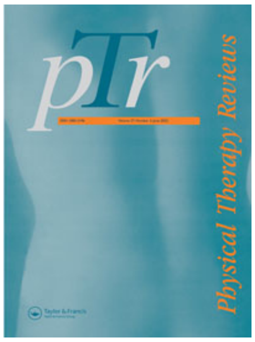

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Do the kinematics and sensorimotor control of people with chronic non-specific neck pain differ from those of healthy individuals when assessed in an immersive virtual reality environment? A systematic review

Alexandre Luc[a], Stephany Tamer[b], Renaud Hage[a,c], Christine Detrembleur[a,b] and Laurent Pitance[a,b,d]

[a]Neuro Musculo Skeletal Lab, Institut de Recherche Expérimentale et Clinique, Secteur des Sciences de la Santé, Université Catholique de Louvain, Brussels, Belgium; [b]Faculté des Sciences de la Motricité, Secteur des Sciences de la Santé, Université Catholique de Louvain, Louvain-la-Neuve, Belgium; [c]Centre de Recherche et de Formation (CeREF), HELHa, Mons, Belgium; [d]Cliniques Universitaires Saint-Luc, Stomatologie et Chirurgie Maxillo-Faciale, Université Catholique de Louvain, Brussels, Belgium

ABSTRACT

Objective: To compare the cervical kinematics and sensorimotor control (i.e., all the afferent, efferent, central integration, and processing components involved in maintaining joint stability) of people with chronic non-specific neck pain (CNSNP) to healthy controls, as assessed in an immersive virtual reality (VR) environment.

Methods: A comprehensive electronic search was conducted in four databases to identify articles published from inception up until June 2022. The search terms were related to 'neck pain' and 'virtual reality'. Inclusion criteria were observational studies, written in English or French, including a majority of people with CNSNP (≥ 60%), and comparing the cervical kinematics or sensorimotor control between people with CNSNP and healthy controls in an immersive VR environment. Methodological quality was assessed using the Joanna Briggs Institute Critical Appraisal Checklist for Cross-Sectional Studies. The overall certainty of evidence was assessed using the GRADE approach.

Results: Seven studies were included in the review. A narrative summary of results is provided for each study in relation to the outcomes assessed. Methodological quality was moderate to good. Cervical kinematics seemed to be altered in people with CNSNP compared with healthy controls, except for range of motion and response time. Sensorimotor control assessment showed inconsistent results. The certainty of evidence was very low for both kinematics and sensorimotor control.

Conclusion: This systematic review provides very low certainty of evidence in favor of different kinematic neck patterns between healthy individuals and people with CNSNP when assessed in an immersive VR environment. No conclusion can be drawn concerning sensorimotor control.

List of abbreviations: CNSNP: chronic non-specific neck pain; HMD: head-tracked mounted display; JBI: Joanna Briggs Institute; NSNP: non-specific neck pain; RoM: range of motion; VR: virtual reality

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Introduction

Neck pain is a highly prevalent musculoskeletal disorder, with a prevalence peak in middle-aged adults and a more frequent incidence in women [1,2]. Approximately 22–70% of the population will suffer from neck pain at some point in their lifetime [1]. Neck pain leads to important economic costs and is ranked fourth in terms of disability contribution around the world [3]. 'Non-specific' neck pain (NSNP) refers to most patients with neck pain and is defined as 'neck pain occurring in the absence of trauma, signs or symptoms of major structural pathology, neurological signs or specific pathology' [1]. The cause of NSNP remains unclear but a multifactorial etiology, with modifiable and non-modifiable risk factors, is suggested. These factors include ergonomic/physical, personal, behavioral, and psychosocial factors [4–12]. NSNP is a highly recurrent musculoskeletal disorder, where 50–75% of affected patients in the general population will report another episode 1 to 5 years later [4], and 60–80% of the working population will report another episode 1 year later [5]. The prognosis of NSNP is poor [13], and nearly half of all patients with NSNP may develop chronic pain (> 3 months), persistent or occurring through recurrent episodes [14].

Literature shows that NSNP is frequently associated with functional impairments such as decreased active cervical range of motion (RoM), decreased velocity of movements, and altered sensorimotor

CONTACT Alexandre Luc alexandre.luc@uclouvain.be Neuro Musculo Skeletal Lab, Institut de Recherche Expérimentale et Clinique, Secteur des Sciences de la Santé, Université Catholique de Louvain, Avenue Mounier 53, Brussels 1200, Belgium.

control (i.e., all the afferent, efferent, central integration, and processing components involved in maintaining joint stability) [15–20]. In people with neck pain, cervical sensory inputs can be altered by different factors (e.g., pain, direct damage to joints or muscles, functional impairments, morphological changes in neck muscles) and can consequently lead to impaired sensorimotor control and cervical kinematics [19]. In addition, these impairments may be associated with disability and activity limitations [16]. Current clinical guidelines for neck pain recommend the assessment of active RoM and sensorimotor impairments, as well as active treatments (e.g., mobility, proprioception, muscle coordination exercises) that aim to address individuals' functional impairments [1,21,22]. Therefore, a precise assessment of functional impairments in people with neck pain should be the basis for an individualized active treatment [19].

