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The impact of neck pain and movement performance on the interarticular compressive force of the cervical spine: a cross-sectional study based on OpenSim

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Abstract

Background Excessive interarticular compressive force (CF) caused by poor posture increases the risk of neck pain. However, existing research on cervical CF is based on healthy individuals, and studies on those with neck pain are lacking. This study aims to address this gap by simultaneously collecting data from individuals with neck pain and asymptomatic individuals, simulating the CF during physiological movements such as flexion–extension, lateral bending, and rotation, to explore the impact of neck pain and movement performance on the interarticular CF.

Methods A 3D motion capture system and a multicervical unit were utilized to collect kinematic data and maximum voluntary isometric contraction (MVIC), respectively. The kinematic data were processed in OpenSim, using individually scaled cervical spine models. Time and peak angles were obtained via inverse kinematics, and the CF was calculated via joint reaction analysis. Regression analysis was conducted to assess the correlations between neck pain status, movement performance characteristics (time, peak angle, MVIC) and CF normalized by body mass. Variables with $p < 0.1$ in the univariate regression were included in the multivariate regression model for further adjustment.

Results Sixty participants were enrolled in the study, comprising 30 individuals in the neck pain group and 30 in the asymptomatic group. The mean peak CF in the neck pain group exceeded that in the asymptomatic group during cervical flexion–extension (13.0 -13.4%), lateral bending (10.4 -15.6%), and rotation (7.0 -8.3%) movements. Multivariate regression analysis revealed that the presence of neck pain was correlated with a significant increase in peak CF during the phases of flexion ($p = 0.02$), right lateral bending ($p = 0.04$ except for C6-C7), and left rotation ($p = 0.02$). The peak CF was positively correlated with peak angles in flexion ($p < 0.001$), extension ($p = 0.001$), left

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lateral bending at C3/4 ($p=0.009$), C4/5 ($p=0.008$), C5/6 and C6/7 ($p=0.007$), right lateral bending at C3/4 and C4/5 ($p=0.002$), C5/6 and C6/7 ($p=0.001$), left rotation ($p<0.001$), and right rotation ($p=0.02$) movements. Conversely, peak CF was negatively correlated with MVIC in flexion ($p=0.02$), extension at C4/5 ($p=0.008$) and C5/6 ($p=0.007$), left lateral bending ($p=0.001$), right lateral bending at C3/4 ($p=0.02$), C4/5 and C5/6 ($p=0.01$), and C6/7 ($p=0.009$) movements. No significant correlation was found between peak CF and the time taken for movement.

Conclusions This study reveals the differences in CF between individuals with neck pain and asymptomatic individuals during identical movements. The peak CF appears to correlate with the presence of neck pain, MVIC, and peak angle. These findings highlight the importance of muscle strength training. Early identification of reduced neck muscle strength could be crucial for preventing and relieving neck pain.

Keywords Biomechanical phenomena, Computer simulation, Motion capture, Neck pain

Introduction

Neck pain is a prevalent health issue that not only impacts an individual's quality of life and work performance but also may impose an economic burden [1]. It is estimated that 22–70% of people will experience neck pain at least once in their lifetime [2]. The exact cause of chronic neck pain is not fully understood, but biomechanical abnormalities are generally considered a significant factor [3]. Factors such as cervical facet joint dysfunction, forward head posture, weakened muscle strength, and abnormal motor control may contribute to the onset and persistence of neck pain [4–7].

A substantial body of evidence indicates that the compressive forces (CF) are significantly greater when the cervical spine is in a flexed position than when it is in a neutral position and continues to increase with increasing angle [8–10]. One study used a musculoskeletal model to predict load patterns during head flexion–extension, lateral bending, and axial rotation movements [11]. Excessive CF caused by poor posture may increase the risk of neck pain [12]. However, these studies explored the CF of the healthy population through simulation, and few studies have collected data during physiological movement from individuals with neck pain for simulation; thus, strong evidence directly elucidating the relationship between the CF and neck pain is lacking. Abnormal movement performance [13, 14], such as reduced muscle strength and variations in movement speed and angle, may result in disparities in CF during movement between individuals with neck pain and healthy individuals. Previous research has confirmed a positive correlation between joint angle and CF [8–10], but the correlations between muscle strength, movement speed, and CF are still unclear. Strength training can alleviate neck pain [15], potentially by reducing the CF on the cervical intervertebral discs.

To fill the aforementioned theory gap, this study aimed to collect experimental data from individuals with neck pain and asymptomatic individuals during physiological movements such as flexion–extension, lateral bending, and rotation. This helps to comprehensively reveal the differences in CF between individuals with neck pain and asymptomatic individuals. Moreover, we explored the correlation between movement performance characteristics and the CF to help deepen our understanding of the biomechanical mechanisms of neck pain. OpenSim is an open-source software package for creating and analyzing dynamic simulations of movement, offering accurate estimation of interarticular loads [16], which is challenging to measure directly under real-world conditions. The movement speed was reflected by the time it took to complete the same movement process. The time, angle, and CF were simulated through the OpenSim musculoskeletal model, and the maximum voluntary isometric contraction (MVIC) was used to reflect muscle strength.

Method

Participant

This cross-sectional study was conducted and presented following the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) [17]. The case group in this study included individuals with a history of chronic nonspecific neck pain [18] for at least three months, who voluntarily participated in the trial and were literate enough to understand the test. Exclusion criteria encompassed a range of conditions such as congenital or known diseases affecting the musculoskeletal, nervous, endocrine, mental systems, infections, traumatic diseases, inability to perform neck movements in all directions, cognitive impairments, and other conditions deemed unsuitable by the researcher. The control group comprised asymptomatic individuals without a history of neck pain, with the same inclusion and exclusion criteria as the case group.

The study was approved by the Ethics Committee of Zhujiang Hospital of Southern Medical University (2023-KY-227-02). Participants were recruited through the Department of Rehabilitation Medicine of Zhujiang Hospital and posters shared in WeChat Moments. In compliance with the WHO standards and the Declaration of Helsinki, participants gave written consent before the study. They could withdraw anytime during the study.

