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Neck stiffness and range of motion for young males and females

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A R T I C L E I N F O

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A B S T R A C T

Well characterised mechanical response of the normal head-neck complex during passive motion is important to inform and verify physical surrogate and computational models of the human neck, and to inform normal baseline for clinical assessments. For 10 male and 10 female participants aged 20 to 29, the range of motion (ROM) of the neck about three anatomical axes was evaluated in active-seated, passive-lying and active-lying configurations, and the neck stiffness was evaluated in passive-lying. Electromyographic signals from the agonist muscles, normalised to maximum voluntary contractions, were used to provide feedback during passive motions. The effect of sex and configuration on ROM, and the effect of sex on linear estimates of stiffness in three regions of the moment–angle curve, were assessed with linear mixed models and generalised linear models. There were no differences in male and female ROM across all motion directions and configurations. Flexion and axial rotation ROM were configuration dependent. The passive-lying moment–angle relationship was typically non-linear, with higher stiffness (slope) closer to end of ROM. When normalising the passive moment–angle curve to active lying ROM, passive stiffness was sex dependent only for lateral bending region 1 and 2. Aggregate moment–angle corridors were similar for males and females in flexion and extension, but exhibited a higher degree of variation in applied moment for males in lateral bending and axial rotation. These data provide the passive response of the neck to low rate bending and axial rotation angular displacement, which may be useful for computational and surrogate modelling of the human neck.

1. Introduction

The stiffness and range of motion (ROM) of the human head-neck complex during passive motions has both clinical and biomechanical relevance. Neck kinematic and kinetic responses characterised in an asymptomatic population can be used to benchmark clinical assessments of cervical spine disorders and therapeutic treatment efficacy (Kauther et al., 2012; Rudolfsson et al., 2012; Woodhouse and Vasseljen, 2008). *In vivo* physical measures of passive spinal moment–angle relationships and ROM can be used in the development and verification of computational musculoskeletal models of the head and neck (Barrett et al., 2021). Similar data may be used to inform the design specifications and/or evaluate the biofidelity of surrogate neck models created to investigate injury mechanisms (Farmer et al., 2022) or used as training tools for

Abbreviations: ROM, range of motion; L, left; R, right; T, tragion; IO, orbit inferior margins; EMG, electromyography; SCM, sternocleidomastoid; CPE, cervical paraspinal extensors; TRP, trapezius; MVC, maximum voluntary contraction; LMM, linear mixed models; GLM, generalised linear model; ID, identification; EMM, estimated marginal means; CI, confidence interval; BMI, body mass index.

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neck immobilisation and chiropractic manipulation (Chapman et al., 2015; Duquette et al., 2021). Determining if there are sex-specific passive neck responses to applied rotations could potentially improve such clinical assessments and improve the validity of sex-specific computational and surrogate modelling.

Several studies have investigated between-sex differences in active (i.e. participant-controlled) head-neck ROM in seated positions, but with somewhat contradictory outcomes. Some studies have found that ROM in young adults does not differ between males and females (Castro et al., 2000; Dvorak et al., 1992; Lansade et al., 2009; Trott et al., 1996), while others reported higher ROM for females, in all directions except flexion, in children through to the elderly (Youdas et al., 1992; Zarate-Tejero et al., 2023). One study concluded that females had greater ROM in flexion, extension and lateral bending, but not in axial rotation (Demaille-Wlodyka et al., 2007).

Few studies have reported head-neck stiffness and ROM during researcher-initiated motion, with minimal muscle activation (i.e. a "passive" condition). With participants in a lying position, McGill et al. (1994) measured researcher-guided neck stiffness in flexion, extension, and lateral bending, while Dugailly et al. (2018) measured stiffness and ROM in axial rotation. McClure et al. (1998) measured "relaxed" ROM and flexibility (inverse of stiffness) in flexion, lateral bending, and axial rotation, with participants seated. Males and females had similar passive ROM in flexion and lateral bending, but axial rotation ROM for males was lower than females (McClure et al., 1998). McGill et al. (1994) found young adult males had a stiffer response than females in flexion, extension, and lateral bending, while McClure et al. (1998) found similar stiffness for flexion and lateral bending, but no sex-dependency of stiffness in axial rotation. Stiffness in axial rotation was not evaluated by sex by Dugailly et al. (2018). In each of these studies, participants were instructed to relax, but it is unclear if muscle activation was minimised during testing, and the mass of the head did not appear to be counter balanced for the seated tests (McClure et al., 1998).

The aims of this study were to: (1) assess head-neck ROM and between-sex difference in active-seated, passive-lying and active-lying configurations; and, (2) assess passive-lying neck stiffness and between-sex difference; in flexion, extension, left and right lateral bending, and axial rotation, among a healthy young cohort.

2. Methods

Ethical approval was granted by the institutional Human Research Ethics Committee (Approval number: H-2020-181), and written consent was provided by participants prior to testing.

2.1. Participants

Healthy, 20- to 30-year-old participants, without neck pain in the previous three months, were recruited. People who had vertigo, spinal disorders, spinal injuries, or neurological or cardiovascular disease, were excluded. Participants were requested to limit alcohol intake to one standard drink (10 g of alcohol), and avoid heavy neck or shoulder training, for 24 and 72 h prior to testing, respectively.

2.2. Experimental procedure

Head-neck flexion, extension, and left and right lateral bending and axial rotation, were performed in seated and lying positions. Seated tests were used to determine participant-guided ROM (seated-active), lying tests investigated researcher-guided ROM and stiffness (passive-lying), and participant-guided ROM (active-lying). Two apparatus were used for the lying tests: *bending* for flexion, extension and lateral bending; *rotation* for axial rotation. Seated tests were conducted first; head-neck rotation directions were randomised. For each lying head-neck rotation, passive-lying tests preceded active-lying tests, and the trials were semi-randomised by the order of apparatus (bending or rotation apparatus), motion (flexion/extension or lateral bending in the bending apparatus), and direction (flexion/extension or left/right). Five trials were completed for each motion.

Prior to testing, participants performed a neck warm-up exercise. Height, weight, head girth (through glabella and opisthocranion), and neck girth (through C4), were measured (Seacrist et al., 2012). A flexible ruler (Art Studio Flexible Curve 60 cm, Rioti, Australia) was used to record the neutral head-neck posture in upright standing (Supplementary material S.1).