Cervical kinematics (e.g., RoM, velocity, joint angles, and their timing) are commonly evaluated by a variety of assessment methods, including visual RoM estimation, goniometer, inclinometer, potentiometer, and other more sophistical devices [16,23,24]. Cervical muscle coordination and proprioception are usually assessed by the craniocervical flexion test and head-to-neutral repositioning tests, respectively [15,25,26]. According to de Zoete et al. [18], seven cervical sensorimotor control tests have been suggested useful and are usually performed with a laser pointer, force platform, or electromagnetic device [18,27]. However, these methods produce voluntary motion on external command and do not always evaluate spontaneous functional neck movements (i.e., movements based on real-world situational biomechanics), which occur during activities of daily living in response to different stimuli (e.g., sound, vision, and odors) [28]. This accentuates the importance of identifying impairments in both cervical kinematics and sensorimotor control within subjects suffering from CNSNP in the most precise, reliable, and functional way. Virtual reality (VR) could be the adequate method to do this.

Immersive VR is 'a computer-generated 3 D environment, usually displayed in a head-tracked mounted display (HMD)' [29]. Immersive VR is a technology with almost endless possibilities [30], and its usage is growing fast in the clinical medicine area. Thanks to different mechanisms (e.g., distraction, stimulation of senses, focus shifting, interactivity, and illusion) [29,31], VR can effectively reduce acute and chronic pain during a short period of time [32–35]. This would allow patients to show their 'real' capacities, independent of the perception of pain or other factors (e.g., internal focus) that influence conventional assessments. Virtual reality is considered a more functional and ecological approach, as it creates real-life situations, motivating the patient to perform neck movements and allowing clinicians to better evaluate cervical kinematics and sensorimotor control [28,36]. Thus, VR assessments may lead to different results than conventional methods (e.g., oral command to move the head).

Researchers started assessing cervical kinematics using VR almost a decade ago [37]. Since then, several papers have aimed at investigating different kinematic and sensorimotor control outcomes (e.g., RoM, velocity, accuracy of movements, proprioception) of subjects with CNSNP when an immersive VR environment was used as both an assessment tool and a rehabilitation device. A few randomized controlled trials have demonstrated the clinical utility of assessing kinematics and sensorimotor control in people with chronic neck pain in a VR environment [38–43]. The literature on this topic is growing; however, currently available systematic reviews are based on methods evaluating kinematics and sensorimotor control in the real world, or a combination of real-world and VR assessments [15–19]. To date, no systematic review has been conducted exclusively on the VR assessment of cervical kinematics and sensorimotor control in people with CNSNP compared to healthy individuals, creating a lack of a global vision approach on this matter.

Thus, the aim of this review was to compare the cervical kinematics and sensorimotor control of subjects with CNSNP to healthy controls, as assessed in an immersive VR environment.

Methods

This systematic review was registered on PROSPERO before completion of the initial search (registration number: CRD42020159577). The updated Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [44] and the recommendations of Mueller et al. [45] were followed.

Search strategy

A systematic electronic search was performed by two independent authors (A.L and S.T) in PubMed, Embase, Scopus, and Google Scholar to identify potentially eligible published studies from inception up until March 2020. Comprehensive and exhaustive search equations were developed according to the PICO format and validated by an experienced librarian at the Université Catholique de Louvain-la-Neuve (UCLouvain, Belgium). An updated search was performed on June 30, 2022, to find any newly relevant published article. To be as exhaustive as possible, search terms were related to 'neck pain', 'virtual reality', and their synonyms. In PubMed, MeSH terms and Boolean operators were used. Search equations are provided in Appendix. Handsearching was performed using the reference lists of related articles.

Inclusion and exclusion criteria

Articles were included in the final review if all the following PICO-based criteria were met:

- Observational design
- Assessing cervical kinematics (e.g., RoM, velocity, joint angles, and their timing) and/or sensorimotor control (e.g., proprioception, postural sway, subjective visual vertical, head steadiness) of people with CNSNP in an immersive VR environment, compared with healthy controls
- Majority of the study's patient population ($\geq$ 60%) had CNSNP (criteria used if data on subjects with CNSNP were not available and if the study population was described sufficiently in detail)
- Written in English or French and available in full-text.

Studies were excluded if one of the abovementioned eligible criteria was not met. Systematic reviews, other reviews, and trials were also excluded. No restrictions to publication date were made. Only studies published in peer-reviewed journals were included.

Cervical kinematics

The kinematic outcomes assessed in this review were RoM, peak velocity, mean velocity, time to peak percentage, response time from target appearance to motion initiation, number of velocity peaks, and head movement accuracy. The definitions of these kinematic outcomes are presented in Table 1.

Sensorimotor control

The sensorimotor control outcomes assessed in this review were the subjective visual vertical and the head tilt response. Subjective visual vertical was assessed using the subjective visual vertical test [46,47]. Head tilt response was assessed using the head tilt response test [46]. Descriptions of these tests can be found in Table 2.

Study selection

Two independent reviewers (A.L and S.T) identified studies in the database searches and imported them into EndNote X8. After duplicates were removed manually by both reviewers independently and *via* EndNote's automation tool, the titles and abstracts were screened based on the predefined inclusion and exclusion criteria. Full-text articles were then reviewed by both reviewers independently for a definitive inclusion in the systematic review. Discrepancies at each stage were discussed and agreed up on by both reviewers. If a consensus was not reached, a third reviewer (L.P) made a final decision.

Data extraction

Data related to sample characteristics (sample size, age, and sex), experiment description, VR device and motion tracking system used, comparators, and outcome measures of interest were independently extracted by two reviewers (A.L and S.T) from each primary study using a standardized Word form. In cases of missing data or a need to specify information about the study, respective authors were contacted *via* email.

Methodological quality assessment

The methodological quality was assessed at a study level, independently, by two reviewers (A.L and S.T), using the Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Cross-Sectional Studies. This tool was chosen because it was specifically designed to assess the methodological quality of cross-sectional studies and to determine the extent to which these studies addressed the possibility of bias in their design, conduct, and analysis. It consists of eight items (assessing different criteria such as the study population, the measurement of the exposure

Table 1. Definitions of cervical kinematic outcomes [51,52].

