Effects of orthoses on three-dimensional load–displacement properties of the cervical spine

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Abstract

Purpose Our objectives were to develop a skull-neck-thorax model capable of quantifying spinal motions in an intact human cadaver neck with and without cervical orthoses, determine the effect of orthoses on three-dimensional load–displacement properties of all cervical spinal levels, and compare and contrast our results with previously reported in vivo data.

Methods Load input flexibility tests were performed to evaluate two cervical collars (Vista® collar and Vista® Multipost collar) and two cervicothoracic orthoses (CTOs: Vista® TS and Vista® TS4) using the skull-neck-thorax model with 10 intact whole cervical spine specimens. The physiologic range of motion (RoM) limit was the peak obtained from flexibility tests with no orthosis. Pair-wise repeated measures, analysis of variance ($p < 0.05$), and Bonferroni post hoc tests determined significant differences in average peak RoM at each spinal level among the experimental conditions.

Results Significant reductions below physiologic limits were observed due to all orthoses in: three-dimensional head/T1 RoMs, all sagittal intervertebral RoMs, and lateral bending at C4/5 through C7/T1. Both CTOs significantly reduced C6/7 sagittal RoM as compared to both collars. Intervertebral RoMs with the orthoses could not be differentiated from physiologic limits at the upper cervical spine in lateral bending and throughout the entire cervical spine in axial rotation, with the exception of C1/2.

Conclusions Our results indicate that cervical orthoses effectively immobilized the entire cervical spine in flexion/extension and the lower cervical spine in lateral bending. The CTOs improved immobilization of the lower cervical spine in flexion/extension as compared to the collars. The orthoses were least effective at restricting lateral bending of the upper spinal levels and axial rotation of all spinal levels, except C1/2. Understanding immobilization provided by orthoses will assist clinicians in selecting the most appropriate brace based upon patient-specific immobilization requirements.

Keywords Cervical collar · Cervicothoracic orthosis · Biomechanics · Spine · Motion

Introduction

Cervical orthoses are commonly used to immobilize the neck during emergency management, post-operatively following surgical fixation, or as definitive treatment of neck injuries [1–3]. Several types exist, with varying immobilization capabilities and comfort, including soft and hard cervical collars, cervicothoracic orthosis (CTO), and halo-vest [4–8]. The CTO aims to improve neck immobilization offered by the collar. Understanding cervical spine immobilization provided by orthoses assists clinicians in selecting the most appropriate device based upon the anatomical location and severity of injury, and patient-specific immobilization requirements including magnitude and direction (flexion–extension, axial rotation, and/or lateral bending).

Previous biomechanical studies have determined neck motion restriction due to cervical orthoses in human volunteers [4–7, 9–14] or whole cadavers [15–19] using

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standard radiography, video fluoroscopy, goniometry, or optoelectronic measurement techniques. Even the most sophisticated studies are limited to measuring intervertebral motions only in the sagittal plane [4–7, 9], or three-dimensional motions only of the head or one or two spinal levels [19, 20]. In a pioneering study of healthy volunteers, Johnson et al. [4, 5] generally observed increased cervical spine immobilization due to increased orthosis length and rigidity. They found that: (1) cervical collars and CTOs did not adequately restrict head motions in axial rotation or lateral bending or upper cervical spine motions in flexion–extension, and (2) the CTO improved immobilization of the lower cervical spine as compared to the collar alone. In more recent studies of healthy volunteers, Gavin et al. [7] and Schneider et al. [6] found that modern cervical collars and CTOs significantly reduced all sagittal intervertebral motions as compared to unrestricted. Although attempts have been made to standardize effort during the *in vivo* studies by measuring electromyographic activities of some neck muscles, actual neck loads may vary among subjects and orthoses. The human volunteer model cannot be used to study the effectiveness of orthoses in limiting motions of the injured spine.

The first goal of this study was to develop a skull-neck-thorax model capable of quantifying spinal motions in an intact human cadaver neck with and without cervical orthoses. Next, we used the model to determine the three-dimensional load–displacement properties of all cervical spinal levels with and without modern cervical collars and CTOs. Lastly, we compared and contrasted our results with previously reported *in vivo* data.

