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Evaluation of efficacy and 3D kinematic characteristics of cervical orthoses

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Abstract

Background. Cervical orthoses are often prescribed for both extrication stabilization of trauma patients and a treatment option of injuries to the cervical spine. The objective of this study was to compare effectiveness of two new and two established cervical orthoses in restricting 3D range of motion in the cervical spine.

Methods. Twenty healthy males and females (ten each) participated in the study. Two new cervical collars, C-Breeze and XTW and two established collars, Miami J and Aspen, were examined. A 3-camera Vicon system was used to collect 3D kinematic data. Subjects performed three trials in each of the 15 test conditions wearing no collar and the four cervical collars and performing three different head movements: flexion–extension, left–right lateral flexion, and left–right axial rotation.

Findings. The results comparing with the unbraced movements indicated that the Miami J and C-Breeze collars had significantly greater percent reduction on range of motion in flexion than the XTW collar. For both extension and lateral bending, all three collars showed greater percent reduction than the Miami J. The XTW also showed greater reduction than the C-Breeze and Aspen in extension. Finally, the C-Breeze collar showed a significantly more reduction in axial rotation than the Miami J collar.

Interpretation. The results suggested that C-Breeze and XTW along with the Miami J and Aspen collars are effective in restricting range of motion in the cervical spine. The two new cervical orthoses also performed either comparably as or better than the two established cervical orthoses.

Keywords: Range of motion; Orthotic devices; Spine; 3D kinematics; Cervical collar

1. Introduction

Patients who have sustained a cervical spine injury are often prescribed cervical orthoses (collars) post injury. The objectives for spinal orthoses applications include correction of spinal deformity and misalignment, intervertebral segmental immobilization, regional stabilization, maintaining a specific spinal posture, and protection from damaging stresses (White and Panjabi, 1990). Main purposes for applying a spinal orthosis are to protect the injury site, alter the existing patterns of deformity and kinematics of the spine, and improve load-bearing tolerance. The cervical spine enjoys the greatest range of motion (RoM) of the entire spine, but soft-tissue injury to the region may last well beyond the expected period (Bogduk and Mercer, 2000). Cervical orthoses are often prescribed in both extrication stabilization of trauma patients and as a treatment option of injuries to the cervical spine (Richter et al., 2001), which may include soft-tissue trauma, degenerative conditions, and postoperative immobilization to provide stability in a degenerative cervical spine (Johnson et al., 1977; Sandler et al., 1996).

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There are three types of conventional cervical braces with variation within each category (White and Panjabi, 1990; Johnson et al., 1977). The simplest one is the soft cervical collar that is mainly made of foam rubber covered with cotton stockinette. The second type is called a poster-brace with padded mandibular and occipital supports, and two or four rigid metal upright supports and straps. The third category is the cervicothoracic orthosis with support similar to the poster brace, but further reinforced by rigid metal connections between the anterior and posterior components (White and Panjabi, 1990; Johnson et al., 1977). An unconventional cervical brace is the halo that uses a skeletal fixation through connections to the trunk by metal uprights attached to a plastic vest. Even though the soft collar is considered to provide the least restriction to movements in the cervical spine, several variations of the device with more rigid plastic supports have been shown to be rather effective (Johnson et al., 1977; Ducker, 1990; Mosenkis, 2001).

Johnson and his colleagues (Johnson et al., 1977) showed that the Philadelphia collar, a reinforced hard collar, provided 70%, 44% and 66% reduction of RoM in flexion–extension, lateral bending (flexion), and axial rotation, respectively. The traditional soft collar, on the other hand, provided only 16%, 8% and 17% of reduction on these movements. One study showed a two-piece plastic rigid collar, Miami J, offered better immobilization than a one-piece rigid collar (Ducker, 1990). Other studies demonstrated that Miami J provided greater immobilization of RoM in the cervical spine than two other similar collars, Aspen and Philadelphia (Ducker, 1990; Mosenkis, 2001). Hartman and his colleagues (Hartman et al., 1975) showed that an adjustable plastic Thomas collar offered a similar amount of restriction on cervical RoM in all three planes compared to a four-poster cervical collar. These authors also found that there was no difference in the percent of RoM reduction of the cervical flexion–extension and lateral bending evaluated with cinematography and video-fluoroscopy techniques. Therefore, the main purpose of this study was to examine and compare the efficacy of two new cervical collars, C-Breeze and XTW, with two other established collars, Miami J and Aspen, in restricting range of motion in the cervical spine.

