0.505$), however, the difference between control and arthrodesis groups on the first test date was statistically significant ($p = 0.041$) (Figure 3).

During head flexion/extension, maximal intervertebral flexion/extension ROM was not significantly different between test sessions for the control group (all $p = 0.061$) (Figure 3). In the C5/C6 arthrodesis group, the C5/C6 maximal intervertebral flexion/extension ROM significantly decreased from 7 months to 28 months after surgery ($p = 0.012$), but did not change significantly over time at any other motion segment (all $p = 0.051$). The control and the arthrodesis groups were different only at the C5/C6 motion segment ($p = 0.003$ on both the first and the second test date) (Figure 3).

Maximal clinical AP translation during head flexion/extension was not significantly different between test dates in the control group (all $p = 0.133$) (Figure 4). In the C5/C6 arthrodesis group, the clinical AP translation ROM significantly decreased from 7 months to 28 months after surgery at C5/C6 ($p = 0.016$), but did not change significantly over time at any other

motion segment (all $p = 0.161$). On the second test date, maximal clinical AP translation at the C4/C5 motion segment was significantly greater in the arthrodesis group than in the control group ($p = 0.002$), while at the C5/C6 motion segment, clinical AP translation was significantly less in the arthrodesis group than in the control group ($p = 0.001$) (Figure 4).

Midrange intervertebral flexion/extension ROM was not significantly different between test sessions for the control group (all $p = 0.171$) (Figure 5). Adjacent segment midrange motion was greater in the C5/C6 arthrodesis group than in controls on both test dates, with the differences reaching statistical significance on the second test date for the superior (C4/C5) adjacent segment ($p = .03$) (Figure 5).

Head Rotation Movement

Head rotation ROM during the rotation movement was not significantly different between test sessions in the control group ($124^\circ \pm 10^\circ$ vs. $118^\circ \pm 15^\circ$; $p = 0.169$). In contrast, global head rotation ROM in the arthrodesis group increased significantly between test sessions, from $101^\circ \pm 18^\circ$ at 7 months post-surgery to $108^\circ \pm 17^\circ$ at 28 months post-surgery ($p = 0.015$). Additionally, the arthrodesis group head rotation ROM was significantly less than control group head rotation ROM on the first test date ($p = 0.018$).

In the control group, during head rotation, no significant differences between test sessions were observed in intervertebral rotation (all $p = 0.224$) or lateral bending (all $p = 0.249$) ROM at any motion segment (Figure 6 and Figure 7, respectively). In the C5/C6 arthrodesis group, the C5/C6 intervertebral rotation ROM significantly decreased from 7 months to 28 months after surgery ($p = 0.036$) (Figure 6). No other differences in rotation (all $p = 0.335$) or in lateral bending (all $p = 0.110$) ROM were observed between tests sessions in the arthrodesis group. The control and arthrodesis group rotation ROM was only different at the C5/C6 motion segment on the second test date ($p = 0.005$) (Figure 6). Coupled intervertebral lateral bending ROM during rotation at the C3/C4 motion segment was significantly greater in the control group than in the arthrodesis group on the second test date ($p = 0.035$) (Figure 7), while group differences were also identified in coupled lateral bending ROM at the C5/C6 motion segment at the first ($p = 0.010$) and second ($p = 0.002$) test dates (Figure 7).

During midrange head rotation, superior adjacent segment rotation was greater in the C5/C6 arthrodesis group than in controls on both test dates, with the differences reaching statistical significance on the second test date ($p = .05$) (Figure 8). Similar results were found in the intervertebral lateral bend motion during midrange head rotation, with significantly greater lateral bend motion at the C6/C7 motion segment in the arthrodesis group ($p = .048$).

None of the participants indicated that the dynamic movements were painful or uncomfortable.

Discussion

This longitudinal study of cervical spine ROM during flexion/extension and rotation assessed global head ROM and intervertebral ROM in C5/C6 single-level arthrodesis patients and similar-aged asymptomatic control subjects. Maximal adjacent segment ROM

during flexion/extension and rotation did not increase significantly from 7 to 28 months after arthrodesis, while operated site ROM decreased significantly over the same time period. Adjacent segment maximal rotational ROM during flexion/extension and rotation was not greater in arthrodesis patients than in corresponding motion segments of similar-aged control subjects at either test date. The only significant difference in maximal adjacent segment ROM between controls and arthrodesis patients was at the C4/C5 motion segment in clinical AP translation on the second test date. However, this difference was largely due to decreased ROM in the control group rather than increased ROM in the arthrodesis group. In contrast, adjacent segment motion during the midrange of flexion/extension and the midrange of rotation was greater in the arthrodesis patients than in the healthy controls.