Data acquisition

Demographic data of all participants were collected, along with the average and most severe pain intensity over the past week, and the immediate pain intensity at the time of the experiment (numerical rating scale).

Kinetic data

Kinetic data was collected using a 3D motion capture system (BTS SMART-DX EVO2, Italy) equipped with six infrared cameras at a sampling frequency of 100 Hz. The system demonstrated a precision of less than 0.1 mm within a measurement volume of 4 m x 3 m x 3 m (L x W x H). Ten reflective markers were attached to the surface of the participants' bodies to track the motion. Nine markers, following the OptiTrack's Biomech 57 marker set, were placed: four on the head, one each on C7, T7, left and right acromioclavicular joints, and the sternal jugular notch. An additional marker was placed on L4 to help identify the spinal position. The placement of the markers was consistently done by the same person to minimize positional errors.

Initially, static postures were collected for scaling the OpenSim model, followed by data collection during neck movements. Participants were asked to perform three neck movements at their habitual speed: (a) flexion from a neutral position to the maximum extent, then extension to the maximum extent, and back to the neutral position, hereafter referred to as flexion–extension movement; (b) lateral bending from a neutral position to the maximum extent on the left, then to the maximum extent on the right, and back to the neutral position, hereafter referred to as lateral bending movement; (c) axial rotation from a neutral position to the maximum extent on the left, then to the maximum extent on the right, and back to the neutral position, hereafter referred to as rotation movement. Each movement was repeated at least three times to ensure three valid data sets, one used for analysis. Valid data is defined as: when the original data is exported, there are no missing markers or movement artifacts, and the entire movement process is fully captured [19]. Prior to the formal testing, participants were allowed to familiarize themselves with the experimental environment and movements.

Flexion–extension movements were divided into two phases in quantitative analysis: the forward flexion phase, which involved flexing from the neutral position to the maximum extent and then returning to the neutral position. And the backward extension phase, which involved extending from the neutral position to the maximum extent and then returning to the neutral position. Lateral bending movements were divided into the left lateral bending phase, which involved bending to the left from the neutral position to the maximum extent and then returning to the neutral position, and the right lateral bending phase, which involved bending to the right from the neutral position to the maximum extent and then returning to the neutral position. Rotation movements were divided into the left rotation phase, which involved rotating to the left from the neutral position to the maximum extent and then returning to the neutral position, and the right rotation phase, which involved rotating to the right from the neutral position to the maximum extent and then returning to the neutral position.

Maximum voluntary isometric contraction

The MVIC was evaluated using the Multi-cervical Unit (MCU, BTE Technologies, USA). MCU has been reported to have good to excellent test-retest reliability [20]. The participants were asked to sit on the adjustable chair equipped with this device, with their waist close to the backrest, their head and neck in a neutral position, and their body secured with straps to prevent excess movement. The MVIC in four directions: flexion, extension, left lateral bending, and right lateral bending were collected in the neutral position. This device is unable to collect the MVIC of axial rotation. Each MVIC collection was maintained for 3 s, and the peak strength during the maintenance period was recorded. Each direction was repeated three times, and the maximum value of the three data was used for analysis. Sufficient rest time was reserved between each repetition.

Musculoskeletal model and compressive force estimation

The kinetic data were processed in the SMART tracker software to allow for data exportation for OpenSim. The HYOID model [21], a head and neck model that includes the hyoid muscle group, was selected for inverse kinematics (IK), static optimization (SO), and joint reaction (JR) analysis using OpenSim v.4.1 [22, 23]. This model utilized the inertial properties and joint definitions from the MASI model [24]and the muscle strengths and other properties from the Vasavada model [25]. Additionally, elements for estimating passive forces generated by ligaments and other structures had been added. The attachment points of the hyoid muscles were assumed to move with the cervical bones, with the infrahyoid muscles following C3 [26] and the suprahyoid muscles moving with C1. The model can simulate movements such as flexion, extension, lateral bending, and axial rotation, which require complex muscle coordination. These movements were validated through experimental motion capture, supporting the model's applicability in simulating complex muscle coordination. However, one limitation of the model is that it does not model the interactions between physiological muscles, which naturally wrap around and interact during movements. And the model assumes a fixed center of rotation for each of the upper and lower cervical. Despite these limitations, the inclusion of the hyoid muscle group allowed the model to simulate head and neck movements more realistically than previous models, aiding in our understanding of CF during head and neck movements. Its accuracy has been validated [21] and it has been employed to investigate the role of passive ligaments versus muscles in head stability [27], the influence of muscle characteristics and impact parameters on head injury risk in football [28], the mediation of head oscillation by neck muscles through the vestibular system during walking [29], and the dynamic and kinematic properties of the neck musculoskeletal system [30].

The positions of the markers in a static posture and the weight were used to scale the HYOID model to match the size and weight of each participant. Once each participant had their scaled model, the IK tool was used to obtain the Movement time and peak angle. Then, the SO tool [31] was used to get the controls and activation files to input into the Analyze tool for JR analysis along with the IK files. The filter for the SO analysis was set to 6 Hz, and the precision for both SO and JR analyses was set to 20. Spike noise was removed from the calculated CF, and body mass normalization was performed.

Data analysis

For demographic data, qualitative data was analyzed using the Chi-square test. Quantitative data that follows a normal distribution and has homogeneity of variance was analyzed using the independent samples t-test. If the data does not follow a normal distribution, the Mann-Whitney U test was used. The Shapiro-Wilk test was used for normality testing. For CF data, combined methods of qualitative and quantitative analysis were adopted: Qualitative analysis was for observing the overall changes in CF during the movement process and the differences between the two groups, and multiple regression analysis was used to explore the impact of neck pain and movement performance indicators on the peak value of CF. For qualitative analysis, forces between the lower cervical vertebrae (C3-C7) during flexion–extension and lateral bending, and between the upper cervical vertebrae (C1-C2) during rotation were considered, as lower and upper cervical vertebrae mainly perform these movements respectively. A review of cervical spine kinematics research (1980–2021, excluding Cadaveric studies) indicated maximum contribution to flexion–extension from C4-C5 and C5-C6, to lateral bending from C3-C4 to C6-C7, and to axial rotation from C1-C2 [32]. Hence, for quantitative analysis, this study selected C4-C5, C5-C6 for flexion–extension; C3-C4, C4-C5, C5-C6, C6-C7 for lateral bending; and C1-C2 for rotation.