2. Methods

2.1. Subjects

Twenty healthy subjects of mean 24.0 (SD 2.4) years with no impairments to their spine at the time of the data collection and no history of major spinal pathology participated in the study. Among them, ten are male of mean 24.7 (SD 2.2) years and the other ten are female of mean 23.3 (SD 2.6) years. All subjects signed an informed consent form, approved by the Institutional Review Board at the University of Tennessee, prior to the actual data collection.

2.2. Three-dimensional kinematics

A three-camera motion analysis system (120 Hz, Vicon, Oxford, UK) was used to obtain three-dimensional (3D) kinematic data during the test session. The Vicon system has a mean error of 0.42 mm in linear measurements and 0.14° in angular measurements (Ehara, 2002). Three retroreflective spherical markers were placed on the anterior maxilla, the forehead, and the top of the head. The FRHD and CRN markers were placed on the corresponding positions on a plastic head frame that was affixed to the head of the subject using a rubber band to ensure a stable frame attachment to the head. The 3D coordinates of the reflective markers were saved in a C3D file format and were later imported into a customized Matlab program to compute 3D angular kinematic variables.

The RoM was determined by finding the maximum or minimum of the angular positions for each movement. The percent reduction of RoM (RoM_{pct}) for a braced condition was determined by using this equation:

$$RoM_{pct} = \left(1 - \frac{RoM_i}{RoM_{unbraced}}\right) \times 100$$

where RoM_i is the RoM of the ith collar and $RoM_{unbraced}$ is the RoM of the unbraced condition for a particular movement.

2.3. Cervical collars

Four cervical collars were tested in a test session, which included the two new cervical orthoses, C-Breeze and XTW (DeRoyal Industries, Inc., Powell, TN, USA) and two established orthoses, Miami J (Jerome Medical, Moorestown, NJ, USA) and Aspen (International Healthcare Devices, Long Beach, CA, USA). Two anthropometric measurements were taken to determine the sizes of the cervical collars to be used in the test session for each subject according to the sizing instructions of each manufacturer, in a measurement session prior to the test day. The same investigator applied all cervical collars to all subjects according to the patient instruction manual provided by the manufacturers.

2.4. Experimental protocol

All subjects participated in two sessions: a measurement session and a biomechanical test session. The measurement session discussed earlier was used to determine the proper size of the collars for each subject; the test session was to collect kinematic data wearing no collar (unbraced) and the four different collars performing three different head/neck movements of flexion–extension, left–right lateral flexion (side to side bending), and left–right axial rotation, in 15 test conditions. A static post was also filmed at the beginning for the purpose of data analysis. The subjects performed three trials in each of the 15 test conditions. In all of the conditions, the subject began while sitting up straight with their back firmly against the back support of a chair. The subject's head was placed in a neutral position facing forward with eyes focused anteriorly on a spot positioned horizontally at the height of the eyes. A research assistant was positioned behind the subject with his hands placed firmly on top of the shoulders to prevent any movements of the shoulders during the testing process. In the flexion/extension trials, the subject was instructed to lower the chin to the chest (flexion), then extend the head backwards (extension), and finally return to the starting (neutral) position. In the lateral flexion trials, the subject was instructed to bend the neck to the left first, then to bend their neck to the right, and return to the starting (neutral) position. In the axial rotation trials, the subject was instructed to turn their head to the left and then to the right before returning to the starting (neutral) position. During the lateral bending and axial rotation trials, the subject was instructed to minimize the rotation of shoulders. During all these movements, each subject was asked to reach the end of range of motion, which was defined as meeting a resistance, before reversing the direction of motion immediately to ensure a consistent and smooth movement pattern. This criterion for the end of RoM was chosen because it resembles real-life situations for patients wearing a cervical orthosis and therefore the testing employed in this study should be considered as an active test. The order of the five testing collar conditions was randomized. In addition, the three movements were further randomized within each of the collar conditions.