Peak velocity	Maximal value of velocity recorded (in degrees per second) from motion initiation to target hit
Mean velocity	Mean value of velocity recorded (in degrees per second) from motion initiation to target hit
Time to peak percentage	Time from motion initiation to peak velocity (as a percentage of the total movement time)
Response time	Response time from target appearance to motion initiation (motion initiation toward the target is defined as the point where velocity passes a threshold value set at 2.5% of velocity peak)
Number of velocity peaks	Number of velocity peaks from motion initiation to target hit (reflecting motion smoothness)
Head movement accuracy	Angular difference between the target position and the subject's head position during the virtual reality assessment

Table 2. Descriptions of the sensorimotor control tests [46,47].

Subjective visual vertical test	In a virtual reality device, two dots representing the end points of a 20° tilted imaginary line were presented within a square that was tilted 18°. Both the tilted square and dots were positioned either clockwise or anticlockwise, which was randomized by custom software. The computer mouse could be used to rotate a button by clicking and holding, allowing rotation of the dots by a minimum of 0.01°. The participant was instructed to reposition the dots so that the imaginary line was positioned vertically (i.e. dots right above each other). The rotational de*via*tion of the imaginary line represented by the two dots from the true vertical (°) was recorded as the outcome.
Head tilt response test	A white line, tilted either (5 or 15°) clockwise or (25 or 15°) anticlockwise, was displayed in the virtual reality device. The participant was instructed to laterally flex the neck so that the presented line was positioned exactly vertically in space. While holding the head still in the required position, the head position was recorded before the next line was presented. Head position (error of the line from the true vertical in degrees) was recorded.

and condition, the presence of confounding factors, and the statistical analysis used) and each one can be answered by 'Yes', 'No', 'Unclear' or 'Not applicable'. No studies were excluded based on their methodological quality.

Data synthesis

Data are presented by outcome (kinematics and sensorimotor control), as retrieved from the primary studies. Statistically significant differences were presented using p-values ($p < 0.05$). Effect sizes were presented as Cohen's 'd'. It was expected that there would be a high heterogeneity between studies due to their novelty and their observational design (tests, protocols, devices, etc.); therefore, the results were summarized in a narrative format.

Certainty of evidence

The recommended GRADE approach was used to assess the certainty of evidence [48]. The certainty of evidence for each outcome ranges from very low to high according to five criteria (risk of bias, inconsistency, indirectness, imprecision, and publication bias). According to the GRADE approach and the Cochrane Handbook, because of the observational design, assessment started with a 'low' certainty of evidence [49]. Downgrades were performed when studies had a high risk of bias, showed inconsistent results (according to the p-values), indirectness of evidence (indirect comparisons or addressing a restricted version of the main review question according to the PICO criteria), imprecision, or suspicion of publication bias (missing data, selective reporting, and search strategy).

Results

Study selection

The primary electronic search yielded 291 articles, and 37 additional references were added after screening the Google Scholar database ($n = 34$), references lists ($n = 1$), and the updated electronic search ($n = 2$). After removal of duplicates ($n = 106$), 222 articles were screened based on titles and abstracts. Among these, 191 of them were excluded because they did not match the inclusion criteria. Then, 31 full-text articles were read and assessed for eligibility, and 24 of them were excluded with reasons (i.e., only healthy individuals, no precision about the population studied, no comparison between CNSNP and healthy individuals, mixed chronic neck pain population with less than 60% of subjects with CNSNP , no results available, and not observational design). After the full-text screening, seven articles were included in this review (Figure 1).

Methodological quality assessment

All included studies were cross-sectional. Overall, the methodological quality was moderate to good (Table 3). Five articles [28,46,47,50,51] were considered of good quality and two articles [52,53] were considered of moderate quality. All articles clearly defined the inclusion criteria, study subjects, and setting. All articles measured the kinematic and sensorimotor control outcomes in a valid and reliable way, used standard criteria to identify CNSNP, and used appropriate statistical analyses. All but one article [53] measured the exposure in a valid and reliable way. Only two articles [46,51] clearly identified confounding factors, but only one [52] did not use strategies to deal with them.

Study characteristics

All included articles recruited a majority of people with CNSNP ($\geq$ 60%); thus, all subjects were considered as suffering from CNSNP in this review. Articles that did not include only individuals with CNSNP also included individuals with chronic traumatic neck pain (whiplash-associated disorders). The seven articles selected represented a total of 453 adult participants, of which 209 suffered from