Reflective markers placed on the participants' head, neck, and torso were tracked by a thirteen-camera motion capture system (Vantage, Vicon Motion System, UK, sampled at 100 Hz) (Supplementary material S.2). Marker locations were recorded in a neutral standing posture, to define the relative locations of anatomical and tracking markers. Surface electromyography (EMG) electrodes (Trigno Mini and Avanti sensors, Delsys Incorporated, USA) were placed bilaterally on the sternocleidomastoid, trapezius, and cervical paraspinal extensor muscles (Supplementary material S.3), to monitor neck muscle activation (Keshner et al., 1989; Moroney et al., 1988; Seacrist et al., 2012).

Active-seated ROM tests were performed on a chair with the torso strapped to the back support. Participants performed self-initiated rotations of their head and neck from neutral position to the end of their comfortable ROM, at their preferred speed, in each prescribed direction. Participants were instructed to minimise motion about other axes.

Active- and passive-lying tests were conducted on a bending apparatus (Fig. 1A: flexion, extension; Fig. 1B: lateral bending) that consisted of a head support on a low-friction platform, and a rotation apparatus (Fig. 1C: axial rotation) that consisted of a head plate mounted on a shaft. The torso was secured to an adjustable bed in prone (lateral bending, axial rotation) or right lateral decubitus (flexion, extension) position, while the head was strapped to either apparatus head support. The apparatus was adjusted to achieve a neutral posture, referencing the previously contoured flexible ruler.

Maximum voluntary contractions (MVC) were conducted prior to the lying tests. Participants exerted maximum isometric effort for each head-neck rotation, in the neutral lying position. MVC was defined as the greatest mean activity of three consecutive contractions. For the passive-lying tests, the participant's head was rotated at approximately 10°/sec until they verbally indicated the end of their comfort range. Load cells recorded the applied tangential force (bending test, 9327C, Kistler Group, Switzerland; 2 kHz) or moment (rotational tests, MC3A, AMTI, USA; 2 kHz) throughout the applied motion. 40 % MVC was defined as the passive muscle activation threshold because in pilot testing most participants could remain below this threshold for the majority of passive trials, and self-initiated (active) motion elicited EMG signals around an order of magnitude greater than this threshold across the range of motion (Liu et al., 2024). A real-time EMG feedback system allowed the researcher to visually monitor agonist muscle activation and provide an audible signal to the participant if muscle activation rose above 20 % MVC. Participants were familiarised with the feedback system prior to commencing the trials, and were instructed to relax their muscles if the audible signal was heard. Trials were reacquired if muscle activation consistently exceeding the threshold was detected via the visual feedback. Pilot testing suggested that antagonist muscles maintained low activation levels throughout the head-neck motion, so their activation were not monitored in real-time. For active-lying tests, participants self-initiated rotation to the end of their comfortable range, at their preferred speed. All lying tests started at approximately 20° from the neutral position, in the opposite direction, to eliminate the contribution of static friction in the region of interest.

To maintain low friction between the bending apparatus platform and head support, plastic cleaning liquid (Glitz, Australia) was applied to the platform periodically. The sliding (kinetic) friction force was measured with the head support mounted load cell, after cleaning fluid application (2.3 ± 0.8 N) and at the completion of each test series (2.5 ± 0.9 N), by simulating passive-lying test with a 5 kg mass. For the axial

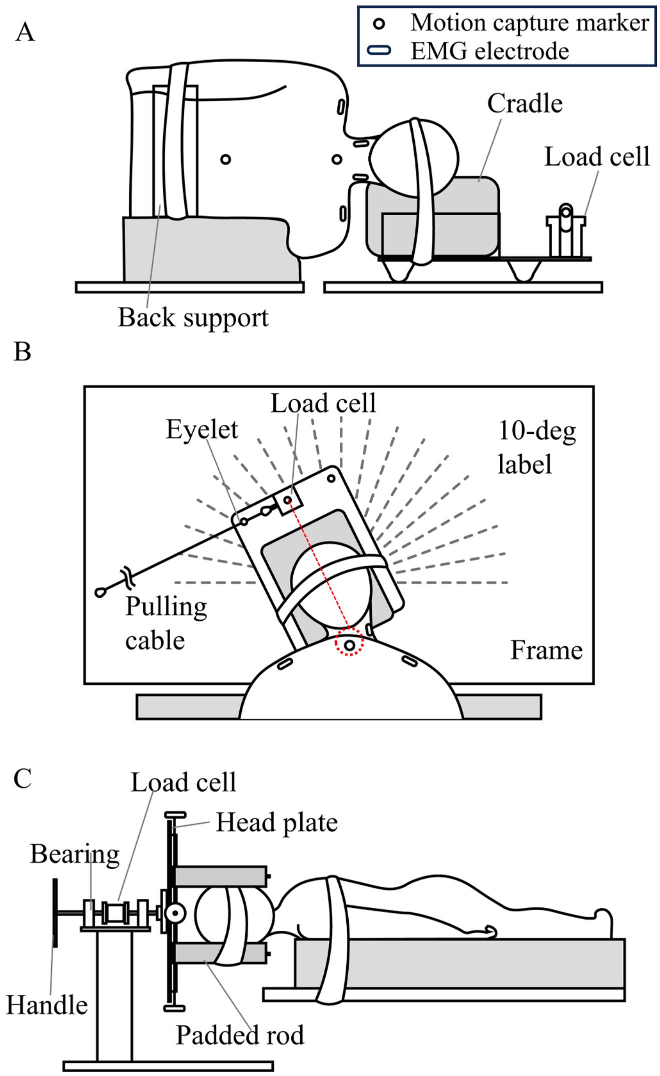

Fig. 1. Schematic of the lying tests. A: Participant in neutral lateral recumbency for flexion and extension tests. B: Passive left lateral bending test, performed in the prone position. Participant's head was pulled in an arc via the cable connected to the load cell mounted on the head support; rotation speed was directed by a metronome. Eyelets were mounted bilaterally adjacent the load cell, to ensure the cable remained tangential to the head motion. Reflective markers on the eyelets were used to calculate the instantaneous centre of rotation (ICR) at 20-frame intervals using the perpendicular bisector theorem. Instantaneous moment arm (red dotted line) was the distance between the centre of the load cell and the ICR (located approximately within the dotted circle region; Liu et al., 2024) in the horizontal plane. C: Passive-lying axial rotation test, performed in the prone position. The head plate, load cell and handle were axis-symmetric about the shaft that was supported by two low-friction bearings. Participant's head was secured to four position-adjustable padded rods with straps, and was rotated by the handle.

rotation apparatus, the moment profile throughout rotation (Fig. 1) was measured after each session with the participant-specific rod locations, using the shaft-mounted load cell (Fig. 1C).