Materials and methods

Skull-neck-thorax model with cervical orthoses

Ten fresh-frozen human osteoligamentous whole cervical spine specimens were mounted in resin at the occiput and T1 vertebra. The average age of the specimens was 81.4 years (range 76–90 years) with five male and five female donors. Apart from typical age related degenerative changes, the specimens did not suffer from any disease or injury that could have affected the osteoligamentous structures.

The skull-neck-thorax model consisted of the whole cervical spine specimen, plastic skull, and mannequin thorax (Fig. 1). The whole cervical spine was anatomically positioned in neutral posture between the plastic skull and the mannequin thorax, with the skull rigidly fixed to the occipital mount and the T1 mount rigidly fixed to the mannequin thorax. The thorax was fitted with a shirt. In neutral posture, the occipital mount and skull were aligned

horizontally and the average anterior tilt of the T1 vertebra was 27.1° (SD 5.7°), consistent with *in vivo* thoracic kyphosis [21, 22]. To attach motion measuring flags, a custom plastic support was fitted rigidly onto the anterior aspect of the skull and each vertebra (C1 through T1). The flags, each with three non-collinear markers, were rigidly fixed onto the plastic supports. The C1 flag extended through an enlarged opening of the mouth, while the inferior vertebral flags extended through the tracheal opening of the collar anterior panel.

Two cervical collars (Vista[®] collar and Vista[®] Multipost collar) and two CTOs (Vista[®] TS and Vista[®] TS4) were tested, all manufactured by Aspen[®] Medical Products Inc., Irvine, CA, USA. The orthoses were applied to the model according to the manufacturer's written instructions, as they would be applied clinically. The anterior collar panel of all orthoses was the same, while the posterior collar panel of the Vista[®] collar differed from that of the Vista[®] Multipost collar, Vista[®] TS, and Vista[®] TS4. Neither the Vista[®] collar nor the Vista[®] Multipost collar included anterior or posterior thoracic/lumbar panels. The Vista[®] TS, which included the Vista[®] Multipost collar, utilized an anterior thoracic/lumbar panel connected to the anterior collar panel via a strut and to the posterior thoracic/lumbar panel above the waist (Fig. 1). The Vista[®] TS4, which included the Vista[®] TS, utilized a posterior strut connection

Fig. 1 Photograph of the skull-neck-thorax model with cervical orthosis. The global coordinate system (*xyz*) was fixed to the ground with its positive *x*-axis directed to the left, positive *y*-axis oriented superiorly, and positive *z*-axis oriented anteriorly relative to the model in neutral posture. Motion tracking markers were rigidly fixed to the skull and vertebrae, C1 through T1. The loading jig was rigidly fixed to the skull

Fig. 2 Flexibility testing protocol in which pure moments were applied in three equal steps up to peak loads of 1.5, 3, and 1.5 Nm in flexion–extension, axial torque, and lateral bending, respectively. Motion data were recorded on the third loading cycle. The rotation–moment curves, ranges of motion (RoMs), and neutral zones (NZs) were determined for head/T1 and each spinal level and each specimen

between the posterior collar and thoracic/lumbar panels. To replicate the in vivo environment during testing with the orthoses, the osteoligamentous neck was wrapped bilaterally and posteriorly with surrogate soft tissue prior to applying the orthoses.

To prepare the model for flexibility testing, a loading jig was applied to the occipital mount, while the thorax was fixed to the test table. The combined weight of the loading jig, skull, and occipital mount were counterbalanced throughout the flexibility tests.

Three-Dimensional Flexibility Testing

Three-dimensional flexibility testing was initially performed with no orthosis (unrestricted), and was repeated to evaluate the effects of the Vista® collar, Vista® Multipost collar, Vista® TS, and lastly Vista® TS4. For each experimental condition, pure moments were applied to the occipital mount in three equal steps up to peak loads of 1.5, 3, and 1.5 Nm in flexion–extension, axial torque, and lateral bending, respectively (Fig. 2). At each moment step, the loading was held constant for 30 s to allow for viscoelastic creep, after which the time kinematic data were recorded. Two preconditioning cycles were performed and data were recorded on the third loading cycle. A custom-built loading apparatus was used for automated flexibility testing. The kinematic data were measured using the Optotrak three-dimensional motion measuring system (Optotrak 3020, Northern Digital, Waterloo, Ontario, Canada). Motions of each vertebra were expressed relative to and in the coordinate system of the directly inferior