In the qualitative analysis, the time series of each movement was normalized in time from 0 to 100% using a cubic spline interpolation. In regression analysis, the dependent variable was the peak CF during movement, and the independent variables were the state of neck pain and movement performance indicators (movement time, peak angle, MVIC), without including the MVIC of the rotation direction (The equipment used in this study cannot measure MVIC in rotational directions, as cervical rotation resistance movement generates high detrimental shear forces [33]). First, univariate regression analyses were performed on the dependent variable and each corresponding independent variable. Independent variables with $p < 0.1$ were selected for multiple regression analysis, and a total of 14 multiple linear regression models were established. The linear relationship between the dependent variable and the independent variables was checked through scatter plots, and multicollinearity was tested through the variance inflation factor and tolerance. The independence, normality, and homoscedasticity of the residuals were tested through the Durbin-Watson test, the residual P-P plot, and the scatter plot of the standardized residuals and predicted values. All established models met the relevant assumptions. All analyses were performed using IBM SPSS 25.0 and R 4.4.0. Continuous data are shown as mean (standard deviation), and categorical data are shown as frequency (percentage). The significance level was set at $p < 0.05$.

Sample size

Using G*Power (Version 3.1.9.7) and data from a pilot study with 16 participants (8 asymptomatic and 8 with neck pain), the sample size was calculated for a linear multiple regression (fixed model) with four independent variables, a power of 0.95, and an alpha level of 0.05 [34]. Peak CF during flexion served as the dependent variable, the required sample size was calculated to be 44 subjects, with a partial R^2 of 0.24 and an effect size of 0.316. Considering potential recruitment and data collection challenges, we estimated an additional 20% of subjects, targeting 55 participants. Ultimately, 60 participants were recruited for this study.

Results

A total of 60 participants were included, with 30 in the neck pain group and 30 in the control group. The demographic characteristics and pain scores were shown in Table 1. There were no significant differences between the two groups in terms of gender, age, height, weight, and education level (all $p > 0.05$). Table 2 summarized the movement performance characteristics of the two groups, and Table 3 provided the descriptive statistics for the peak CF during movement for both groups. Table 4 showed the variables with $p < 0.1$ in the univariate regression. For the univariate regression equations constructed with the Movement time and the standardized peak CF in all directions and segments, the p-values were all > 0.1.

Table 1 Clinical and demographic characteristics of all participants, mean (SD)

Variable	Neck pain (*n* = 30)	Asymptomatic (*n* = 30)	*p*
Gender n(%)			0.07
Female	26(86.7%)	20(66.7%)	
Male	4(13.3%)	10(33.3%)	
Age	24.93 (2.95)	24.57 (3.01)	0.13
Height (m)	1.62 (0.06)	1.66 (0.09)	0.14
Weight (kg)	53.39 (8.62)	58.23 (12.04)	0.13
Most severe NRS	4.37(0.96)	-	-
Mean NRS	3.30(0.99)	-	-
Current NRS	2.97(0.96)	-	-
Education (years)	17.60 (1.57)	18.00 (2.02)	0.8

The Chi-square test for gender and the Mann-Whitney U test for other variables

Qualitative analysis

Figures 1 and 2, and 3 respectively illustrated the changes of interarticular CF during flexion–extension, lateral bending, and rotational movements in two groups. It can be observed that, across all segments, the interarticular CF in the neck pain group is consistently higher than those in the asymptomatic group throughout the entire process of flexion–extension, lateral bending, and rotational movements.

From Table 3, it can be calculated that during the forward flexion phase, the standardized peak interarticular CF means for the C4-C5 and C5-C6 segments in the neck pain group increased by 13.4% and 13.1% respectively compared to the asymptomatic group. During the backward extension phase, the standardized peak interarticular CF means for the C4-C5 and C5-C6 segments in the neck pain group increased by 13.4% and 13.0% respectively compared to the asymptomatic group. During the left lateral bending phase, the standardized

Table 3 The peak compressive force during movement in each group, mean (SD)

Compressive Force (× BM)	Neck pain (*n* = 30)	Asymptomatic (*n* = 30)
Flexion		
C4/5	5.25 (1.36)	4.63 (0.94)
C5/6	5.25 (1.33)	4.64 (0.92)
Extension		
C4/5	6.00 (1.25)	5.29 (1.10)
C5/6	6.17 (1.26)	5.46 (1.11)
Left lateral bending		
C3/4	5.10 (0.85)	4.62 (0.98)
C4/5	5.86 (0.99)	5.28 (1.13)
C5/6	5.95 (0.98)	5.37 (1.13)
C6/7	5.83 (0.94)	5.26 (1.09)
Right lateral bending		
C3/4	5.55 (1.04)	4.82 (1.12)
C4/5	6.37 (1.26)	5.51 (1.30)
C5/6	6.44 (1.25)	5.57 (1.28)
C6/7	6.32 (1.23)	5.49 (1.26)
Left rotation		
C1/2	4.18 (0.73)	3.86 (0.60)
Right rotation		
C1/2	4.28 (0.66)	4.00 (0.69)

BM, body mass

Table 2 Movement performance characteristics in neck pain patients and asymptomatic controls, mean (SD)