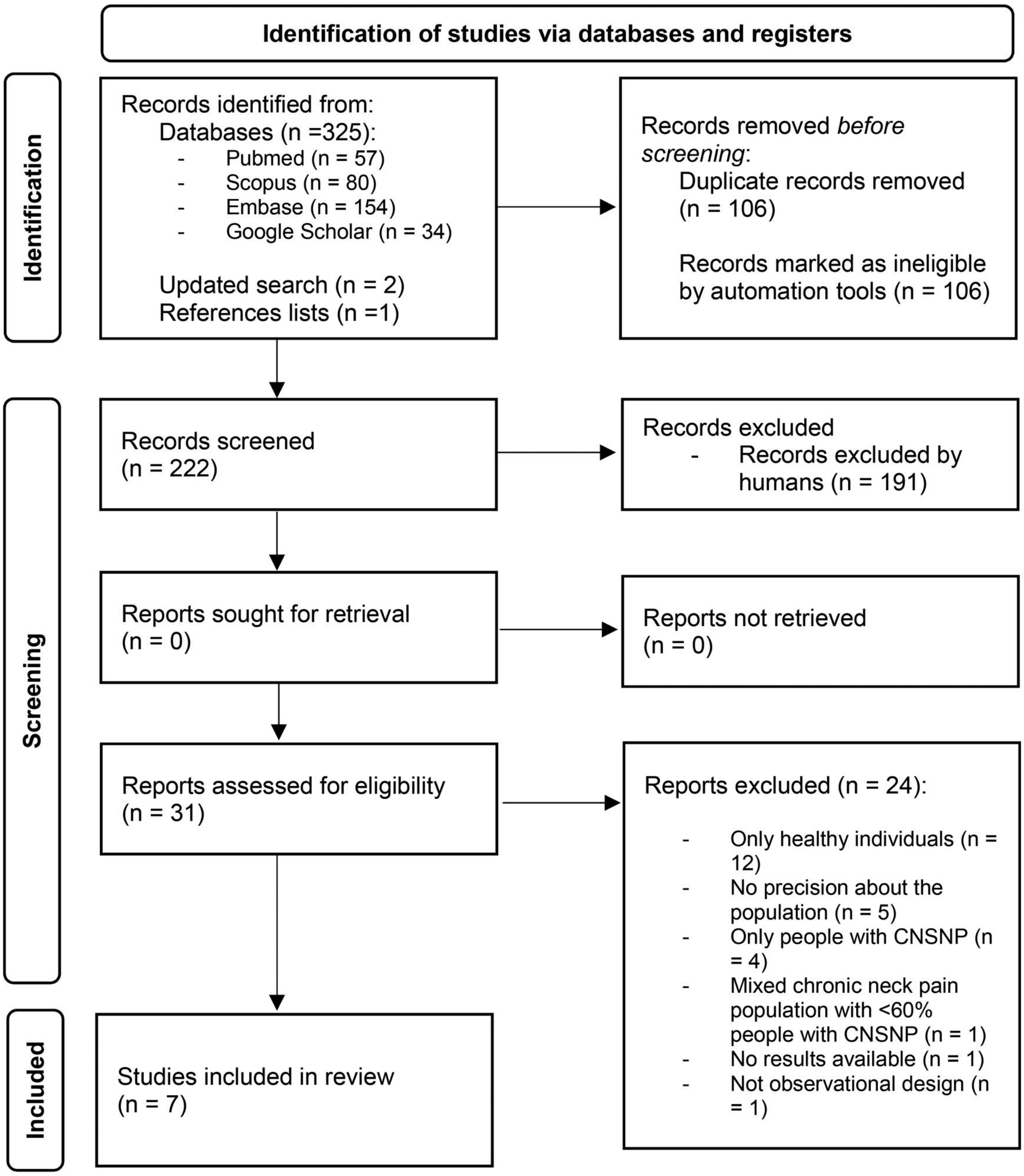

Figure 1. PRISMA 2020 flow diagram .

Table 3. Methodological quality assessment according to the Joanna Briggs Institute (JBI) Critical Appraisal Checklists for Cross-Sectional studies.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Quality
De Zoete et al. 2019	Y	Y	Y	Y	Y	Y	Y	Y	Good
Sarig-Bahat et al. 2010a	Y	Y	Y	Y	N	Y	Y	Y	Good
Sarig-Bahat et al. 2010 b	Y	Y	Y	Y	N	N	Y	Y	Moderate
Sarig-Bahat et al. 2015a	Y	Y	U	Y	N	Y	Y	Y	Moderate
Sarig-Bahat et al. 2020a	Y	Y	Y	Y	Y	Y	Y	Y	Good
Treleaven et al. 2015	Y	Y	Y	Y	N	Y	Y	Y	Good
Williams et al. 2017	Y	Y	Y	Y	N	Y	Y	Y	Good

Y = Yes, N = No, U = Unclear, NA = Not applicable.

CNSNP and 244 were healthy controls. Four articles used different HMDs with a built-in motion tracking system to capture kinematics: Oculus Rift [46,50,51] and Wrap-1200VR [53]. Three articles used a device to create a virtual environment, without using it as a motion tracking system: I-glasses HRV-pro [28,52] and virtual video glasses [47]. Different tracking systems other than HMDs were also used: Fastrak [28,52] and computer [47] (Table 4).

Kinematic assessment

Summary results are presented in Table 4. The GRADE assessment is shown in Table 5.

Range of motion

Two articles [28,50] assessed RoM in a VR environment. Overall, the results were inconsistent between healthy individuals and people with CNSNP. The certainty of evidence was very low.

Comparing RoM (using an electromagnetic tracking system) in people with CNSNP to controls

Table 4. Summary results of neck kinematic and sensorimotor control VR assessments in healthy individuals and people with chronic non-specific neck pain (CNSNP).