vertebra. Each vertebral coordinate system, which was fixed to and moved with the vertebra, had its z-axes horizontal and positive forward, y-axes vertical and positive upward, and x-axes horizontal and positive to the left, and was initially aligned with the global coordinate system (Fig. 1) in neutral posture. The Euler angles were calculated at each load increment for each spinal level, C0/1 through C7/T1, and head/T1 in the sequence Rx, followed by Ry and Rz [23, 24]. Flexion, left axial rotation, and right lateral bending were positive, while extension, right axial rotation, and left lateral bending were negative. Average (SD) system errors as determined in a separate study [25] were -0.05° (0.05°), -0.03° (0.04°), and -0.01° (0.02°) for rotations around the x, y, and z axes, respectively.

Data analyses

Average rotation–moment curves were plotted, and ranges of motion (RoMs) and neutral zones (NZs) (Fig. 2) were computed for head/T1 (head relative to T1) and each spinal level, motion direction, and experimental condition. The physiologic motion limit was defined at head/T1, and each spinal level as the peak RoM obtained from the unrestricted flexibility tests. Pair-wise repeated measures, analysis of variance ($p < 0.05$) and Bonferroni post hoc tests were performed to determine significant differences in the average total RoM at each spinal level among the five experimental conditions (unrestricted, 2 cervical collars, 2 CTOs). Adjusted p values were computed based upon the 270 post hoc tests performed (3 motion planes by 9 spinal regions, C0/1 through C7/T1 and head/T1, by 10 pair-wise tests among experimental condition). To visualize the results, the percentages of average unrestricted RoM and NZ allowed by the orthoses were determined.

Results

The average rotation–moment curves are presented in graphical form for flexion/extension (Fig. 3a–i), axial rotation/torque (Fig. 3j–r), and lateral bending (Fig. 3s–aa). These data are provided for head/T1 and each spinal level, C0/1 through C7/T1 without orthosis (unrestricted) and with the orthoses. For each experimental condition and motion direction, head/T1 and all spinal levels consistently rotated in the direction of the applied moment. The average physiologic rotation limits for head/T1 as determined from the unrestricted flexibility tests were: 73.5° total, 38.7° flexion, 34.8° extension for sagittal RoM (Table 1a–c); 116.5° total, 53.3° right, 63.2° left for axial RoM (Table 1d–f); and 44.9° total, 21.6° right, 23.3° left for lateral bending (Table 1g–i). Among spinal levels, the physiologic limits were highest at C0/1 and least at C7/T1

◀ **Fig. 3** The average rotation–moment curves for head/T1 and each spinal level, C0/1 through C7/T1, without orthosis (unrestricted *filled circle*) and with orthoses (Vista® collar *open circle*, Vista® Multipost collar *square*, Vista® TS *triangle*, and Vista® TS4 *diamond*) for: flexion/extension (**a–i**), axial rotation/torque (**j–r**), and lateral bending (**s–aa**). Flexion, left axial rotation/torque, and right lateral bending are positive while extension, right axial rotation/torque, and left lateral bending are negative. To improve readability, the *plot symbols* are slightly offset and *error bars* are shown only for the unrestricted tests

for sagittal RoM, highest at C1/2 and least at C2/3 for axial RoM, and highest at the upper spinal levels, C0/1 and C1/2, and least at the inferior spinal levels for lateral bending.

All orthoses significantly reduced average unrestricted total RoMs at head/T1 in all motion directions (Table 1a,d,g). All orthoses generally reduced average intervertebral RoMs to below physiologic limits in all motion directions with the exception of C1/2 in lateral bending (Table 1g–i; Fig. 3u). Significant reductions in intervertebral total RoMs below physiologic limits due to the orthoses were observed in sagittal RoM (all spinal levels, all orthoses; Table 1a), axial RoM (C1/2, Vista® Multipost collar and Vista® TS; Table 1d), and lateral bending (C4/5 through C7/T1, all orthoses; C3/4, Vista® Multipost collar; Table 1g).