2.5. Data processing and analysis

The coordinates of the reflective markers obtained from the Vicon were smoothed using the supplied spline function with a general cross-validation (Woltring, 1986). The 3D coordinates from the C3D file format were imported into a Matlab program to compute 3D angular kinematic variables using a method adapted from Areblad et al. (1990). A detailed account of mathematical derivations is provided in Appendix A.

2.6. Statistical analysis

Gender differences on selected RoM variables were examined initially using a one-way repeated measures analysis of variance (ANOVA). Due to a lack of significant differences, two gender data sets were therefore combined in subsequent statistical analyses to examine effects of the cervical collars on selected RoM variables using a one-way repeated measures ANOVA (SAS 8.2). Pair-wise t-tests were used in post hoc comparisons and the significant level of $P < 0.05$ was adjusted using a Bonferroni approach to correct for errors due to multiple comparisons. Specifically, the adjusted alpha level was set at 0.005 for the raw RoM comparisons and at 0.009 for the percent RoM comparisons.

3. Results

The descriptive data of average range of motion and the percent reduction of RoM in all four movements are provided in Tables 1 and 2. The results of the repeated measures ANOVAs showed significant omnibus effects for all movements. The post hoc comparisons indicated that all four braces had significantly reduced RoM in the movements compared to the unbraced conditions (Table 1). The XTW collar demonstrated less restriction in flexion than Miami J and C-Breeze collars. All three collars had less RoM in extension compared to the Miami J. For the same movement, the XTW collar performed better than the C-Breeze and Aspen collars. Furthermore, the C-Breeze showed less RoM than the Miami J in lateral bending (flexion). In addition, the C-Breeze, Aspen and XTW cervical orthoses all had less RoM in axial rotation than the Miami J.

Table 1
Average RoM (deg) during the cervical movements: mean (standard deviation)

Brace	Flexion	Extension	Lateral flexion	Rotation
Unbraced	56.0 (7.2)	68.6 (12.9)	83.5 (11.2)	137.4 (15.4)
Miami J	8.5[a] (7.8)	31.1[a] (16.7)	51.5[a] (14.6)	48.2[a] (22.4)
C-Breeze	9.6[a] (7.1)	27.2[a,b] (15.7)	46.3[a,b] (15.1)	42.0[a,b] (17.8)
Aspen	11.6[a] (10.5)	26.2[a,b] (16.2)	46.6[a] (14.9)	45.0[a,b] (20.5)
XTW	12.5[a,b,c] (8.9)	23.0[a,b,c,d] (13.8)	45.3[a] (14.7)	44.1[a,b] (20.1)

[a] Significantly different from unbraced.
[b] Significantly different from Miami J.
[c] Significantly different from C-Breeze.
[d] Significantly different from Aspen.

Table 2
Average percent reduction of RoM compared to the unbraced movements: mean (standard deviation)

Brace	Flexion	Extension	Lateral flexion	Rotation
Miami J	84.8 (14.2)	55.5 (20.1)	37.9 (17.1)	65.4 (14.7)
C-Breeze	82.9 (13.1)	60.8[a] (20.2)	44.6[a] (16.0)	69.6[a] (12.4)
Aspen	79.7 (18.2)	62.5[a] (19.4)	44.0[a] (15.8)	67.4 (14.5)
XTW	77.9[a,b] (15.9)	67.0[a,b,c] (17.2)	45.5[a] (17.0)	68.1(13.9)

[a] Significantly different from Miami J.
[b] Significantly different from C-Breeze.
[c] Significantly different from Aspen.