2.3. Data analysis

Load cell, motion capture marker coordinates, and EMG data were acquired synchronously (Lock Lab, Vicon Motion System, UK) at 2000, 100, and 2000 Hz respectively. Post-processing was performed in MATLAB (R2020a and 2023a, MathWorks, USA). Load cell and marker data were low-pass filtered with a 4th order bi-directional Butterworth filter at 10 Hz and 4 Hz cut-off frequencies, respectively. EMG data were full-wave rectified and root-mean-square smoothed with a 200-millisecond moving window. Filtered load cell data were down-sampled to 100 Hz.

The neck angle was defined as the primary Euler transformation angle describing the orientation of the head coordinate system (aligned with the Frankfort plane, Supplementary material S.4) with respect to the standard torso coordinate system (Wu et al., 2005), about each axis of interest. Moment-angle relationships were derived for each passive-lying trial. Zero head-torso angle (i.e. neutral position) was defined with a stationary marker capture performed immediately after positioning the participant on the apparatus. For the bending tests, the applied moment was the applied tangential force multiplied by the instantaneous moment arm. For the axial rotation tests, the applied moment was that recorded during the test minus the participant-specific "empty" apparatus moment at the equivalent angle. Within a trial, subsequent data were excluded if agonist muscle activation exceeded 40 % MVC for a period exceeding 5 % of ROM.

Aggregate moment–angle corridors for the male and female cohorts were created using an arc-length re-parametrisation and signal registration method (Hartlen and Cronin, 2022; ARCGen R2023a, MathWorks, USA), and contained one standard deviation from the mean of all trials.

Passive stiffness was calculated in three regions of each moment–angle relationship (Fig. 2). To minimise the effect of participants indicating end-of-ROM prematurely, each moment–angle data were normalised to the mean active-lying ROM for the corresponding motion and participant. Then, for each motion, the mean moment-% curve among all trials of all participants was calculated (ARCGen R2023a, MathWorks, USA) and a cubic spline was fitted and divided into three regions using a continuous 3-step piecewise linear function (Shape Language Modelling Version 1.14, MathWorks, USA) (Liu et al., 2024). The division points (in % of ROM) were then translated to their corresponding angle for each trial, and stiffness in each region was defined by linear regression. Some trials ended before traversing region 2 and/or 3; stiffness was evaluated when at least 10 % of a region was traversed, in a minimum of two trials.

2.4. Statistical analyses

Statistical analyses were conducted using SPSS 28 (IBM, USA). Separate linear mixed models (LMM) were used to assess the association between sex (male/female), configuration (active-seated, passive-lying, active-lying), and ROM, for the flexion and extension motions; a random effect of participant identification (ID) number was included in each model. Similar separate LMMs were used to assess the association between sex, configuration, and rotation direction (left/right), and ROM or stiffness (in each region) in lateral bending and axial rotation. Generalised linear models (GLM) were used to assess the effect of sex on stiffness in flexion and extension, in each region. For each model in which the main effect *configuration* was significant, Bonferroni adjusted post-hoc comparisons were completed. An alpha level of 0.05 was used for all statistical tests. Estimated marginal means (EMMs), their 95 % confidence interval (95 % CI), and the p-value associated with the difference in EMMs, are reported for each effect. Complete statistical outcomes are provided in Supplementary material S.5 and S.6.

3. Results

Ten males and ten females participated in this study (Table 1). Of the 1800 movement trials recorded and analysed, two active-seated, six passive-lying and five active-lying trials were excluded from ROM analysis due to marker detachment (two trials, one participant), marker occlusion (five trials, five participants), marker tracking failure (three trials, one participant) and incomplete motion (three trials, three participants). A further 10 trials (eight participants) were excluded from