The results of this in vivo study contradict previous in vitro studies that indicated maximal adjacent segment rotational ROM increases after arthrodesis^{2,10,16,17}. This discrepancy between in vitro and in vivo may be due to the inability of in vitro testing to replicate in vivo kinematics and due to incorrect assumptions made by in vitro test protocols⁵⁴. For example, in the hybrid test method to evaluate spinal adjacent level effects⁵⁵, it is assumed that the total motion of the spine does not change after fusion. Thus, under the hybrid protocol, the motion “lost” due to fusion must (of course) be accompanied by increased ROM at other levels. The present results indicate that it is incorrect to assume that the spine moves through the same ROM before and after arthrodesis. Because current in vitro test paradigms are unable to replicate in vivo motion and loading conditions, the results from in vitro studies are unlikely to yield useful information about in vivo physiological behavior and should be interpreted with caution.

Previous in vivo studies provide conflicting results regarding the effects of cervical arthrodesis on adjacent segment rotational motion. While some in vivo studies have reported increased adjacent segment motion after arthrodesis^{18–21}, others have reported no change at the superior^{21,22} or inferior¹⁸ motion segments. The present study is believed to be the first to indicate that single-level arthrodesis does not affect either superior or inferior adjacent segment maximal rotational ROM. Careful observation of the adjacent segment rotational ROM data from the present study reveals that adjacent segment rotational ROM increased slightly from 7 months to 28 months after surgery (Figures 3, 6 and 7). Therefore, differences between the current and previous studies may be due to the amount of time elapsed between test sessions; it may require more than 21 months between tests (7 to 28 months post-surgery) for adjacent segment maximal rotational ROM to significantly increase.

This is believed to be the first in vivo study to assess adjacent segment effects during the midrange of motion. Information from midrange motion may provide more clinically and functionally relevant information than full ROM measurements due to the fact that the majority of daily activities do not require full ROM movements of the cervical spine^{36,52,53}. Data from the present study suggests that if intervertebral adjacent segment motion in C5/C6 arthrodesis patients is compared to corresponding motion segments in asymptomatic controls over identical ranges of head motion, the adjacent segment motion is greater in arthrodesis patients. The topic of adjacent segment kinematics during midrange functional

motions has not received nearly as much attention as end-range ROM and is clearly worthy of future investigation given the high functional relevance of midrange motions.

Although researchers often focus on within-subject changes in ROM after arthrodesis, comparing adjacent segment ROM to corresponding motion segments of similar-aged controls may also be valuable. After all, if the adjacent segment ROM is not significantly greater than the ROM at the corresponding motion segments in asymptomatic controls, then it can be argued that the arthrodesis does not lead to “excessive” motion and loading at the adjacent segments.

The observed difference between groups in head ROM on the first test date was greater than the difference in intervertebral motion at the arthrodesis site, and therefore may have reflected a difference in neuromuscular function between groups. At 28 months after surgery, although the head ROM was still less in arthrodesis patients than in controls, the difference between groups was no longer statistically significant and could be attributed almost entirely to the loss in ROM at the C5/C6 motion segment.

A strength of this study was the established, reproducible and accurate technique used to measure in vivo three-dimensional intervertebral kinematics during dynamic, multi-planar movements^{45,56}. A limitation of the study was the lack of pre-surgical data. Pre-surgical data may have assisted in determining if any group differences in kinematics were due to pre-existing conditions or if they were the result of the operation⁵⁶. However, patient pain can be a confounding factor that limits the utility of pre-surgical data. The unreliability of pre-surgical ROM data has been demonstrated in a study that reported adjacent segment ROM is as likely to decrease as it is to increase after arthrodesis²², casting doubt on the value of pre-surgical data. Due to the large inter-subject variability in static orientation, pre-surgical data would have also provided more statistical power to analyze the effect of arthrodesis on this parameter. Another limitation is that only single-level C5–C6 arthrodesis patients were studied. Future studies are needed to confirm or refute these findings following single-level arthrodesis at other levels and following multi-level arthrodesis. Although the number of participants was relatively small, the statistical power of the study was sufficient to identify longitudinal differences as small as 1.4° as significant, and to identify differences between groups as small as 3.2° in rotation and 1.1 mm in translation as significant. Nonetheless, due to the relatively small sample size, the initial results derived from this unique dataset should be confirmed in a larger sample. Another limitation of the study was that the follow-up time for the controls was approximately twice as long as that for the arthrodesis group. The longer follow-up period for the controls provided valuable information about the natural history of spine kinematics in asymptomatic individuals. The control group did not demonstrate a significant change in any ROM parameter over 58 months, so it is unlikely that additional data at the 28-month time point would have been informative. Finally, the effects of arthrodesis on adjacent segment motion were only assessed up to approximately 28 months after surgery. Given the expected decrease in intervertebral ROM that occurs with age^{26,57}, it is interesting that the current study observed small but consistent increases in ROM from 7 to 28 months after arthrodesis. This suggests that longer-term follow-up testing may provide increasingly valuable longitudinal data on adjacent segment kinematics after arthrodesis.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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CT Segmentation

X-Ray System Geometry

Model-Based Tracking

Figure 1.