Intervertebral RoMs and NZs due to the orthoses, expressed as percentages of average unrestricted motions appear in Fig. 4. These data generally demonstrate reduced sagittal motions due to the CTOs as compared to the collars at the lower cervical spine, C4/5 through C7/T1 (Fig. 4a). Both CTOs significantly reduced total sagittal RoM at C6/7 as compared to the collars (13.6–14.8 % unrestricted RoM allowed by the CTOs vs. 42.0–44.3 % allowed by the collars; Table 1a). The orthoses generally reduced the intervertebral NZs below unrestricted values for sagittal rotation and lateral bending (Fig. 4a, c), with the exception of C1/2 in lateral bending. Intervertebral NZs in axial rotation due to the orthoses above unrestricted values were generally observed at C0/1, C1/2, C5/6, and C6/7 (Fig. 4b).

Discussion

The present study, using a skull-neck-thorax model (Fig. 1), determined the three-dimensional load–displacement properties of the cervical spine with cervical collars (Vista® collar and Vista® Multipost collar) and CTOs (Vista® TS and Vista® TS4) and compared these data to unrestricted. The physiologic motion limit was defined at each spinal level as the peak RoM obtained from the unrestricted flexibility tests. Significant reductions below physiologic limits were observed due to all orthoses in: three-dimensional head/T1 RoM (Table 1a, d, g), all sagittal intervertebral RoMs (Table 1a), and lateral bending at C4/5 through C7/T1 (Table 1g). Both CTOs significantly reduced C6/7 sagittal RoM as compared to both collars (Table 1a).

Our study protocol has strengths as well as limitations that should be considered before translating our findings towards recommendations for clinical use of orthoses. Varying subject effort during prior human volunteer studies may confound previously reported results [4–7, 9–14]. Our load input flexibility tests applied the same peak pure moment with and without each orthosis. This enabled direct comparisons of the immobilization capabilities between the orthoses and relative to unrestricted. Previous research has observed high repeatability of spinal motions, within 0.8°, due to multiple flexibility tests of the same specimen under consistent experimental conditions [26]. We did not investigate neck motions due to axial force. To determine the spinal load–displacement properties, we computed the main spinal rotation around each anatomical axis in response to a pure moment applied around that axis. We did not compute coupled rotations or helical axis of motion [28]. Our neck specimens, with an average age of 81.4 years, were stiffer than the younger population. However, each specimen served as its own control in our statistical analyses. The average unrestricted head/T1 RoMs of our specimens (Table 1a, d, g) were within ranges reported in a previous *in vivo* study of individuals over 80 years of age [27], validating our load protocol. We did not study spinal motions due to the orthoses during simulated activities of daily living, which likely produce motion patterns that differ from our results. Our model utilized normal, uninjured cervical spine specimens to enable comparisons of our results with previously reported *in vivo* data, and to provide baseline data for future studies of the effects of orthoses on stabilizing specific neck injuries. These latter data are not obtainable using human volunteer or computational models. The present findings require extrapolations before being applied to the injured spine, and such extrapolations have yet to be proven.

Our skull-neck-thorax model is limited by factors inherent to *in vitro* studies. While we did not explicitly compare contact zones or pressures between our model and *in vivo* data, we hypothesize that contact zones of the orthoses with the skull and torso of our model were similar to *in vivo* contact zones. The inclusion of a rigid mannequin torso in our model likely enhanced the neck immobilization capabilities of the CTOs as compared to the previous *in vivo* studies, which allowed physiologic soft tissue deformation at the thoracic-lumbar region. We used single surrogate skull and torso models, and thus did not investigate changes in body habitus. To enable rigid placement of vertebral motion tracking flags, we dissected neck skin, fat, and muscle and replaced these with surrogate soft tissue wrapped bilaterally and posteriorly around the osteoligamentous cervical spine specimens during testing with the orthoses. Our study is the first to comprehensively report the three-dimensional load–displacement properties of all cervical

Table 1 Average range of motion (RoM) in degrees for each spinal level, C0/1 through C7/T1 and head/T1 without orthosis (unrestricted) and with orthoses (Vista® collar, Vista® Multipost collar, Vista® TS, and Vista® TS4) for: (a) total sagittal (flexion plus extension) RoM, (b) flexion, and (c) extension; (d) total (right plus left), (e) right, and (f) left axial RoMs; and (g) total (right plus left), (h) right, and (i) left lateral bending