Study details	Population	Intervention	Outcomes of interest	Comparison	Devices	Results	Authors' conclusion
No differences between individuals with chronic idiopathic neck pain and asymptomatic individuals on seven cervical sensorimotor control tests: a cross-sectional study (de Zoete et al. **2019)**	Sample size = 100 50 subjects with CNSNP (30 females, median of 35.5 years) 50 healthy controls (27 females, median of 34.5 years)	Seven cervical sensorimotor control tests, including 2 in virtual reality (subjective visual vertical [SVV] test, head tilt response [HTR] test)	SVV and HTR tests	Subjects with CNSNP vs. Healthy controls	HMD: Oculus Rift SDK 2.0 Tracking system: Oculus Rift SDK 2.0 (HTR test) and computer (SVV test)	No between-group difference for any of the tests ($p > 0.05$) No between-group difference in proportions of poor performers for each test ($p > 0.05$)	The outcomes of both VR CSMC tests are not significantly different between individuals with CNSNP and age and sex matched controls.
Neck pain assessment in a virtual environment (Sarig-Bahat et al. **2010a)**	Sample size = 67 25 subjects with CNSNP (16 females, 39 +/- 12.7 yeas) 42 healthy controls (31 females, 35.3 +/- 12.4 years)	One conventional assessment (oral instruction to move the head as far as possible in all directions), followed by a VR assessment (VR game consisting of a reaching task, eliciting movements in all directions) and then a second conventional assessment (same as the first one)	Full cycle Flexion + Extension RoM Full cycle Right rotation + Left rotation RoM	Subjects with CNSNP vs. Healthy controls VR assessment vs. Conventional assessment	HMD: I-glasses HRV pro Tracking system: Fastrak (Polhemus)	Full-cycle RoM: Significant differences between groups ($p = 0.0002$), between experimental stages ($p < 0.0001$), and between sagittal and horizontal planes of motion ($p < 0.0001$) VR-RoM was significantly greater than both conventional RoMs ($p < 0.05$) Half-cycle RoM: Significant differences between groups ($p = 0.0002$), between experimental stages ($p < 0.0001$), and between the 4 directions of motion ($p < 0.0001$) VR-RoMs were significantly greater than both conventional measures ($p < 0.05$) for right rotation, left rotation, and extension	Neck pain was significantly associated with reduced cervical RoM in both VR and conventional methods of assessment. The developed VR method is an objective and sensitive method of cervical RoM assessment capable of significant RoM enhancement. The novel VR method presented in this study provides a means to assess functional movement required both for evaluation and treatment.
The effect of neck pain on cervical kinematics, as assessed in a virtual environment (Sarig-Bahat et al. **2010b)**	Sample size = 67 25 subjects with CNSNP (16 females, 39 +/- 12.7 yeas) 42 healthy controls (31 females, 35.3 +/- 12.4 years)	VR assessment using a game consisting of a reaching task and eliciting fast cervical movements in flexion, extension, and rotations	Response time Peak velocity (Vpeak) Mean velocity (Vmean) Time to peak percentage (TTP%) Number of velocity peaks (NVP)	Subjects with CNSNP vs. Healthy controls	HMD: I-glasses HRV pro Tracking system: Fastrak (Polhemus)	Significantly lower Vpeak and Vmean ($p < 0.0001$) and significantly higher NVP ($p = 0.0036$) in subjects with CNSNP compared to healthy controls No significant group differences ($p > 0.05$) for response time and TTP%	The findings of reduced velocity and smoothness of cervical motion in patients with CNSNP contribute to a better understanding of the impairment associated with neck pain and should be addressed in the clinical assessment and management of neck pain.
Interactive cervical motion kinematics: Sensitivity, specificity, and clinically significant values for identifying kinematic impairments in patients with chronic neck pain	Sample size = 55 33 subjects with CNSNP (20 females, 37.56 +/- 9.95 years) 22 healthy controls (8 females, 33 +/- 6.78 years)	VR assessment using a game with 2 interactive modules (velocity and accuracy), consisting of reaching and pursuit tasks involving movements in flexion,	Peak velocity (Vpeak) Mean velocity (Vmean) Time to peak percentage (TTP%) Number of velocity peaks (NVP) Head	Subjects with CNSNP vs. Healthy controls	HMD + Tracking system: Wrap 1200VR, Vuzix	Significant and strong effect-size differences in Vpeak, Vmean, NVP and TTP% in all directions ($p < 0.05$; Cohen's d: 0.81-3.01), excluding TTP% in left rotation ($p = 0.25$; Cohen's d: 0.32) Significant group differences for accuracy in both X and Y for	These findings suggest cervical kinematics should be evaluated clinically, and screened by the provided cut-off values for identification of relevant impairments in those with neck pain. Such identification of presence or absence of

(*continued*)

Table 4. Continued.