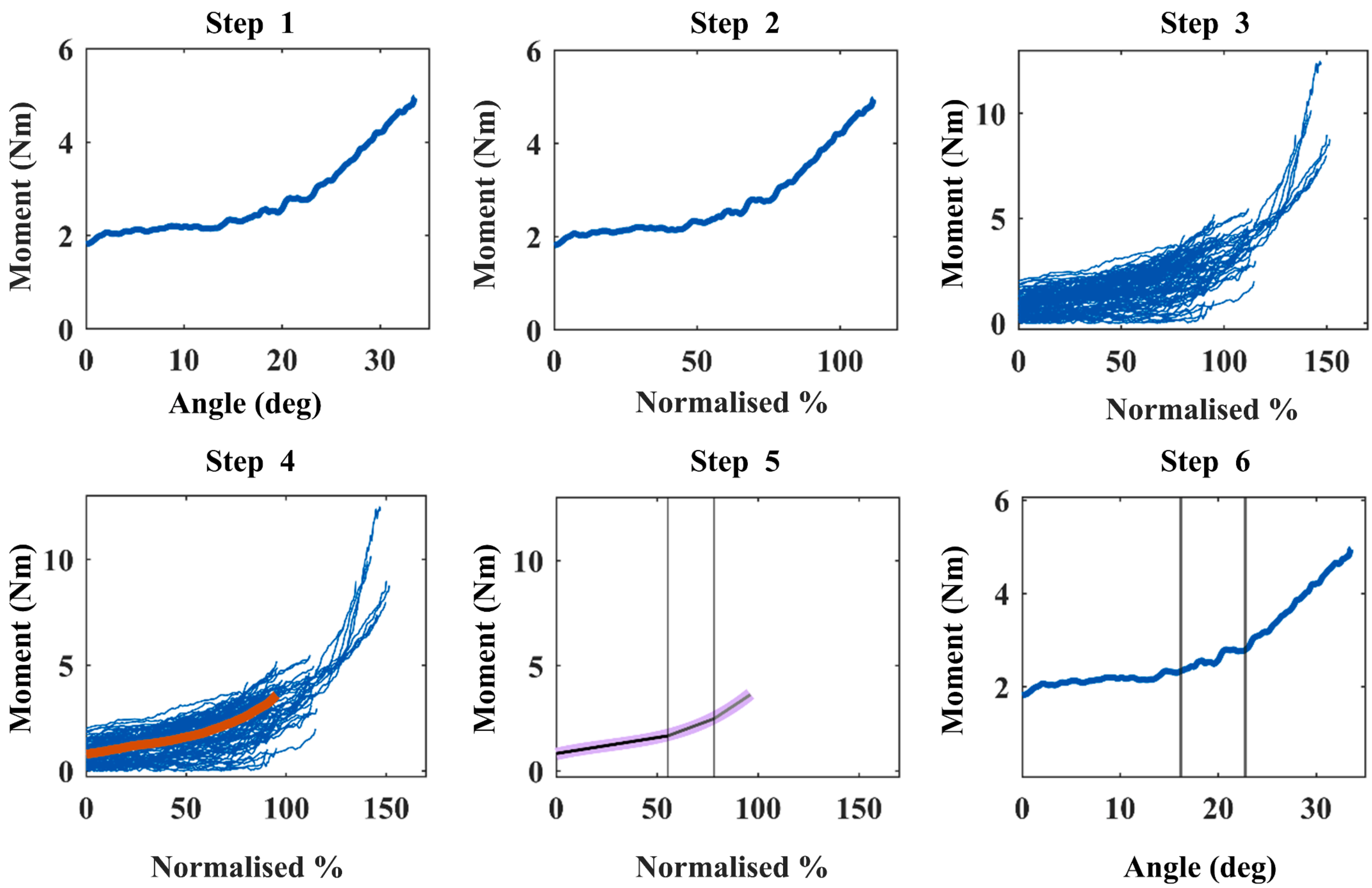

Fig. 2. Demonstration of the stiffness calculation method on a left lateral bending trial from a male participant. Step 1: plot the moment–angle curve. Step 2: normalise passive-lying rotation angle to the mean active-lying ROM for the same participant. Step 3: plot normalised moment-% curve for all trials and participants. Step 4: compute the mean moment-% curve (orange) among all trials and participants (blue), using a MATLAB toolbox (ARCGen R2023a, MathWorks, USA). Step 5: fit a cubic spline (thick purple line), then divide it into three regions using a continuous 3-step piecewise linear function (thin line in black and grey). The division points (black vertical lines) are the region boundaries of the piecewise function. Step 6: convert the division points in % to angles in degrees for the specific participant, by multiplying the normalised % values by the mean active-lying ROM of the same participant.

Table 1
Participant age and anthropometric information, aggregated by sex (mean ± standard deviation (range)).

Sex	Age (years)	Height (cm)	Mass (kg)	Body mass index (kg/m^2)	Head girth (cm)	Neck girth (cm)	Head-neck girth ratio
Male	25.3 ± 2.0 (22–28)	175.7 ± 5.8 (167–186)	75.2 ± 8.1 (62.4–88.0)	24.3 ± 1.5 (22.1–27.1)	56.8 ± 2.0 (53.0–60.0)	37.0 ± 1.7 (30–40)	1.5 ± 0.1 (1.4–1.7)
Female	24.8 ± 3.3 (20–29)	163.9 ± 7.1 (155–177)	60.2 ± 9.6 (45.0–74.0)	22.3 ± 2.4 (17.1–25.6)	55.6 ± 1.6 (53.0–57.5)	32.6 ± 1.6 (29–35)	1.7 ± 0.1 (1.6–1.8)

stiffness analysis only, due to inconsistent force application in the bending apparatus. After exclusions, each participant had at least three successful trials in each test category.

Males and females had similar ROM in all motion directions and configurations ($0.215 < p < 0.885$, Fig. 3, Supplementary material S.5, S.7). No differences were observed between ROM in the active-seated, passive-lying and active-lying configurations in extension (active-seated: EMM 69° [95 % CI: 63°–75°], passive-lying: 66° [60°–72°], active-lying: 74° [67°–80°]; $p = 0.088$) and lateral bending (active-seated: 44° [40°–47°], passive-lying: 41° [37°–45°], active-lying: 43° [39°–46°]; $p = 0.299$). Active-seated ROM was higher than passive- and active-lying ROM in flexion ($p < 0.001$, active-seated ROM and passive-lying ROM, estimated mean difference 18° [95 % CI: 12°–24°]; active-seated ROM and active-lying ROM, 13° [7°–18°]). Active-seated ROM was lower than passive- and active-lying ROM in axial rotation ($p < 0.001$, active-seated ROM and passive-lying ROM, −9° [−15° to −3°]; active-seated ROM and active-lying ROM, −10° [−15° to −4°]). There was no difference between left and right ROM for lateral bending (0° [−2° to 3°], $p = 0.933$) and axial rotation (−3° [−7° to 1°], $p = 0.149$).

The moment–angle relationship was usually non-linear, with a lower slope close to the neutral neck posture, and a higher slope towards the end of ROM. The divisions between region 1 and 2, and region 2 and 3, were approximately 50 % and 75 % of the normalised ROM, respectively (Supplementary material S.8). Males had higher ($p < 0.03$) passive neck stiffness than females in lateral bending region 1 (22 Nmm/° [5–40 Nmm/°]), and region 2 (39 Nmm/° [12–67 Nmm/°]) (Fig. 4; Supplementary material S.6, S.9). There were no between-sex differences in stiffness detected for the other motion directions and stiffness regions. Left and right motions had similar stiffness in lateral bending and axial rotation ($p > 0.134$).