Variable	Neck pain (*n* = 30)	Asymptomatic (*n* = 30)	Estimated Difference, (95% CI)[†]	*p*
Movement time (s)				
Flexion	4.02 (2.07)	3.12 (1.38)	-0.69 (-1.36, -0.06)	0.04
Extension	5.08 (2.53)	3.68 (1.34)	-0.98 (-1.81, -0.26)	0.01
Left lateral bending	3.46 (1.38)	3.14 (1.39)	-0.35 (-0.95, 0.27)	0.25
Right lateral bending	3.62 (1.39)	3.24 (1.48)	-0.43 (-1.08, 0.21)	0.16
Left rotation	3.07 (0.94)	3.08 (1.70)	-0.30 (-0.83, 0.23)	0.23
Right rotation	3.28 (1.47)	3.37 (1.62)	0.03 (-0.44, 0.54)	0.91
Peak angle (radians)				
Flexion	0.50 (0.11)	0.52 (0.09)	-0.001 (-0.004, 0.001)	0.82
Extension	0.82 (0.03)	0.79 (0.09)	-0.000 (-0.005, 0.001)	0.37
Left lateral bending	0.53 (0.06)	0.54 (0.06)	-0.001 (-0.008, 0.01)	0.71
Right lateral bending	0.55 (0.06)	0.55 (0.05)	-0.001 (-0.004, 0.001)	0.54
Left rotation	0.58 (0.09)	0.60 (0.07)	0.004 (-0.01, 0.03)	0.64
Right rotation	0.61 (0.06)	0.60 (0.09)	0.000 (-0.02, 0.01)	0.96
MVIC (N)				
Flexion	46.90 (22.07)	61.14 (34.28)	10.90 (-2.60, 23.40)	0.09
Extension	70.49 (31.21)	85.42 (41.84)	14.20 (-2.70, 30.80)	0.09
Left lateral bending	42.25 (22.25)	53.31 (24.90)	9.90 (1.40, 18.90)	0.02
Right lateral bending	39.14 (20.14)	55.50 (28.41)	16.70 (6.00, 25.50)	0.003

[†]A pseudo-median difference calculated with the use of the Hodges–Lehmann estimate based on the Mann–Whitney U test. MVIC, maximum voluntary isometric contraction

Table 4 Independent variables with $p < 0.1$ in univariate regression analysis

	Neck pain			Peak angle			MVIC		
Dependent Variables	**B**	**t**	***p***	**B**	**t**	***p***	**B**	**t**	***p***
Flexion									
C4/5	0.63	2.07	0.04	5.55	4.03	< 0.001	-0.02	-3.43	0.001
C5/6	0.61	2.05	0.04	5.47	4.08	< 0.001	-0.02	-3.48	< 0.001
Extension									
C4/5	0.71	2.32	0.02	9.60	4.78	< 0.001	-0.02	-4.09	< 0.001
C5/6	0.71	2.31	0.02	9.70	4.77	< 0.001	-0.02	-4.13	< 0.001
Left lateral bending									
C3/4	0.48	2.03	0.05	4.35	2.19	0.03	-0.02	-3.62	< 0.001
C4/5	0.58	2.13	0.04	5.16	2.23	0.03	-0.02	-3.63	< 0.001
C5/6	0.58	2.14	0.04	5.20	2.27	0.03	-0.02	-3.72	< 0.001
C6/7	0.57	2.17	0.03	5.03	2.27	0.03	-0.02	-3.71	< 0.001
Right lateral bending									
C3/4	0.73	2.61	0.01	6.44	2.55	0.01	-0.01	-2.60	0.01
C4/5	0.87	2.63	0.01	7.77	2.61	0.01	-0.02	-2.69	0.009
C5/6	0.88	2.69	0.009	7.75	2.62	0.01	-0.02	-2.67	0.01
C6/7	0.82	2.57	0.01	7.77	2.70	0.009	-0.02	-2.77	0.008
Left rotation									
C1/2	0.31	1.82	0.07	3.40	3.28	0.002	-	-	-
Right rotation									
C1/2	-	-	-	2.73	2.40	0.02	-	-	-