	C0/1	C1/2	C2/3	C3/4	C4/5	C5/6	C6/7	C7/T1	Head/T1
(a) Total sagittal RoM									
Unrestricted	18.6 (5.9)	12.0 (4.3)	6.4 (4.4)	7.9 (4.5)	8.1 (2.1)	9.9 (4.1)	8.8 (2.7)	5.3 (1.3)	73.5 (17.7)
Vista® Collar	3.9 (4.2)	2.5 (2.8)	1.9 (2.7)	2.0 (1.3)	2.6 (1.1)	3.1 (1.1)	3.7 (1.7)	2.1 (1.6)	16.6 (7.4)
Multipost Collar	3.3 (2.8)	2.0 (1.5)	1.5 (1.1)	2.6 (2.1)	2.8 (1.5)	3.0 (1.1)	3.9 (2.3)	2.0 (1.6)	18.7 (7.3)
Vista® TS	4.6 (2.8)	2.5 (1.6)	1.4 (1.2)	2.0 (1.8)	1.7 (0.9)	1.3 (0.5)	*1.2 (0.8)	1.0 (0.8)	14.7 (7.5)
Vista® TS4	4.6 (3.1)	2.9 (1.5)	1.3 (1.1)	2.6 (1.9)	1.6 (0.9)	1.2 (0.7)	*1.3 (1.5)	0.7 (1.2)	13.8 (7.6)
(b) Flexion									
Unrestricted	9.7 (5.0)	8.7 (4.1)	3.1 (2.5)	4.4 (2.4)	4.0 (1.8)	4.1 (1.7)	3.4 (1.7)	2.6 (1.3)	38.7 (12.4)
Vista® Collar	1.0 (1.3)	1.1 (0.8)	0.7 (0.6)	1.5 (1.0)	1.4 (0.5)	1.3 (0.6)	1.3 (0.6)	0.8 (0.4)	9.1 (5.1)
Multipost Collar	1.3 (1.4)	1.4 (1.1)	0.8 (0.6)	1.5 (1.0)	1.5 (1.1)	1.3 (0.6)	1.8 (0.8)	1.0 (0.5)	10.2 (4.6)
Vista® TS	2.4 (2.0)	1.6 (1.3)	1.1 (0.9)	1.2 (1.0)	1.0 (0.7)	0.5 (0.4)	0.6 (0.3)	0.5 (0.5)	8.3 (5.2)
Vista® TS4	2.5 (1.9)	1.8 (1.3)	0.8 (0.8)	1.5 (1.1)	0.9 (0.7)	0.5 (0.4)	0.6 (0.7)	0.2 (0.5)	7.6 (5.3)
(c) Extension									
Unrestricted	8.9 (3.7)	3.3 (1.5)	3.3 (3.3)	3.6 (2.2)	4.2 (1.8)	5.8 (3.1)	5.4 (2.1)	2.7 (1.1)	34.8 (11.7)
Vista® Collar	2.9 (4.0)	1.4 (2.8)	1.2 (2.7)	0.5 (0.4)	1.2 (0.7)	1.7 (1.0)	2.4 (1.2)	1.2 (1.8)	7.5 (4.5)
Multipost Collar	1.9 (2.1)	0.6 (0.7)	0.8 (1.1)	1.2 (1.4)	1.3 (1.0)	1.9 (0.9)	2.2 (1.9)	1.0 (1.3)	8.5 (4.3)
Vista® TS	2.4 (1.9)	0.9 (0.7)	0.4 (0.4)	0.9 (0.8)	0.8 (0.5)	0.8 (0.4)	0.6 (0.6)	0.6 (0.6)	6.4 (3.1)
Vista® TS4	2.1 (1.4)	1.1 (0.9)	0.5 (0.6)	1.1 (1.6)	0.7 (0.6)	0.7 (0.7)	0.8 (0.8)	0.5 (1.2)	6.2 (3.5)
(d) Total axial RoM									
Unrestricted	10.2 (4.0)	62.9 (13.1)	5.8 (4.1)	7.4 (5.7)	7.5 (2.6)	7.2 (2.3)	6.1 (3.0)	6.6 (3.6)	116.5 (28.0)
Vista® Collar	4.7 (5.8)	47.9 (11.9)	4.2 (3.5)	4.7 (4.0)	4.8 (3.9)	2.9 (1.7)	4.1 (2.8)	5.4 (6.5)	71.7 (35.5)
Multipost Collar	5.4 (6.0)	38.6 (18.7)	4.7 (6.5)	4.4 (3.8)	4.4 (3.8)	5.4 (4.2)	5.2 (5.1)	5.0 (6.1)	70.2 (31.9)
Vista® TS	7.3 (6.8)	42.3 (17.7)	4.3 (3.4)	5.8 (5.5)	4.4 (4.3)	4.9 (7.4)	4.2 (2.6)	4.0 (6.2)	64.8 (28.1)