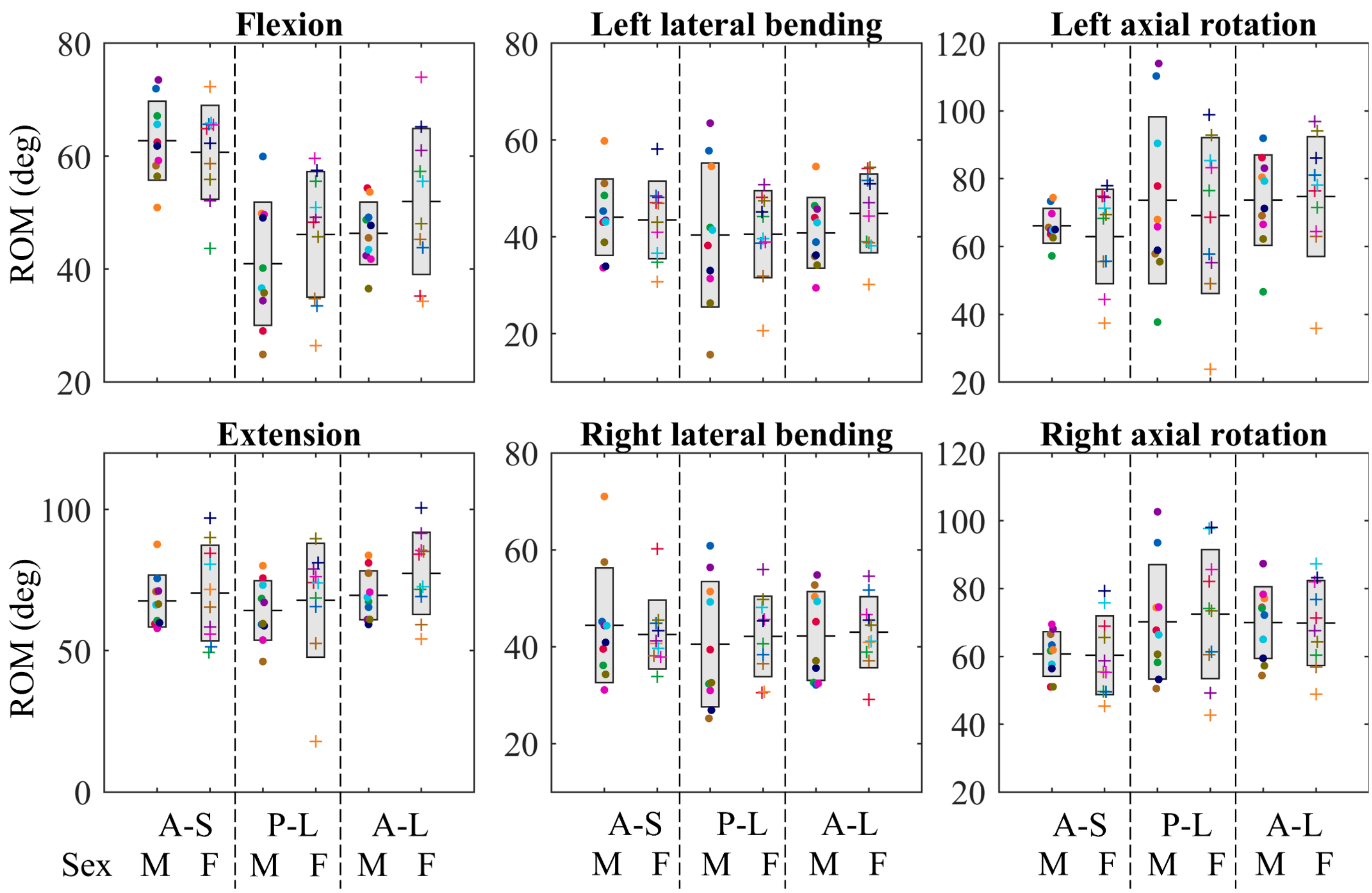

Fig. 3. Range of motion for males (M) and females (F) in different test configurations (A-S: active-seated, P-L: passive-lying, A-L: active-lying). Box is mean ± standard deviation for all participants. Each coloured symbol (circle: males, cross: female) is the mean ROM across all trials for one participant.

In lateral bending and axial rotation, the moment–angle corridor for males was qualitatively wider than for females (Fig. 5), due to a greater variation in applied moment, typically at higher ranges of motion than achieved by the female cohort. In flexion and extension, the male and female moment–angle corridors were qualitatively similar.

4. Discussion

Previous reports of the relationship between male/female sex and the quasistatic mechanical response of the neck to active and passive motions are limited and somewhat contradictory. This study assessed passive neck stiffness, and passive and active ROM in seated and lying positions, in young healthy adults. ROM was similar for males and females across the motion directions and test configurations. Passive neck stiffness was also independent of sex for most motions.

Active-seated and passive-lying ROM were similar to that previously reported (Demaille-Wlodyka et al., 2007; Dugailly et al., 2018; Dvorak et al., 1992; Lansade et al., 2009; McGill et al., 1994; Trott et al., 1996). We are not aware of available comparative data for active-lying ROM. Differences between male and female active-seated ROM were not detected in any motion direction, similar to previous reports of active ROM in young adults (Castro et al., 2000; Dvorak et al., 1992; Lansade et al., 2009; Trott et al., 1996). In the seated position, without a counterbalanced head mass, McClure et al. (1998) reported relaxed researcher-initiated ROM was similar for males and females in flexion and lateral bending, but was lower in males than females in axial rotation. The latter relationship was not detected in the current study, potentially due to differences in test apparatus and protocol.

Flexion and axial rotation ROM were configuration dependent. In general, lying position head-neck motion may have been influenced by reduced physical comfort, spinal postures deviating from neutral despite careful positioning (Supplementary material S.10), and restriction of the head to planar (bending apparatus) and axial (rotation apparatus) motion compared to the active-seated posture in which out-of-plane/-axis motion was discouraged but not physically restricted (Supplementary material S.11). Flexion ROM in passive-lying and active-lying was lower than in the active-seated configuration. The lying position removed the effect of gravity which may have assisted head flexion in active-seated motion, and participant behaviour may have been influenced by line-of-sight to the researcher, cable, and platform edge. Axial rotation ROM was higher in the passive- and active-lying configurations, than in the active-seated configuration. This may have been due to the asymmetric head supports inducing an additional rotational moment due to gravity as the apparatus was rotated beyond the equilibrium point (for active-lying) and the researcher-applied moment (for passive-lying) exceeding that generated by musculature in the active-seated position. Lateral bending and axial rotation ROM were bilaterally symmetric for all configurations, suggesting a lack of bias in the apparatus-participant system.