MVIC, maximum voluntary isometric contraction

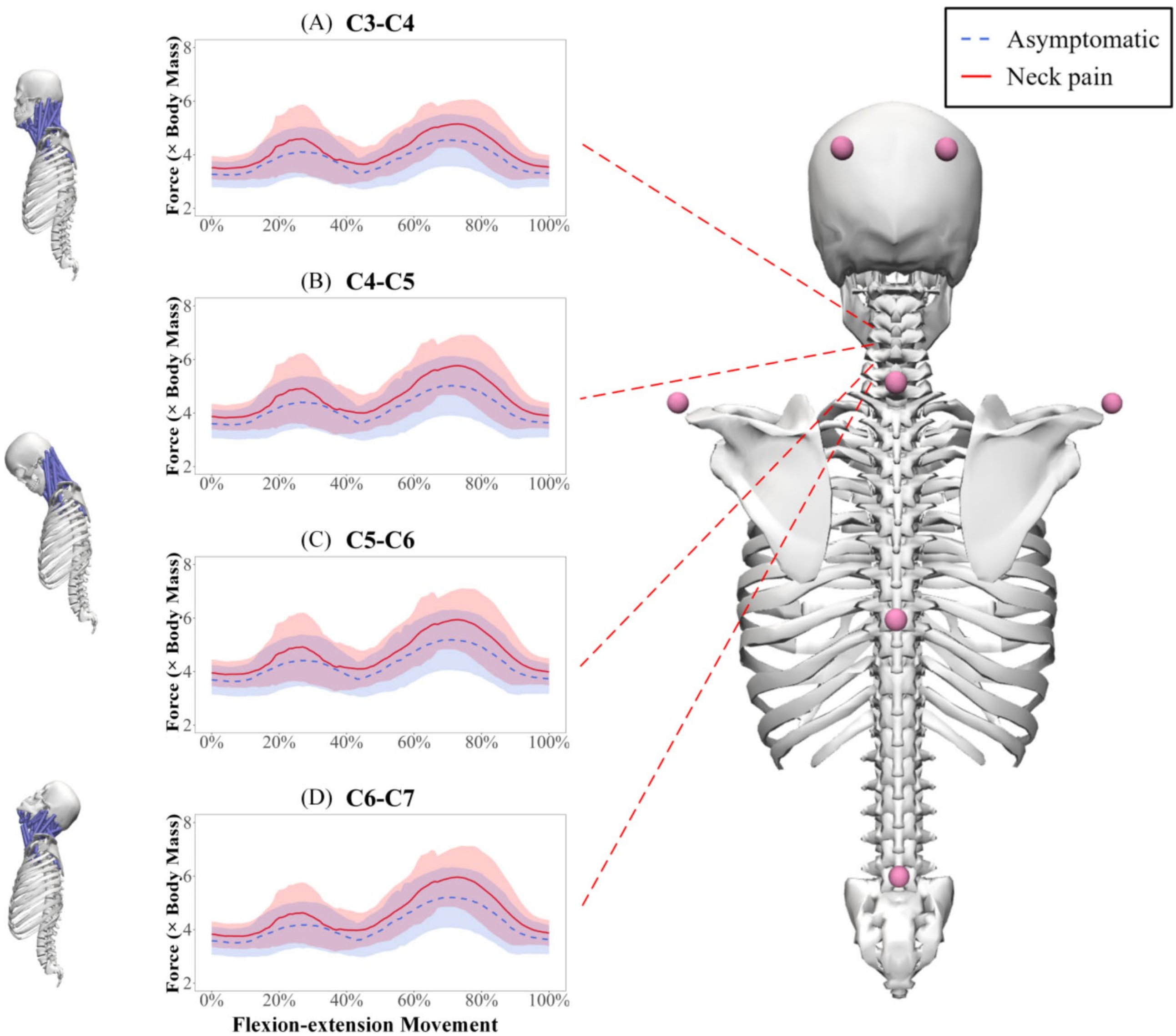

Fig. 1 Interarticular compressive force during flexion extension movements: flexion from a neutral position to the maximum extent, then extension to the maximum extent, and back to the neutral position. (**A**) The compressive force of C3-C4. (**B**) The compressive force of C4-C5. (**C**) The compressive force of C5-C6. (**D**) The compressive force of C6-C7. The shaded area represents ± 1 standard deviation

peak interarticular CF means for the C3-C4, C4-C5, C5-C6, and C6-C7 segments in the neck pain group increased by 10.4%, 11.0%, 10.8%, and 10.8% respectively compared to the asymptomatic group. During the right lateral bending phase, the standardized peak interarticular CF means for the C3-C4, C4-C5, C5-C6, and C6-C7 segments in the neck pain group increased by 15.1%, 15.6%, 15.6%, and 15.1% respectively compared to the asymptomatic group. During the left rotation phase, the standardized peak interarticular CF mean for the C1-C2 segment in the neck pain group increased by 8.3% compared to the asymptomatic group. During the right rotation phase, the standardized peak interarticular CF mean for the C1-C2 segment in the neck pain group increased by 7.0% compared to the asymptomatic group.

Quantitative analysis

Flexion–extension movement

In the univariate regression analyses conducted for both flexion and extension phases at the interarticular levels of C4-C5 and C5-C6, significant correlations were observed between the standardized peak CF and the presence of neck pain, peak angle, and MVIC (all $p < 0.05$) (Table 4).

In the two multiple regression models of the flexion phase, neck pain, peak angle, and MVIC significantly explained the standardized peak CF (all $p < 0.05$). The models of C4-C5 and C5-C6 explained 38% and 39% of