Study details	Population	Intervention	Outcomes of interest	Comparison	Devices	Results	Authors' conclusion
(Sarig-Bahat et al. 2015a)		extension, and rotations	movement accuracy			flexion ($p < 0.05$; Cohen's d: −1.23 and −1.31, respectively), in X for extension ($p < 0.05$; Cohen's d: −1.57), and in Y for right and left rotations ($p < 0.05$; Cohen's d: −0.83 and −0.75, respectively) CNSNP subjects moved more slowly throughout the trial (less Vmean), and accelerated to a lower Vpeak than the healthy control subjects Difference in symmetry (TTP%) between the acceleration and the deceleration phases in the controls' velocity profile and the CNSNP subjects' profile	kinematic impairments may direct treatment strategies and additional evaluation when needed.
High- vs low-tech cervical movement sense measurement in individuals with neck pain (Sarig-Bahat et al. 2020a)	Sample size = 40 20 subjects with CNSNP (14 females, median of 42 years) 20 healthy controls (10 females, median of 27.5 years)	VR assessment using a game consisting of a pursuit task involving movements in flexion, extension, and rotations	Cervical movement accuracy	Subjects with CNSNP vs. Healthy controls	HMD + Tracking system: Oculus Rift DK2	Significantly greater accuracy errors in subjects with CNSNP compared with healthy controls for rotation (left and right), flexion, and extension ($p < 0.05$) Significantly greater total rotation accuracy error (sum of left and right rotations) in subjects with CNSNP ($p < 0.05$)	Overall, the VR test has identified CNSNP participants to have greater error and reduced speed during self-paced accuracy tasks.
High variability of the subjective visual vertical test perception, in some people with neck pain – Should this be a standard measure of cervical proprioception? (Treleaven and Takasaki, 2015)	Sample size = 84 36 subjects with CNSNP (55% females, 32.7 +/- 13.8 years) 48 healthy controls (72% females, 29.4 +/- 10.8 years)	Subjective visual vertical (SVV) test performed in VR	SVV test Mean absolute error (AE), mean constant error (CE), mean variable error (VE) and mean root mean square error (RMSE)	Subjects with CNSNP vs. Healthy controls	HMD: Video eyeglasses (80″ 3 D Virtual Video Glasses) Tracking system: Computer	Subjects with CNSNP had significantly larger variability of SVV errors compared to healthy controls (VE: $p = 0.001$ / RMSE: $p = 0.01$)	Variability measures rather than absolute or constant error are likely to be more sensitive to assess SVV in those with neck pain. CNSNP subjects had an altered strategy for maintaining the absolute error of the perception of vertical, by increasing variability of their performance.
Cervical kinematics in patients with vestibular pathology vs patients with neck pain: A pilot study (Williams et al. 2017)	Sample size = 40 20 subjects with CNSNP (11 females, 48.3 +/- 13.6 years) 20 healthy controls (10 females, 45 +/- 12.8 years)	VR assessment using a game with 3 interactive modules (range of motion, velocity, and accuracy), consisting of reaching and pursuit tasks involving movements in flexion, extension, and rotations	Range of motion (RoM) Peak velocity (Vpeak) Mean velocity (Vmean) Time to peak percentage (TTP%) Number of velocity peaks (NVP) Head movement accuracy	Subjects with CNSNP vs. Healthy controls	HMD + Tracking system: Oculus Rift DK2	Reduced Vmean and TTP% in both rotation ($p = 0.04$ and $p = 0.001$, respectively) and Flexion/Extension ($p = 0.007$ and $p = 0.01$, respectively) for subjects with CNSNP compared to healthy controls No difference between group for NVP, accuracy, and RoM ($p > 0.05$)	The results of this study support that kinematics are altered in neck pain patients, with velocity being most affected.

during a VR assessment (i.e., maximal RoM in flexion, extension, and rotations, during a VR game consisting of a reaching task) and a conventional assessment (i.e., oral instruction to move the head as far as possible until the perception of pain), Sarig-Bahat et al. [28] found significant differences between populations ($p = 0.0002$). In addition, they found significant differences between VR and conventional assessments ($p < 0.05$), with greater RoM achieved in VR (in rotation and extension) [28]. Williams et al. [50] also compared the cervical RoM (using the HMD 3 D motion tracker) of people with CNSNP to healthy controls, during a VR game, and did not find any significant difference between these two groups ($p > 0.05$).

Velocity, smoothness, accuracy, time to peak percentage, and response time

Four articles [50–53] assessed velocity (mean and peak), smoothness (i.e., number of velocity peaks during movement), head accuracy (i.e., angular difference between the target position and the subject's head position during the VR assessment), time to peak percentage (i.e., time from motion initiation to peak velocity, as a percentage of the total movement time) or response time (i.e., point where velocity passes a threshold value set at 2.5% of velocity peak) in a VR environment. Overall, most findings demonstrated that people with CNSNP had lower mean and peak velocities, lower accuracy, altered time to peak percentage, and higher number of velocity peaks than healthy controls. Response time was not found to be different between people with CNSNP and healthy controls. The certainty of evidence was very low.

Sarig-Bahat et al. [52] compared different kinematic outcomes (peak velocity, mean velocity, response time from target appearance to motion initiation, time to peak percentage, and number of velocity peaks) between people with CNSNP and healthy controls, using a VR game developed to monitor the dynamic characteristics of fast goal-directed functional movements in response to visual stimuli (in flexion, extension, and rotations). All kinematic outcomes were significantly different between both populations, except for time to peak percentage and response time. Subjects with CNSNP demonstrated lower velocities (peak and mean) and a higher number of velocity peaks (lower smoothness).

Sarig-Bahat et al. [53] assessed peak and mean velocities, number of velocity peaks, time to peak percentage, and head movement accuracy between people with CNSNP and healthy controls, using a VR game consisting of fast cervical movements and a head pursuit task in response to visual stimuli (in flexion, extension, and rotations). Their study demonstrated strong effect size differences for peak and mean velocities, number of velocity peaks, and time to peak percentage in all directions ($p < 0.05$; Cohen's d: 0.81-3.01), excluding time to peak percentage in left rotation ($p = 0.25$; Cohen's d: 0.32). Accuracy measures (i.e., difference between the target position and the participant's head location, in degrees, during a head pursuit task) demonstrated significant group differences in flexion ($p < 0.05$; Cohen's d: between -1.23 and -1.31), extension ($p < 0.05$; Cohen's d: -1.57), and right and left rotations ($p < 0.05$; Cohen's d: -0.83 and -0.75, respectively).

Williams et al. [50] used the same VR game and assessed the same kinematic outcomes as Sarig-Bahat et al. [53] but only found statistical differences for mean velocity and time to peak percentage between people with CNSNP and healthy controls in both rotation and flexion/extension, with lower values in people with CNSNP.

In 2020, Sarig-Bahat et al. [51] assessed cervical movement accuracy in people with CNSNP and healthy controls, using the same head pursuit task as Sarig-Bahat et al. [46], and showed significantly greater accuracy errors in people with CNSNP compared to healthy controls for each direction of movement ($p < 0.05$).