For the percent RoM reduction compared to the corresponding unbraced movement condition, the Miami J and C-Breeze collars showed significantly greater reduction on flexion RoM than the XTW collar (Table 2). For both extension and lateral flexion, all three collars showed greater percent RoM reduction than the Miami J. The XTW collar also showed greater reduction than the C-Breeze and Aspen in extension. Finally, only the C-Breeze showed a significantly greater reduction in percent RoM in axial rotation than the Miami J collar.

4. Discussion

The purpose of the study was to compare the effectiveness of two new cervical collars with two other established collars in restricting range of motion in the cervical spine. The cervical collar restrictions were evaluated through reduction of the raw RoM and percent RoM. The RoM data of the unrestricted movements from the current study showed 56° of flexion, 69° of extension, 83.5° of lateral bending, and 137.4° of axial rotation. These values are within the range of RoM data for each type of movements reported in the previous cervical orthoses studies (Sandler et al., 1996; Ducker, 1990; Mosenkis, 2001; Lunsford et al., 1994). Unrestricted range of motion reported in the other studies indicated 56–70° for flexion and 62–65° for extension (Ducker, 1990; Mosenkis, 2001; Lunsford et al., 1994). The lateral bending ranged from 58–92° (Sandler et al., 1996; Ducker, 1990; Mosenkis, 2001; Lunsford et al., 1994). The axial rotation values in the literature are 126–179° (Sandler et al., 1996; Ducker, 1990; Mosenkis, 2001; Lunsford et al., 1994).

The results on the head movements from this study compared to the unrestricted conditions exhibited significant reductions of RoM for all tested collars, suggesting effectiveness of all tested collars. The percent reductions on RoM were 78–85% for flexion and 56–67% for extension, 38–46% for lateral flexion, and 65–70% for axial rotation. Further analyses suggested that the C-Breeze cervical collar demonstrated more superior immobilization effects in extension, lateral bending and axial rotation than the Miami J. The XTW and Aspen cervical collars also showed greater restriction than the Miami J collar in extension and lateral bending. On the other hand, the Miami J and C-Breeze collars showed greater effect on RoM reduction in flexion than the XTW collar. The XTW cervical collar showed better capacity in restricting RoM than all other three collars in lateral bending. These results from the current study suggested that the two new cervical orthoses are effective in restricting RoMs in the cervical spine. The RoM reductions for these two new collars are either comparable to or better than what was reported in the previous studies on the Miami J and Aspen collars (Sandler et al., 1996; Ducker, 1990; Mosenkis, 2001; Lunsford et al., 1994).

The results from the current study demonstrated varied effectiveness of the tested ortheses on restricting different cervical movements. The percent reductions in RoM of the tested collars were better in flexion (81%) than extension (61%). This finding is in agreement with literature (Sandler et al., 1996; Ducker, 1990; Mosenkis, 2001; Lunsford et al., 1994; Askins and Eismont, 1997). Because the range of motion tested is of active nature and the strength of cervical extensors is greater than the flexors, it is conceivable that the difference in percent RoM reduction may be due to the strength difference between the two muscle groups. The results from this study showed that on average restriction on flexion RoM (81%) was better than those of axial rotation (68%) and lateral bending (43%); restriction on axial rotation was better than lateral bending. These trends are in general agreement with the results found in literature (Sandler et al., 1996; Ducker, 1990; Mosenkis, 2001; Lunsford et al., 1994; Askins and Eismont, 1997; Graziano et al., 1987). Clinicians should take into consideration these results when prescribing these cervical collars to their patients with different cervical impairments.