The passive-lying moment–angle curves generally suggested lower stiffness close to the neutral posture, and increasing stiffness (slope) closer to end ROM. This relationship is broadly consistent with that generally observed for ex vivo “pure moment” tests of multi-segment spinal specimens (Panjabi, 1992), and reported for similar passive-lying participant trials (Dugailly et al., 2018; McGill et al., 1994). Between-sex difference in stiffness was detected in lateral bending (region 1 and 2) only. In contrast, McGill et al. (1994) reported greater passive-lying neck stiffness for young adult males than females (without detailed statistical description) at 10° intervals, in flexion, extension and lateral bending. While the mean moment–angle curve from that study

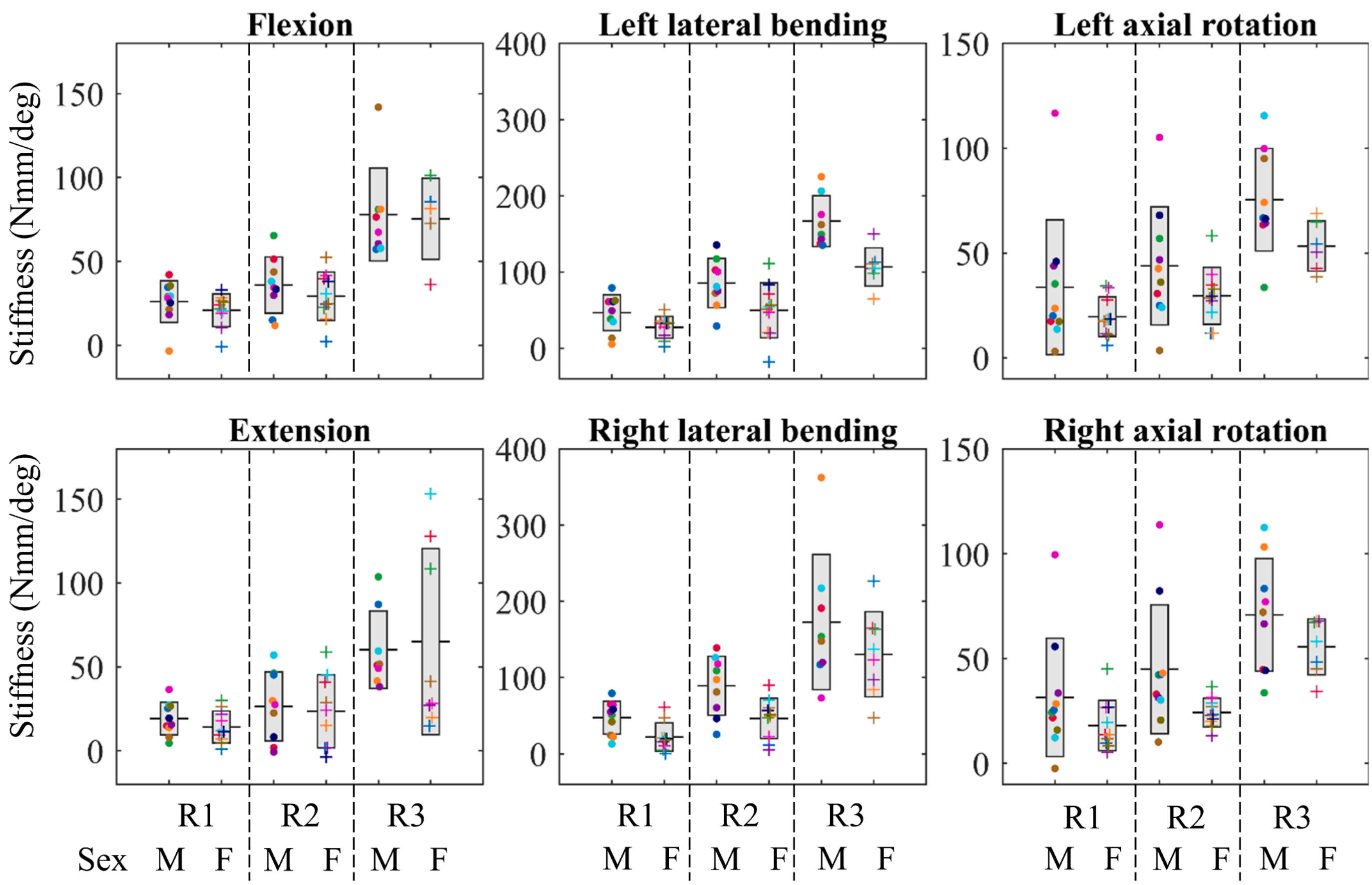

Fig. 4. Passive neck stiffness for males (M) and females (F) for each region (R) in six motions. Box is mean ± standard deviation for all participants. Each coloured symbol (circle: males, cross: female) is the mean stiffness across all trials for one participant.

was largely contained within the current study's corridor for lateral bending, the mean flexion and extension moment–angle data suggested generally higher stiffness throughout ROM (Supplementary material S.12). In the older healthy cohort (48 ± 14 years) of Dugailly et al. (2018), mean passive-lying neck stiffness was higher (left: 84 ± 31 Nmm/°, right: 89 ± 35 Nmm/°) than the current study (region 3 left: 67 ± 23 Nmm/°; right: 64 ± 23 Nmm/°) across both sexes; the former was calculated in the last 10° of ROM whereas region 3 typically encompassed the last 15-30° of ROM. Neither Dugailly et al. (2018) or McGill et al. (1994) reported consistent use of EMG to eliminate whole trials or end-of-ROM data above a threshold, so muscle activity may have contributed to the higher stiffness' measured in those studies. The contribution of surface friction (McGill et al., 1994) and variable apparatus mass distribution (Dugailly et al., 2018) to the measured applied moment were not reported, and these may have effected moment–angle relationships.

Head-neck proportion has previously been reported to influence passive flexion response during dynamic loading in children but not young adults (Seacrist et al., 2012). To explore the potential effect of body habitus and head–neck anthropometry on ROM and stiffness in the current study, the effect of body mass index (BMI) and head-neck girth ratio was assessed with LMM and GLM, with (Supplementary material S.13 and S.14) and without (Supplementary material S.15 and S.16) a fixed effect of sex. Males had higher BMI ($p = 0.045$) but lower head-neck girth ratio ($p < 0.001$) than females, assessed by independent-sample t-tests. Adjusting for BMI and girth ratio did not alter the outcome that ROM was independent of sex for all configurations and directions. However in the presence of these adjusting factors, stiffness (calculated by normalising moment–angle curve to active-lying ROM) was no longer sex dependent in lateral bending zone 1 and 2. Flexion ROM increased with head-neck girth ratio (with sex effect: $p = 0.007$; without sex effect: $p = 0.013$), but BMI and girth ratio were not independent predictors of ROM or stiffness (with the latter calculated by normalising moment–angle curve to active-lying ROM) for any other motion or region Overall, these outcomes suggested that BMI and head-neck proportion were not predictors of head-neck response to low rate passive motion in this young adult cohort, but the relatively low sample size and the relatively homogeneous demographic limit the generalisability of this secondary finding.