The volumetric model-based tracking process. Three-dimensional subject-specific bone models of each cervical vertebra were created from CT scans (upper left). The geometry of the biplane radiography system (upper right) was recreated within the computer. The bone model was placed within the virtual biplane X-ray system (bottom). A ray-tracing algorithm was used to create digitally reconstructed radiographs (DRRs) of the bone model. The bone model was manipulated in 3D space using an automated algorithm to maximize the correlation between the DRRs (in green) and the biplane radiographs (in red). This automated matching process was repeated for each of the 90 paired radiographs collected per dynamic movement trial.

Figure 2.

Intervertebral kinematics (lateral bend = blue, rotation = green, flexion/extension = red) during flexion/extension (left) and rotation (right). Anatomic coordinate systems within each bone (above) were used to determine intervertebral kinematics during full ROM movements (C4–C5 is shown below). The maximum and minimum of each kinematic curve (indicated by arrows) were determined each dynamic movement trial.

Flexion/Extension Range of Motion

Figure 3.

Flexion/extension maximal range of motion during head flexion/extension in control subjects (blue) and arthrodesis patients (green) on the first (solid) and second (dotted) test dates. Error bars indicate ± 1 standard deviation. P-values are provided where significant differences were identified between groups and/or between test dates within a group.

Figure 4.

Maximum clinical anterior-posterior translation range of motion during head flexion/extension in control subjects (blue) and arthrodesis patients (green) on the first (solid) and second (dotted) test dates. Error bars indicate ± 1 standard deviation. P-values are provided where significant differences were identified between groups and/or between test dates within a group.

Figure 5.

Midrange intervertebral flexion/extension motion during $\pm 20^\circ$ head flexion/extension from the neutral position in control subjects (blue) and arthrodesis patients (green) on the first (solid) and second (dotted) test dates. Error bars indicate ± 1 standard deviation. P-values are provided where significant differences were identified between groups and/or between test dates within a group.

Rotation ROM During Rotation

Figure 6.

Rotation range of motion during head rotation in control subjects (blue) and arthrodesis patients (green) on the first (solid) and second (dotted) test dates. Error bars indicate ± 1 standard deviation. P-values are provided where significant differences were identified between groups and/or between test dates within a group.

Lateral Bend ROM During Rotation

Figure 7.

Lateral bending range of motion during head rotation in control subjects (blue) and arthrodesis patients (green) on the first (solid) and second (dotted) test dates. Error bars indicate ± 1 standard deviation. P-values are provided where significant differences were identified between groups and/or between test dates within a group.

Figure 8.

Midrange intervertebral rotation during $\pm 20^\circ$ head rotation from the neutral position in control subjects (blue) and arthrodesis patients (green) on the first (solid) and second (dotted) test dates. Error bars indicate ± 1 standard deviation. P-values are provided where significant differences were identified between groups and/or between test dates within a group.

Table 1

Intervertebral sagittal angle in the static neutral position. Negative values indicate lordosis, positive values indicate kyphosis. Measurements at the level of arthrodesis are highlighted. Group mean $\pm$ standard deviation in degrees.

	C3/C4	C4/C5	C5/C6	C6/C7
Control Day 1	-5.2 $\pm$ 5.8	-4.5 $\pm$ 7.3	1.4 $\pm$ 7.6	-4.2 $\pm$ 3.9
Control 58 Months	-5.8 $\pm$ 5.7	-4.4 $\pm$ 7.0	0.4 $\pm$ 7.6	-2.4 $\pm$ 4.8
Arthrodesis 7 Mo. Post. Op.	-3.9 $\pm$ 6.3	-0.8 $\pm$ 7.4	2.9 $\pm$ 9.1	-6.8 $\pm$ 7.6
Arthrodesis 28 Mo. Post. Op.	-5.0 $\pm$ 7.5	-1.8 $\pm$ 7.8	3.1 $\pm$ 8.2	-6.9 $\pm$ 8.6