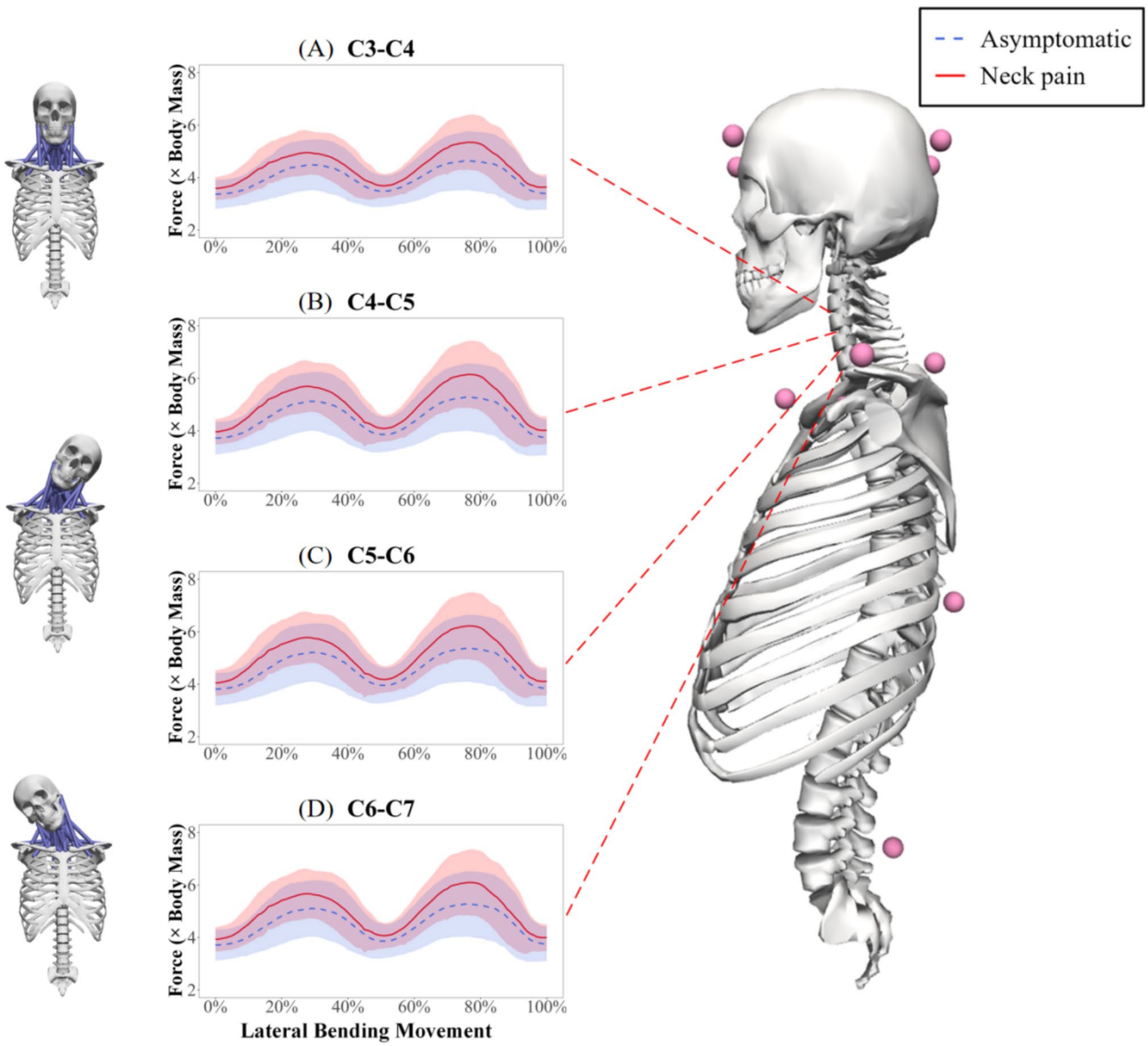

Fig. 2 Interarticular compressive force during lateral bending movements: lateral bending from a neutral position to the maximum extent on the left, then to the maximum extent on the right, and back to the neutral position. (**A**) The compressive force of C3-C4. (**B**) The compressive force of C4-C5. (**C**) The compressive force of C5-C6. (**D**) The compressive force of C6-C7. The shaded area represents ± 1 standard deviation

the variance for the standardized peak CF, respectively (Table 5).

In the extension phase, the two multiple regression models demonstrated that peak angle and MVIC significantly explained the standardized peak CF (all $p < 0.05$). The models for the C4-C5 and C5-C6 segments both explained 39% of the variance in the standardized peak CF (Table 5).

Lateral bending movement

In all univariate regressions during the left and right lateral bending phases at C3-C4, C4-C5, C5-C6, and C6-C7 segments, the standardized peak CF were all significantly correlated with the presence of neck pain, peak angle, and MVIC (all $p < 0.05$) (Table 4).

In the four multiple regression models of the left lateral bending phase, peak angle and MVIC significantly explained the standardized peak CF (all $p < 0.05$). The models of C3-C4, C4-C5, C5-C6, and C6-C7 explained 30%, 31%, 32% and 32% of the variance for the standardized peak CF, respectively (Table 5).

In the four multiple regression models of the right lateral bending phase, neck pain, peak angle, and MVIC significantly explained the standardized peak CF in the models of C3-C4, C4-C5, C5-C6 segments (all $p < 0.05$). In the model of C6-C7 segment, peak angle and MVIC

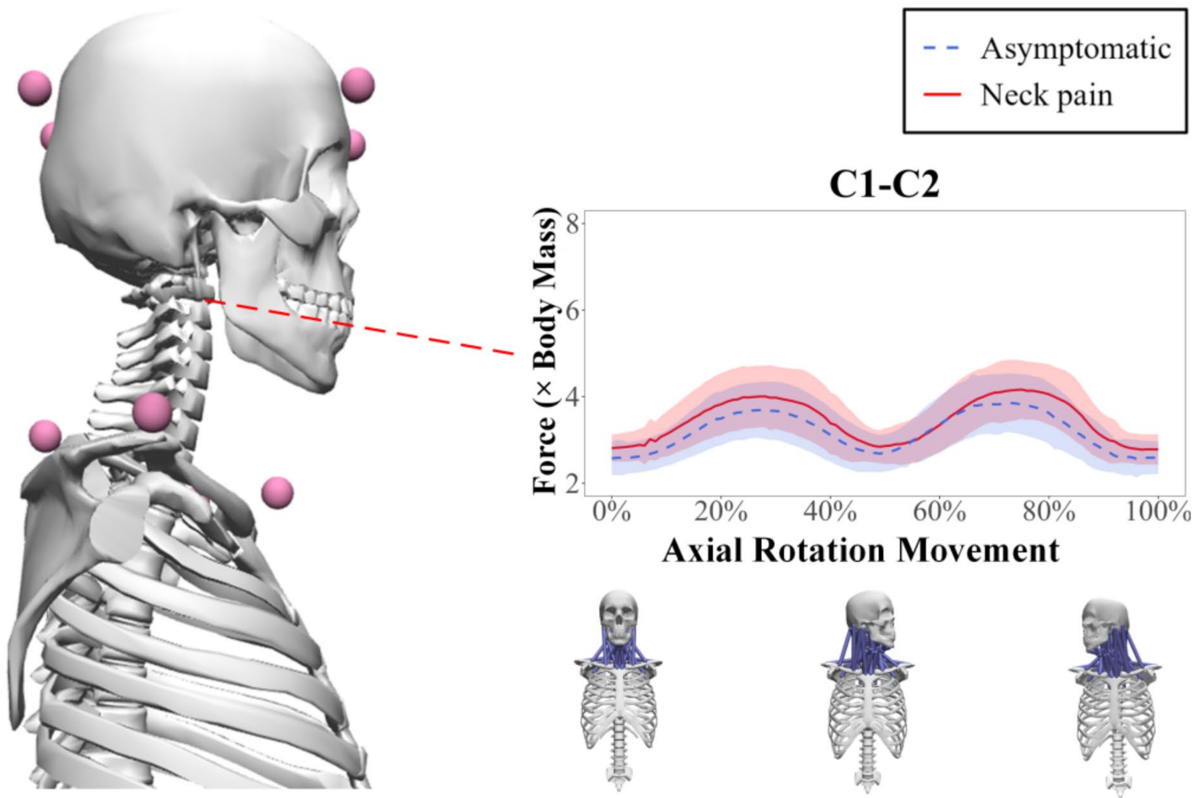

Fig. 3 Interarticular compressive force of C1-C2 during rotation movements: axial rotation from a neutral position to the maximum extent on the left, then to the maximum extent on the right, and back to the neutral position. The shaded area represents ± 1 standard deviation

significantly explained the standardized peak CF (all $p < 0.05$). These four models explained 29%, 30%, 31% and 31% of the variance for the standardized peak CF, respectively (Table 5).