Stiffness was approximated as a linear value in each of three regions across each passive-lying moment–angle curve, to facilitate statistical comparison. Prior to assigning the region boundaries, passive-lying ROM was normalised to active-lying ROM, because some participants appeared to limit their ROM under researcher-guided (passive) motion (particularly in flexion), and qualitative evaluation suggested they were likely in their low stiffness region at the end of ROM. For example, while participants usually met "full" ROM (i.e. 100 % of active-lying ROM) for most of their trials, nearly half of females appeared not to reach region 3 in flexion and left axial rotation (Supplementary material S.17). To explore the effect of an alternate normalisation protocol on stiffness, moment–angle plots were also normalised to active-seated ROM (Supplementary material S.9, S.18). With this secondary processing method, in addition to lateral bending (region 1 and 2), the effect of sex was significant in lateral bending region 3, axial rotation region 3, flexion region 2 (without adjusting for BMI and head-neck girth ratio) and extension region 3 (adjusting for BMI and head-neck girth ratio, Supplementary material S.19, S.20, S.21). The discrepancy in outcomes reflects the observation that active-seated ROM differed from passive-lying and active-lying ROM predominantly in flexion. Nevertheless, the two normalisation methods yielded similar stiffness for all but one

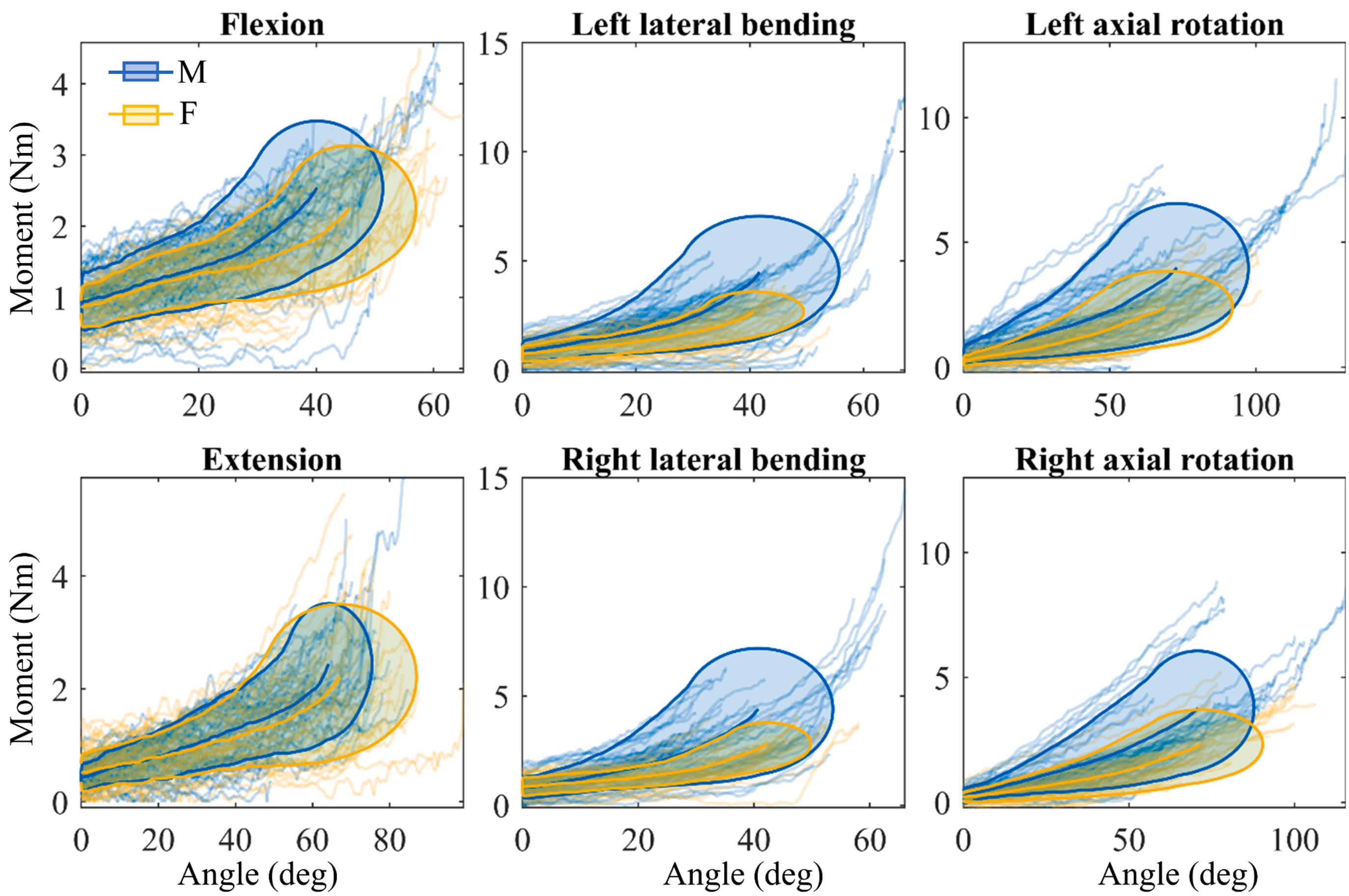

Fig. 5. Stiffness corridor plots (mean ± standard deviation) for males (M) and females (F) across all trials. Thin lines are the moment–angle plot for each trial.

(left axial rotation, $p = 0.034$) outcomes in all regions and for all motions, based on paired-sample T-tests ($p > 0.102$).

There were several limitations in this study. In the bending apparatus, the generated moment was due to a shear load applied to the head rather than a pure couple, and therefore a greater moment was applied at the base of the neck than its top. However, this is representative of a real-world scenario in which a linear force may be applied to the head (McGill et al., 1994). End of motion was participant-defined to ensure safety, but this may have been influenced by physical and mental participant factors unrelated to intrinsic biomechanical response. Although the sample size was relatively low, and no medical imaging was performed to exclude degenerative or other spinal conditions, the population was relatively homogeneous with respect to age and general health status, and a similar sample size (12 males and 8 females) was used by McClure et al. (1998) on reporting sex differences.