Sensorimotor control assessment

Summary results are presented in Table 4. The GRADE assessment is shown in Table 5.

Two articles [46,47] assessed sensorimotor control in an immersive VR environment. Overall, results were inconsistent between people with CNSNP and healthy controls. The certainty of evidence was very low.

Comparing sensorimotor control between healthy individuals and people with CNSNP with two VR tests (subjective visual vertical and head tilt response

Table 5. Grading of Recommendations Assessment, Development and Evaluation (GRADE) summary of findings.

Number of studies	Study design	Risk of bias	Inconsistency	Indirectness	Imprecision	Publication bias	Certainty of evidence
Kinematics							
5	Observational studies	Not serious	Serious○	Serious*	Not serious	Likely●	**Very low** ⊕○○○
Sensorimotor control							
2	Observational studies	Not serious	Not serious	Serious*	Not serious	Likely●	**Very low** ⊕○○○

○ Inconsistency between studies according to the statistical significance (p-value inferior to 0.05).
* Some studies included a mixed neck pain population (non-specific neck pain and whiplash-associated disorders).
● The search strategy did not cover every database and unpublished literature, thus relevant studies with different findings may have been missed.

tests), de Zoete et al. [46] showed no differences ($p > 0.05$). However, Treleaven et al. [47] showed that people with CNSNP had a larger variability of subjective visual vertical errors compared to controls ($p \leq 0.01$).

Discussion

This study aimed at comparing cervical kinematics and sensorimotor control in people with CNSNP to healthy controls, as assessed in an immersive VR environment. Results suggest some altered neck kinematic patterns (peak and mean velocities, time to peak percentage, number of velocity peaks, and head movement accuracy) in people with CNSNP compared to healthy individuals. Results for neck RoM and movement response time were inconsistent. The findings for sensorimotor control were inconsistent between people with CNSNP and healthy controls. According to the GRADE approach, the certainty of evidence was very low for cervical kinematics and sensorimotor control due to the observational design, the suspicion of publication bias and the inconsistency of results.

One article [50] out of two assessing RoM showed no significant differences between people with CNSNP and healthy individuals, which is not consistent with a recent systematic review by Stenneberg et al. (2017) that found significantly reduced active cervical RoM in people with chronic non-traumatic neck pain compared with healthy controls, when assessed in the real environment [16]. However only two studies compared RoM between people with CNSNP and healthy controls in a VR environment in this review, which prevents us from drawing any conclusion concerning the potential difference in RoM between these two populations while being assessed in an immersive VR environment. One study [28] demonstrated a greater RoM performed in VR compared to that in a conventional assessment. However, in a recent study [54], VR did not seem to affect the pain-free RoM in people with CNSNP using visual feedback to overstate or understate the true RoM, which challenges the relevance of the VR-induced illusion mechanism and the associative learning theories for the perception of pain [55,56]. A recent study [57] in patients with chronic neck pain also demonstrated no effect of exercises overstating RoM in VR on pain intensity and pain-free RoM.

Peak and mean velocities were altered in people with CNSNP in two and three articles (out of three) assessing these parameters, respectively, in all directions of movement. These findings are consistent with a recent systematic review by Moghaddas et al. (2019) indicating that chronic neck pain individuals have lower velocity of movement compared to asymptomatic individuals, during reaching and gaming tasks performed in real and virtual environments [17]. Franov et al. (2022) found a conflicting level of evidence regarding differences in peak and mean velocities between individuals with neck pain and healthy individuals when assessed in real and virtual environments, however most studies included showed differences between these two populations [19]. The number of velocity peaks was higher in people with CNSNP compared to healthy individuals in two articles out of three, reflecting lower smoothness of movement in people with CNSNP. This is also consistent with the systematic review by Moghaddas et al. that investigated the differences in smoothness of movement between chronic neck pain individuals and healthy controls [17]. However, the study included in Moghaddas et al. [17] was also included in this review. Franov et al. (2022) found a conflicting level of evidence regarding differences in the number of velocity peaks between individuals with chronic neck pain and healthy individuals when assessed in virtual environments, however these results are based on two studies that are also included in this review [19]. Time to peak percentage and accuracy were significantly different in two out of three articles, whereas response time was not found to be different between people with CNSNP and healthy controls in the only article that investigated this parameter [52].

A recent systematic review and meta-analysis found promising evidence suggesting that interactive VR is highly valid and reliable in assessing the kinematics of patients with chronic neck pain [58]. Virtual reality can quantitatively assess neck kinematics (RoM, velocity, accuracy, and smoothness) during functional tasks and thus may provide an assessment of a patient's ability to perform activities of daily living [17]. Because much of our daily neck function is dynamic in response to multiple stimuli [53], unaltered RoM, velocity, smoothness, and accuracy of neck movements are essential to function normally. Because these kinematic parameters may be altered in chronic neck pain individuals, it may be relevant to assess them and to direct the treatment to improve them. In this way, VR may be a method to quantify the effectiveness of an intervention [17], by measuring the improvements in neck kinematics and by linking these improvements to self-reported measures such as pain intensity, disability, and quality of life. However, further studies are needed to confirm this.

Concerning sensorimotor control, contradictory results emerged between studies. While de Zoete et al. [46] demonstrated no differences between people with CNSNP and healthy controls on the subjective visual vertical test performed in VR, Treleaven et al. [47]

showed a larger variability of subjective visual vertical errors in people with CNSNP. A previous systematic review evaluating these tests (not in VR) in a CNSNP population also showed limited results [18]. Thus, no clear conclusion can be drawn concerning the VR sensorimotor control assessment of people with CNSNP.