Rotation movement

In the C1-C2 segment, among all univariate regressions of left and right rotation, the standardized peak CF were only significantly correlated with peak angle (all $p < 0.05$) (Table 4).

In multiple regressions, Neck pain and peak angle significantly explained the standardized peak CF of C1-C2 in the left rotation phase, while only peak angle significantly explained the standardized peak CF of C1-C2 in the right rotation phase (all $p < 0.05$). These two models explained 24% and 9% of the variance for the standardized peak CF, respectively (Table 5).

Discussion

This study conducted a qualitative comparison of the changes in interarticular CF between the neck pain group and the asymptomatic group during flexion extension, lateral flexion, and axial rotation movements. It was found that the CF of the neck pain group was higher than that of the asymptomatic group at almost all segments of all movements (Figs. 1, 2 and 3). In the segment of interest, the peak values were extracted for comparison and it was found that the mean peak CF in the neck pain group was 13.0 -13.4% higher than the control group during flexion and extension movements, 10.4 -15.6% higher during left and right flexion movements, and 7.0 -8.3% higher during left and right rotation movements (Table 3). To our knowledge, this is the first study to simultaneously collect data from both neck pain and asymptomatic individuals for musculoskeletal simulation, and comprehensively compare the CF changes of two groups during movements in three planes. More importantly, the study investigated the correlation between neck pain, movement performance characteristics (time, peak angle, MVIC) and CF (Table 5). In all segments of interest during all movements, the peak angle was positively correlated with peak CF, which is consistent with previous research [8–11]. The novel findings indicated: (a) the time taken for movements was not correlated with peak CF ($p > 0.05$); (b) MVIC was negatively correlated with peak CF; (c) the presence of neck pain was correlated with a significant increase in peak CF during flexion, right lateral flexion (except for the C6-C7 segment), and left rotation phases.

Table 5 Multiple linear regression model

Compressive Force	Dependent variables	B (95% CI)	t	*p*	R^2
Flexion					
C4/5	Neck pain	0.61 (0.09, 1.14)	2.33	0.02	0.38
	Peak angle	5.33 (2.75, 7.92)	4.13	< 0.001	
	MVIC	-0.01 (-0.02, -0.002)	-2.33	0.02	
C5/6	Neck pain	0.59 (0.08, 1.10)	2.31	0.02	0.39
	Peak angle	5.24 (2.73, 7.76)	4.18	< 0.001	
	MVIC	-0.01 (-0.02, -0.002)	-2.39	0.02	
Extension					
C4/5	Neck pain	0.31 (-0.22, 0.84)	1.18	0.2	0.39
	Peak angle	7.02 (2.90, 11.14)	3.41	0.001	
	MVIC	-0.01 (-0.02, -0.003)	-2.77	0.008	
C5/6	Neck pain	0.31 (-0.22, 0.84)	1.17	0.2	0.39
	Peak angle	7.07 (2.91, 11.24)	3.40	0.001	
	MVIC	-0.01 (-0.02, -0.003)	-2.81	0.007	
Left lateral bending					
C3/4	Neck pain	0.32 (-0.11, 0.75)	1.51	0.1	0.30
	Peak angle	4.75 (1.22, 8.28)	2.70	0.009	
	MVIC	-0.02 (-0.02, -0.01)	-3.52	0.001	
C4/5	Neck pain	0.40 (-0.09, 0.90)	1.62	0.1	0.31
	Peak angle	5.63 (1.55, 9.72)	2.76	0.008	
	MVIC	-0.02 (-0.03, -0.01)	-3.52	0.001	
C5/6	Neck pain	0.40 (-0.09, 0.89)	1.63	0.1	0.32
	Peak angle	5.68 (1.65, 9.71)	2.82	0.007	
	MVIC	-0.02 (-0.03, -0.01)	-3.63	0.001	
C6/7	Neck pain	0.39 (-0.08, 0.87)	1.66	0.1	0.32
	Peak angle	5.49 (1.59, 9.39)	2.82	0.007	
	MVIC	-0.02 (-0.03, -0.01)	-3.61	0.001	
Right lateral bending					
C3/4	Neck pain	0.55 (0.02, 1.09)	2.06	0.04	0.29
	Peak angle	7.44 (2.82, 12.06)	3.23	0.002	
	MVIC	-0.01 (-0.02, -0.002)	-2.45	0.02	
C4/5	Neck pain	0.65 (0.02, 1.28)	2.08	0.04	0.30
	Peak angle	8.99 (3.57, 14.40)	3.32	0.002	
	MVIC	-0.02 (-0.03, -0.003)	-2.56	0.01	
C5/6	Neck pain	0.66 (0.04, 1.28)	2.14	0.04	0.31
	Peak angle	8.95 (3.60, 14.30)	3.35	0.001	
	MVIC	-0.02 (-0.03, -0.003)	-2.54	0.01	
C6/7	Neck pain	0.60 (-0.00, 1.20)	1.99	0.05	0.31
	Peak angle	8.98 (3.77, 14.19)	3.45	0.001	
	MVIC	-0.02 (-0.03, -0.004)	-2.70	0.009	
Left rotation					
C1/2	Neck pain	0.39 (0.07, 0.70)	2.45	0.02	0.24
	Peak angle	3.71 (1.70, 5.72)	3.70	< 0.001	
Right rotation					
C1/2	Peak angle	2.73 (0.45, 5.00)	2.40	0.02	0.09

MVIC, maximum voluntary isometric contraction

Inter-group differences in compressive force

This study did not observe a significant difference in the overall range of motion between the neck pain group and the control group (Table 2). This may be related to the relatively young age of the recruited subjects and the mild degree of pain, which was in the early stage of cervical degeneration. Similar to the Kirkaldy-Willis degenerative model [35], the initial stage is characterized by instability, and increased laxity of the facet joints, thus the reduction in the overall range of motion is not obvious. In order to maintain the original range of motion and compensate for instability, the load on the adjacent anatomical structures may increase [32]. However, this is just a hypothesis, and existing studies have not quantified the load on each anatomical structure. The difference in the Instantaneous Center of Rotation (ICR) and Instantaneous Axis of Rotation (IAR) during movement may also support our findings. Studies have shown that degeneration causes the ICR to shift the anterosuperior direction [36], and the IAR distribution differs from that of healthy individuals [37–39]. The increased CF in the neck pain group could be related to these kinematic changes. Furthermore, individuals with neck pain may have structural alterations such as loss of cervical lordosis [40], which could potentially be linked to an increased CF. Future research is suggested to refine the CF on each anatomical structure and verify the association between CF changes and ICR, IAR, and structural alterations.