The normal range of motion in the cervical spine can vary with different age and gender groups (Dvorak et al., 1992). Dvorak et al. (1992), however, found no significant differences in the 20–29 and 60 age groups for all RoMs of unrestricted cervical movements. The statistical comparisons from the current study exhibited no significant gender differences between the male and female groups during the unbraced movements. In addition, the age of the participants in the current study spreads only across one decade (21–29 years) and further minimizes the potential age effect on the outcomes. Age is not commonly used as a subject selection criterion in most cervical orthoses studies. Often these studies employed subjects who were between 20 and earlier 30s (Johnson et al., 1977; Sandler et al., 1996; Askins and Eismont, 1997). Few studies used subjects whose ages spanned more than two decades (Mosenkis, 2001; Lunsford et al., 1994). Even when authors did employ subjects across several age groups, they usually did not compare the results from different age groups nor did they compare across gender groups. The subjects of the age group in this study typically enjoy the largest cervical RoM (Dvorak et al., 1992); it can be assumed that they have greater strength compared to their older counterparts. Therefore, it is logical to consider that the results derived from this age group should be equal to or better than those obtained from their older counterparts. However, the results from this study should not be extended to other age groups directly without further examination; further studies are warranted to verify validity of this extension. In addition, further studies are warranted to examine the gender effect on effectiveness of cervical orthoses, especially with subjects older than 20s.

The results from this study provide useful information regarding restriction of gross cervical movements by the tested cervical orthoses. Effectiveness of a cervical orthosis is not limited to the mechanical restriction of cervical motion. When a compliant subject wears a cervical collar, the collar provides benefits of improved proprioception, decreased loading to injured muscles or ligaments by added support to the region, in addition to the mechanical restraint provided (Sandler et al., 1996). However, extra cares should be taken when a subject cannot comply with a physician's instruction due to unconsciousness, seizure or psychological disturbance. Based on the results of this study, the tested cervical orthoses can be used when required restriction is less than 45° for flexion, 41° for extension, 92° for axial rotation (bilateral), and 36° for lateral bending. If greater restriction is desired, none of the tested orthoses is able to provide adequate support and a more restrictive cervical collar, e.g. sterno-occipital mandibular immobilization device, has to be used.

Many previous studies on cervical collars did not report the number of trials performed by each subject for each collar and movement combination. It seems apparent that majority of studies using radiographs employed only one trial during their measurements. This certainly would increase potential influences of random errors on the outcome. To improve reliability of the movement measurements, we asked our subjects to perform three trials per collar/movement condition. In addition, this is the first study using a triad marker set and a 3D model to evaluate effectiveness of cervical orthoses on restriction of cervical movements, to the knowledge of the authors. Advantages of a 3D model using videography over a traditional medical imaging technique such as radiograph or MRI include accuracy and efficiency. Due to difficulty of alignment between the film plane and body segments, these two-dimensional medical techniques tend to be less accurate in depicting 3D movements (Areblad et al., 1990). Since there is no need to move and re-set up equipment or subjects during testing using 3D videography, it is much more efficient and easier in data collection and analyses, and thus allows multiple measurements for a single movement to achieve greater reliability in the outcome. The Vicon 3D system used in this study uses an optimized auto-tracking algorithm to track reflective markers during movements thus to increase accuracy comparing to potential human and random errors introduced using manual tracing in a traditional X-ray measurement. In addition, the high-speed videography is capable of capturing accurate RoM data, especially at the end of RoM during a dynamic movement, which cannot be accurately determined by a static radiograph or a goniometry technique.

The marker set and computation algorithms used in this study were derived from Areblad et al. (1990). This triad marker set is sufficient to describe 3D motions of the head during the tested movements. The facial morphology of the individual subjects may influence the position of the anterior maxilla marker and therefore the orientation of the head with respect to the vertical axis of the lab coordinate system. However, only the ranges of motion data not the absolute maximal/minimal angles were examined in this study. Therefore the choice of the anterior maxilla marker and the initial position of the head have no effects on the outcomes of the study.