Vista® TS4	5.9 (7.3)	45.6 (16.6)	4.1 (2.2)	4.7 (4.3)	4.8 (4.0)	3.1 (3.4)	4.2 (3.2)	4.6 (9.8)	69.5 (34.3)
(e) Right axial RoM									
Unrestricted	5.1 (2.0)	27.7 (7.4)	2.9 (2.0)	3.7 (2.9)	3.8 (1.3)	3.6 (1.2)	3.0 (1.5)	3.3 (1.8)	53.3 (14.2)
Vista® Collar	2.3 (2.9)	20.7 (7.3)	2.1 (1.7)	2.3 (2.0)	2.4 (1.9)	1.4 (0.9)	2.1 (1.4)	2.7 (3.2)	33.0 (16.9)
Multipost Collar	2.7 (3.0)	16.5 (9.0)	2.3 (3.2)	2.2 (1.9)	2.2 (1.9)	2.7 (2.1)	2.6 (2.6)	2.5 (3.0)	31.8 (16.5)
Vista® TS	3.7 (3.4)	19.2 (10.2)	2.1 (1.7)	2.9 (2.7)	2.2 (2.1)	2.5 (3.7)	2.1 (1.3)	2.0 (3.1)	32.1 (19.3)
Vista® TS4	3.0 (3.6)	20.3 (10.3)	2.0 (1.1)	2.3 (2.1)	2.4 (2.0)	1.6 (1.7)	2.1 (1.6)	2.5 (5.1)	35.0 (18.0)
(f) Left axial RoM									
Unrestricted	5.1 (2.0)	35.1 (8.5)	2.9 (2.0)	3.7 (2.9)	3.8 (1.3)	3.6 (1.2)	3.0 (1.5)	3.3 (1.8)	63.2 (18.1)
Vista® Collar	2.3 (2.9)	27.2 (7.9)	2.1 (1.7)	2.3 (2.0)	2.4 (1.9)	1.4 (0.9)	2.1 (1.4)	2.7 (3.2)	38.7 (21.3)
Multipost Collar	2.7 (3.0)	22.1 (10.7)	2.3 (3.2)	2.2 (1.9)	2.2 (1.9)	2.7 (2.1)	2.6 (2.6)	2.5 (3.0)	38.5 (19.0)
Vista® TS	3.7 (3.4)	23.1 (10.2)	2.1 (1.7)	2.9 (2.7)	2.2 (2.1)	2.5 (3.7)	2.1 (1.3)	2.0 (3.1)	32.7 (12.7)
Vista® TS4	3.0 (3.6)	25.3 (8.1)	2.0 (1.1)	2.3 (2.1)	2.4 (2.0)	1.6 (1.7)	2.1 (1.6)	2.5 (5.1)	38.0 (18.2)
(g) Total lateral bending									
Unrestricted	6.8 (2.3)	6.2 (4.6)	4.6 (3.4)	4.0 (2.8)	4.5 (1.6)	3.9 (1.8)	4.0 (2.0)	4.5 (2.0)	44.9 (16.1)
Vista® Collar	5.4 (1.5)	7.6 (5.9)	3.2 (2.6)	2.7 (2.2)	2.7 (1.1)	2.5 (1.4)	2.5 (1.2)	2.6 (1.2)	27.5 (13.2)
Multipost Collar	4.9 (1.6)	6.7 (5.9)	2.7 (2.4)	2.3 (1.6)	2.7 (1.5)	2.5 (1.6)	2.6 (1.6)	2.2 (1.1)	25.9 (11.1)
Vista® TS	6.6 (3.8)	8.3 (6.8)	2.5 (2.3)	2.9 (2.3)	2.2 (1.1)	2.3 (1.3)	1.9 (1.3)	1.7 (0.9)	25.9 (12.5)
Vista® TS4	5.7 (2.0)	7.6 (6.0)	2.9 (2.2)	2.6 (2.2)	2.1 (1.1)	1.8 (0.7)	1.6 (0.9)	1.3 (1.0)	25.0 (12.0)
(h) Right lateral bending									
Unrestricted	3.0 (0.7)	3.4 (2.9)	1.9 (1.4)	1.9 (1.4)	2.1 (0.9)	2.0 (1.4)	1.7 (1.0)	2.1 (1.4)	21.6 (7.7)
Vista® Collar	1.9 (0.5)	3.3 (3.3)	1.2 (1.0)	1.3 (1.1)	1.2 (0.6)	1.1 (0.8)	1.2 (0.7)	1.0 (0.8)	11.9 (6.8)
Multipost Collar	1.9 (0.9)	3.7 (4.0)	1.2 (1.0)	1.2 (0.9)	1.3 (0.7)	1.1 (1.0)	1.6 (1.2)	1.1 (0.8)	13.0 (6.4)