The correlation between neck pain and CF was only statistically significant during the phases of flexion, right lateral flexion, and left rotation (Table 5). This phenomenon may be attributed to the relatively mild symptoms of the neck pain individuals recruited in this study and the sample size may not be sufficient to reveal statistical differences in other directions of motion. In addition, a study has pointed out that compared with the control group, the neck pain group has reduced right rotation and extension angles [41]. Although the right rotation and extension angles of the two groups in this study did not show statistical differences overall (Table 2), the heterogeneity within the group is inevitable. The reduction of peak angles in these directions in some individuals with neck pain may offset the impact of neck pain on CF. Another possible explanation is that considering that the dominant side of almost all subjects is the right side, and the main function of the right sternocleidomastoid muscle is to promote the flexion, right lateral flexion, and left rotation of the cervical spine [42], this anatomical feature may have an impact on the research results. In the neck pain group, the right sternocleidomastoid muscle may be overdeveloped [43], increasing the CF during flexion, right lateral flexion, and left rotation, while the muscle differences on the non-dominant side are relatively small between the two groups. However, the cervical spine is a complex structure involving multiple muscles, ligaments, and joints [44]. The CF during movement is influenced by various factors, and cannot be explained from a single perspective. More experiments are needed to explain and verify the robustness of the results.

Negative correlation between muscle strength and compressive force

Muscles significantly impact the internal load of interarticular discs, facet joints, and ligaments [45]. In particular, deep muscles can effectively counteract unnecessary movements caused by small joint surfaces [32]. This study found that MVIC was negatively correlated with standardized peak CF, implying that individuals with stronger muscle strength will have reduced CF during movement. This indirectly confirms the potential benefits of enhancing muscle strength [46]. Multiple studies have confirmed the positive effects of strength training on neck pain [47, 48], and this study further provides theoretical support for this therapy. The negative correlation between peak muscle strength and the frequency and intensity of neck pain has also been confirmed [49]. Combined with the results of this study, it can be speculated that enhancing muscle strength training may have a potential positive impact on reducing the CF on the neck during movement, helping to prevent or alleviate symptoms of neck pain. Yet, this hypothesis needs further empirical research to verify its causal relationship and specific mechanism.

Given these findings, healthcare professionals can utilize muscle strength assessments to design targeted interventions. For patients with existing neck pain, such muscle strength assessment allows clinicians to tailor strengthening exercises, which may help reduce CF during movement and alleviate pain. For individuals at risk of developing neck pain, such as those with posture issues, regular strength assessments can help detect weaknesses early, enabling preventive interventions before pain occurs.

It's worth noting that pain avoidance behavior may affect an individual's performance in MVIC testing. The experience of pain may unconsciously cause individuals to reduce their power output during testing to avoid exacerbating the sensation of pain [50], which could potentially impact the test results. Considering this situation, after conducting the MVIC test, all participants were asked about their feelings, and no participants reported an increase in pain.

Limitations

This appears to be the first study to compare the CF between individuals with neck pain and asymptomatic individuals using a musculoskeletal model. It is also the first to explore the correlation between movement performance indicators and CF. As a preliminary exploration, there are still some limitations. Regarding study design, the cross-sectional nature of the study limits our ability to infer causal relationships between neck pain, movement performance indicators, and CF. Future research should determine CF thresholds for neck pain and asymptomatic individuals, dividing them into groups with high CF and normal CF, and using a cohort study design to reveal potential causal relationships. Randomized controlled trials for muscle strength training interventions on CF could also be conducted to verify its reversibility. Regarding computer simulation, this study did not precisely account for the CF on the zygapophyseal joints and other finer anatomical structures, which play a significant role in chronic neck pain [51]. Muscle strength measurement should also be quantified to specific muscles to explore the impact of different muscles on CF. Regarding movement performance indicators, this study only focused on time, muscle strength, and angle, while acceleration, jerk, and other kinematic indicators are also important for reflecting movement [52, 53]. Future research should focus on elucidating the associations between a comprehensive set of indicators—including acceleration, jerk, ICR, IAR, coupled movements, structural alterations, proprioceptive deficits, and psychological factors—and CF. This will provide a more nuanced understanding of the multifactorial influences on the development and progression of neck pain.

Conclusion

The analysis revealed differences in CF between the neck pain and asymptomatic groups. The presence of neck pain was correlated with higher peak CF, and the MVIC was negatively correlated with peak CF. These findings unveil new biomechanical mechanisms of neck pain, strengthen the theoretical foundation for muscle strength training, and underscore the potential benefits of early muscle strength assessments and tailored strength training programs for both the prevention and management of chronic neck pain. However, given the concentrated age distribution and relatively mild pain symptoms of the subjects included in this study, the current findings should not be generalized to other age groups or those with more severe neck pain. Further research with a large sample size, encompassing subjects of various age groups and different severities of neck pain, is warranted.

Abbreviations

CF	Compressive force
MVIC	Maximum voluntary isometric contraction
BM	Body mass
ICR	Instantaneous center of rotation
IAR	Instantaneous axis of rotation

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Author contributions

Study concept and design: GH, PL, QZ; Acquisition of data: JH, ZL, ZZ; Analysis and interpretation of data: JH, MZ, JZ, TF; Drafting of the manuscript: JH, GL, QY; Substantively revising: XL, PZ. All authors contributed to the review and revision of the manuscript. All authors have consented the final manuscript.

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Data availability

The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This study has the formal ethical approval from the Ethics Committee of Zhujiang Hospital of Southern Medical University (2023-KY-227-02).

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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