In conclusion, this study assessed neck ROM in active-seated, passive-lying and active-lying configurations, and passive stiffness, for young males and females in six head rotational motions. Males and females had similar ROM in all motions and test configurations. Stiffness was sex dependent for limited motion direction and regions, and the dependency was sensitive to the normalisation method used. The moment–angle corridors developed in this study could assist the development and verification of computational and surrogate models of the neck, and provide baseline normative moment–angle data for comparison to clinical cohorts in which passive neck response may be affected by pathology.

CRediT authorship contribution statement

Mingyue Liu: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Ryan D. Quarrington:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Investigation, Funding acquisition. **Baptiste Sandoz:** Writing – review & editing, Methodology, Investigation, Funding acquisition. **William S.P. Robertson:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Claire F. Jones:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2024.112090.

References

Barrett, J.M., McKinnon, C.D., Dickerson, C.R., Callaghan, J.P., 2021. An electromyographically driven cervical spine model in OpenSim. J. Appl. Biomech. 37 (5), 481–493.

Castro, W.H.M., Sautmann, A., Schilgen, M., Sautmann, M., 2000. Noninvasive three-dimensional analysis of cervical spine motion in normal subjects in relation to age and sex: an experimental examination. Spine (Phila. Pa. 1976) 25 (4), 443-449.

Chapman, P.D., Stomski, N.J., Losco, B., Walker, B.F., 2015. The simulated early learning of cervical spine manipulation technique utilising mannequins. Chiropr. Man. Ther. 23, 23.

Dugailly, P.M., Coucke, A., Salem, W., Feipel, V., 2018. Assessment of cervical stiffness in axial rotation among chronic neck pain patients: A trial in the framework of a non-manipulative osteopathic management. Clin. Biomech. (Bristol, Avon) 53, 65–71.

Duquette, S.A., Starmer, D.J., Plener, J.B., Dag, B.S., 2021. A pilot study to determine the consistency of peak forces during cervical spine manipulation utilizing mannequins. J. Chiropr. Educ. 35 (1), 8–13.

Demaille-Wlodyka, S., Chiquet, C., Lavaste, J.F., Skalli, W., Revel, M., Poiraudeau, S., 2007. Cervical range of motion and cephalic kinesthesis: ultrasonographic analysis by age and sex. Spine (Phila. Pa 1976) 32 (8), 254-261.

Dvorak, J., Antinnes, J.A., Panjabi, M., Loustalot, D., Bonomo, M., 1992. Age and gender related normal motion of the cervical spine. Spine (Phila. Pa 1976) 17 (10 Suppl), 393-398.

Farmer, J., Mitchell, S., Sherratt, P., Miyazaki, Y., 2022. A human surrogate neck for traumatic brain injury research. Front. Bioeng. Biotechnol. 10, 854405.

Hartlen, D.C., Cronin, D.S., 2022. Arc-length re-parametrization and signal registration to determine a characteristic average and statistical response corridors of biomechanical data. Front. Bioeng. Biotechnol. 10, 843148.

Kauther, M.D., Piotrowski, M., Hussmann, B., Lendemans, S., Wedemeyer, C., 2012. Cervical range of motion and strength in 4,293 young male adults with chronic neck pain. Eur. Spine J. 21 (8), 1522–1527.

Keshner, E.A., Campbell, D., Katz, R.T., Peterson, B.W., 1989. Neck muscle activation patterns in humans during isometric head stabilization. Exp. Brain Res. 75 (2), 335–344.

Lansade, C., Laporte, S., Thoreux, P., Rousseau, M.A., Skalli, W., Lavaste, F., 2009. Three-dimensional analysis of the cervical spine kinematics: effect of age and gender in healthy subjects. Spine (Phila Pa 1976) 34 (26), 2900-2906.

Liu, M., Quarrington, Q.D., Sandoz, B., Robertson, W.S.P., Jones, C.F., 2024. Evaluation of Apparatus And Protocols to Measure Human Passive Neck Stiffness and Range of Motion. Ann. Biomed. Eng. https://doi.org/10.1007/s10439-024-03517-w.

McClure, P., Siegler, S., Nobilini, R., 1998. Three-dimensional flexibility characteristics of the human cervical spine in vivo. Spine (Phila Pa 1976) 23 (2), 216-223.

McGill, S.M., Jones, K., Bennett, G., Bishop, P.J., 1994. Passive stiffness of the human neck in flexion, extension, and lateral bending. Clin. Biomech. (Bristol, Avon) 9 (3), 193–198.

Moroney, S.P., Schultz, A.B., Miller, J.A., 1988. Analysis and measurement of neck loads. J. Orthop. Res. 6 (5), 713–720.

Panjabi, M.M., 1992. The stabilizing system of the spine. Part II. Neutral zone and instability hypothesis. J. Spinal Disord. 5 (4), 390–396.

Rudolfsson, T., Bjorklund, M., Djupsjobacka, M., 2012. Range of motion in the upper and lower cervical spine in people with chronic neck pain. Man. Ther. 17 (1), 53–59.

Seacrist, T., Saffioti, J., Balasubramanian, S., Kadlowec, J., Sterner, R., Garcia-Espana, J. F., Arbogast, K.B., Maltese, M.R., 2012. Passive cervical spine flexion: the effect of age and gender. Clin. Biomech. (Bristol, Avon) 27 (4), 326–333.

Trott, P.H., Pearcy, M.J., Ruston, S.A., Fulton, I., Brien, C., 1996. Three-dimensional analysis of active cervical motion: the effect of age and gender. Clin. Biomech. (Bristol, Avon) 11 (4), 201–206.

Woodhouse, A., Vasseljen, O., 2008. Altered motor control patterns in whiplash and chronic neck pain. BMC Musculoskelet. Disord. 9, 90.

Wu, G., van der Helm, F.C., Veeger, H.E., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X., Werner, F.W., Buchholz, B., 2005. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion–Part II: shoulder, elbow, wrist and hand. J. Biomech. 38 (5), 981–992.

Youdas, J.W., Garrett, T.R., Suman, V.J., Bogard, C.L., Hallman, H.O., Carey, J.R., 1992. Normal range of motion of the cervical spine: an initial goniometric study. Phys. Ther. 72 (11), 770–780.

Zarate-Tejero, C.A., Rodriguez-Rubio, P.R., Brandt, L., Krauss, J., Hernandez-Secorun, M., Lucha-Lopez, O., Hidalgo-Garcia, C., 2023. Association between age, sex and cervical spine sagittal plane motion: A descriptive and correlational study in healthy volunteers. Life (Basel) 13 (2).