Table 1 continued

	C0/1	C1/2	C2/3	C3/4	C4/5	C5/6	C6/7	C7/T1	Head/T1
Vista [®] TS	2.8 (1.8)	4.2 (3.4)	0.8 (0.9)	1.2 (0.9)	1.2 (1.0)	1.2 (1.1)	1.1 (1.0)	0.8 (0.5)	12.6 (6.6)
Vista [®] TS4	2.4 (0.6)	3.9 (2.5)	1.0 (0.9)	1.3 (0.9)	1.2 (0.9)	0.8 (0.6)	0.9 (0.5)	0.6 (0.7)	11.7 (4.5)
(i) Left lateral bending									
Unrestricted	3.8 (1.9)	4.0 (2.6)	2.8 (2.3)	2.1 (1.5)	2.4 (1.1)	1.9 (0.9)	2.3 (1.3)	2.4 (1.0)	23.3 (9.9)
Vista [®] Collar	3.5 (1.4)	4.3 (3.1)	2.0 (2.0)	1.4 (1.2)	1.5 (0.8)	1.4 (1.0)	1.3 (0.8)	1.5 (0.7)	15.6 (6.9)
Multipost Collar	3.0 (1.3)	3.0 (2.3)	1.5 (1.5)	1.1 (0.9)	1.4 (1.0)	1.4 (0.7)	1.1 (1.0)	1.1 (0.6)	13.0 (5.4)
Vista [®] TS	3.7 (2.2)	4.1 (3.7)	1.7 (1.8)	1.4 (1.9)	1.0 (0.4)	1.1 (0.6)	0.9 (0.5)	1.0 (0.5)	13.3 (6.4)
Vista [®] TS4	3.3 (1.9)	3.7 (3.7)	1.9 (1.4)	1.3 (1.4)	0.9 (0.4)	0.9 (0.3)	0.7 (0.5)	0.7 (0.5)	13.3 (8.0)

Standard deviations are provided in parentheses. Significant differences among the pair-wise tests for total RoM among experimental conditions are indicated for each spinal level and head/T1 (bold/italic: significantly less RoM than unrestricted; * significantly less RoM than with Vista[®] collar and Vista[®] Multipost collar). The physiologic motion limit was defined at each spinal level as the peak RoM obtained from the unrestricted flexibility tests

spinal levels with and without cervical collars and CTOs. The collective data of our present study and previously reported results [6–8] may be used to help identify the most appropriate orthosis based upon patient-specific neck immobilization requirements.