In summary, we studied four cervical orthoses in restricting cervical spine RoMs in this study. The results suggested that the two new cervical orthoses, C-Breeze and XTW collars from DeRoyal, along with the two commonly used cervical orthoses in medical practice, Miami J and Aspen, are effective in restricting RoMs in the cervical spine. The C-Breeze and XTW cervical orthoses performed either comparably as or better than the Miami J and Aspen collars.

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Appendix A

The room coordinate system (RCS) was defined by the calibration frame of the Vicon system.

$$\mathrm{RCS} = [\hat{x}, \hat{y}, \hat{z}] \tag{A.1}$$

where $\hat{x}$ is a unit vector in the anterior–posterior direction, $\hat{y}$ is a unit vector in the medial lateral direction, and $\hat{z}$ is a unit vector in the vertical direction.

Three retroreflective spherical markers were placed on the anterior maxilla (MXL), the forehead (FRHD), and the top of the head (CRN). A provisional coordinate system of the head (PCH) was defined from the three markers placed on the head.

$$\mathrm{PCH} = \left[\hat{i}_{\mathrm{PCH}}, \hat{j}_{\mathrm{PCH}}, \hat{k}_{\mathrm{PCH}}\right] \tag{A.2}$$

$$\hat{k}_{\mathrm{PCH}} = \frac{(\mathrm{FRHD} - \mathrm{MXL})}{\|\mathrm{FRHD} - \mathrm{MXL}\|} \tag{A.3}$$

$$\hat{j}_{\mathrm{PCH}} = \frac{\hat{k}_{\mathrm{PCH}} \times (\mathrm{CRN} - \mathrm{MXL})}{\|\hat{k}_{\mathrm{PCH}} \times (\mathrm{CRN} - \mathrm{MXL})\|} \tag{A.4}$$

$$\hat{i}_{\mathrm{PCH}} = \hat{j}_{\mathrm{PCH}} \times \hat{k}_{\mathrm{PCH}} \tag{A.5}$$

where $\hat{i}_{\mathrm{PCH}}$, $\hat{j}_{\mathrm{PCH}}$ and $\hat{k}_{\mathrm{PCH}}$ are unit vectors of PCH in the anterior–posterior, medial–lateral and vertical directions, respectively.

To ensure that the head coordinate system is aligned with the RCS when the subject's head was in the neutral position, a static trial was video taped with the head and neck in a neutral position and the head aligned with the RCS. The static trial was used to determine the transformation matrix of the head (TMH):

$$\mathrm{TMH} = [\mathrm{PCH}]^{-1}[\mathrm{RCS}] \tag{A.6}$$

Henceforth, the head coordinate system (HCS) was computed by multiplying PCH by TMH:

$$\mathrm{HCS} = [\mathrm{PCH}][\mathrm{TMH}] \tag{A.7}$$

Eqs. (A.8)–(A.10) was used to determine the angle of the head in the sagittal plane (σ), in the frontal plane (φ) and in the transverse plane (τ), respectively.

$$\sigma = \cos^{-1}\left(\hat{k}_{\mathrm{HCS}} \cdot \left(\hat{z} \times \hat{j}_{\mathrm{HCS}}\right)\right) \tag{A.8}$$

$$\phi = \cos^{-1}\left(\hat{k}_{\mathrm{HCS}} \cdot \left(\hat{i}_{\mathrm{HCS}} \times \hat{z}\right)\right) \tag{A.9}$$

$$\tau = \cos^{-1}\left(\hat{i}_{\mathrm{HCS}} \cdot \hat{y}\right) \tag{A.10}$$

where $\hat{i}_{\mathrm{HCS}}$, $\hat{j}_{\mathrm{HCS}}$ and $\hat{k}_{\mathrm{HCS}}$ are unit vectors of HCS. The actual RoM for the flexion and extension were determined by finding their deviations from the head neutral position defined as 90°. This neutral position was chosen to have a consistent initial head position during the tested movements. The lateral bending RoM was determined by finding the difference between the maximums of the left and right lateral bending. The axial rotation RoM was determined similarly by finding the difference between the maximums of the left and right axial rotations.

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