Our results are consistent with previous human volunteer studies, which observed significant reductions in sagittal intervertebral RoMs due to collars and CTOs as compared to unrestricted [4–7]. Orthoses effectively restrict sagittal neck motions by transmitting loads to the neck through contact at the mandible, occiput, sternum/clavicle, shoulders, and upper back [29]. Restriction of sagittal RoMs at the upper and middle cervical spine could not be statistically differentiated between the collars and CTOs (Table 1a). Our data demonstrated that CTOs provided more effective immobilization of the lower cervical spine, C4/5 through C7/T1, as compared to the collars (Fig. 4a) consistent with the in vivo data. The greatest total sagittal RoM restriction was provided by the Vista[®] TS4 at C5/6, allowing 12.1 % of unrestricted motion (Table 1a). The present orthoses improved restriction of sagittal head/T1 RoM in extension, but not in flexion as compared to in vivo data reported by Gavin et al. [7] (21.6–24.5 % vs. 32.0–43.0 % unrestricted extension allowed by the collars; 17.8–18.3 % vs. 22.0–38.0 % unrestricted extension allowed by the CTOs). While our study demonstrated that cervical collars and CTOs adequately immobilized flexion/extension of the cervical spine for the experimental conditions studied, Chin et al. [12] observed that these braces significantly increased sagittal motions of the upper cervical spine in healthy volunteers during mastication as compared to no orthosis. Their results suggest that sagittal neck immobilization provided by orthoses during activities of daily living may be less than that reported in our study, particularly at the upper cervical spine.

In a recent review of prior studies that investigated the effectiveness of spinal braces, Agabegi et al. [8] observed that cervical collars were least effective at reducing neck axial rotation and lateral bending, as compared to sagittal motions. Our results confirm their findings. Intervertebral RoMs with the orthoses could not be differentiated from unrestricted at the upper cervical spine, C0/1 through C2/3 in lateral bending (Table 1g), and throughout the entire cervical spine in axial rotation (Table 1d) with the exception of C1/2. While optimized to reduce sagittal neck motions, the design of modern cervical orthoses (Fig. 1) provides insufficient contact at the mandible to effectively limit axial rotation. During axial rotation, we observed that the mandible rotated out of the anterior collar panel in some specimens which may be due, in part, to the absence of soft tissue at the mandible of our model (Fig. 1). This caused reduced frictional force at this region as compared to that of a whole head-neck cadaveric model or in vivo model. This is likely what caused the intervertebral NZs in axial rotation to exceed unrestricted values at some spinal levels due to the orthoses (Fig. 4b). The NZ is the part of the RoM (Fig. 2) that is produced with minimal internal resistance, and is the zone of high flexibility or laxity [30]. Insufficient restraint of the skull by the anterior and posterior collar panels reduced the capabilities of the orthoses to effectively immobilize the upper cervical spine in lateral bending. Caution should be taken when cervical collars are used in the emergency management of those with suspected axial rotation or lateral bending neck instability. Future studies are warranted to investigate the effectiveness of cervical orthoses in limiting axial rotation and lateral bending neck motions in the presence of spinal injury and instability. While prior studies have demonstrated that collars do not effectively immobilize the grossly unstable cervical spine [31], little work has been

(a) Sagittal Rotation **(b) Axial Rotation** **(c) Lateral Bending**

Fig. 4 Percentages of average unrestricted RoM and NZ allowed by the orthoses at each spinal level (Vista® collar *open circle*, Vista® Multipost collar *square*, Vista® TS *triangle*, and Vista® TS4 *diamond*) for: **a** sagittal rotation, **b** axial rotation, and **c** lateral bending. The physiologic RoM bands ($\pm 100\%$) are indicated by grey vertical panels

done to investigate the effectiveness of orthoses for immobilizing clinically relevant neck injuries.

Other factors, in addition to immobilization requirements, should be considered when choosing an appropriate orthosis for clinical use such as patient compliance and potential complications. While these other factors could not be evaluated using our present in vitro model, they have been addressed by previous in vivo studies. The Vista® TS4, with its posterior strut connecting the posterior

collar and thoracic/lumbar panels, would likely not be well tolerated by patients while supine or those who undergo prolonged bed rest. In those individuals, the collar or Vista® TS would serve as effective alternatives. Skin breakdown and pressure ulcers [32, 33] due to prolonged usage have been documented in some patients particularly at the main contact points at the mandible, occiput, ears, shoulders, and clavicles. Prior studies have demonstrated that these complications may be reduced or eliminated with appropriate choice of newer, improved orthotics, an appropriate skin care regimen and monitoring, and proper fitting and application of the orthoses [34–36]. Prolonged or over-usage of orthotics combined with inactivity may weaken spinal muscles [8]. Consideration of these potential complications together with knowledge obtained from biomechanical studies of collar and CTO immobilization efficacy will assist clinicians in selecting the most appropriate patient-specific orthosis.

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Conflict of interest None.

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