In the present review, fear of movement was not correlated with cervical kinematics, which is contradictory with a previous VR study performed on a mixed chronic neck pain population [59]. The correlation between fear of movement and cervical kinematics is not surprising if it was to be linked with the fear avoidance model and its impact on chronic musculoskeletal pain [60,61]. Fear of movement (kinesiophobia), among other psychosocial factors, is associated with the chronicization of NSNP by causing movement avoidance and hypervigilance, which can lead to continued disuse, disability, and depression [61]. According to Tejera et al. [42], kinesiophobia may be associated with decreased cervical RoM and speed of cervical movement. By creating an artificial pain-distracting environment devoid of external stimuli [32,33], VR might reduce kinesiophobia and pain, allowing clinicians to assess the patient's 'real' cervical kinematics (i.e., not influenced by the internal focus, fear, or pain perception). Tejera et al. [42] also demonstrated that VR training was more effective in reducing kinesiophobia than conventional neck exercises; however, more randomized controlled trials are needed to confirm this hypothesis.

A recent systematic review found that pain intensity was significantly reduced during VR exposure in chronic musculoskeletal populations [62]. This further highlights the potential of VR in assessing cervical kinematics better than other conventional methods. Further studies are needed to investigate the level of correlation between kinesiophobia, pain intensity, and cervical movements during kinematic and sensorimotor control assessments in a VR environment in people with CNSNP.

It is noteworthy that a possible disadvantage of VR is the experience of symptoms due to the VR experiment (i.e., VR-induced motion sickness). Virtual reality-induced motion sickness groups different symptoms related to nausea, disorientation, and oculomotor effects, occurring during the use of a VR device [63]. These symptoms could lead to dropouts from the study and may induce bias in assessments. According to a recent systematic review [64], the major contributing factor influencing VR-induced motion sickness is the content. Future studies should take this factor into account when assessing people with CNSNP in a VR environment. However, no article in this systematic review reported such adverse effects, which could mean that their occurrence is very rare. Furthermore, new generation HMDs seem to induce significantly less adverse effects and should be prioritized for future studies [65].

In the included studies, immersive VR demonstrated noteworthy advantages. It appeared to increase the subject's motivation, to achieve a greater RoM, to offer a lower cost than other technology-based assessments, to avoid examiner-related bias, to have the ability to define 'pure' and repeatable movements/tasks, and to allow a safe environment and straightforward data collection, as well as to create a high-level real-world simulation devoid of visual references. Most of these are usually not obtained with conventional assessments, showing the high and promising relevance of applying VR assessments in clinical practice.

Limitations of included studies

Studies included in this systematic review had a moderate to good methodological quality. Except for item 5 ('confounding factors identified'), all other items of the JBI Critical Appraisal Checklist for Cross-Sectional Studies were reported in most studies. Across all studies, some general limitations were encountered. The most common were a small sample size without *a priori* estimation, mild-to-moderate self-report data for people with CNSNP, no control for movement between the head and the HMD, and the HMD weight. These limitations lead to a cautious interpretation of the results and limit their generalization.

Strengths and limitations

To our knowledge, this is the first systematic review to compare the cervical kinematics and sensorimotor control of people with CNSNP to healthy individuals in an immersive VR environment. Strengths of this study are that information biases were minimized by using an independent double data extraction, and transparency was assured by following the updated PRISMA guidelines. This systematic review also has several limitations. First, the design of included studies (observational) implies a low level of evidence due to the potential of confounding and selection biases [49]. However, all included studies were considered as having moderate to good methodological quality. Second, we did not search all available databases and investigated unpublished data, which can imply publication bias. Third, five studies out of seven (71%) assessed a mixed chronic neck pain population, including people with CNSNP and people with chronic whiplash-associated disorders, which could lead to indirectness of evidence. However, because these studies included a majority of people with CNSNP ($\geq$

60%), we could suppose that findings may be more representative of this population. Fourth, the high heterogeneity across studies led to a narrative synthesis and prevented a meta-analysis or another acceptable synthesis method [66,67]. The narrative synthesis is a limitation because it is characterized by a lack of transparency, making assessment of the validity of their findings difficult [68]. Due to these limitations, the certainty of evidence was judged to be very low, and the findings of this review should be interpreted with caution.

Recommendations for future studies

This systematic review highlights the need for further studies to be conducted to investigate both cervical kinematics and sensorimotor control of people with CNSNP in a VR environment. Future studies assessing cervical kinematics and sensorimotor control should use the same HMDs, protocols, and tests to help reduce the heterogeneity and facilitate future comparisons between studies.

To strengthen the evidence of their clinical utility, future studies should evaluate the implementation of VR assessments in a large panel of physiotherapy practices and collect qualitative data from physiotherapists and patients. Furthermore, future studies should investigate the differences between subgroups of patients with neck pain and establish normative and cut-off data from a representative population.

Conclusions

The findings of this systematic review suggest some altered neck kinematic patterns (peak and mean velocities, time to peak percentage, number of velocity peaks, and head movement accuracy) in people with CNSNP compared to healthy individuals, when assessed in an immersive VR environment. Results for neck RoM and movement response time were inconsistent. Only two studies assessed sensorimotor control with no consensus on between-group differences in the subjective visual vertical test, preventing any firm conclusion. However, the certainty of evidence was very low for both cervical kinematics and sensorimotor control. Further research is needed to provide more evidence on neck kinematics and sensorimotor control differences between people with CNSNP and healthy individuals when assessed in an immersive VR environment.

Declarations

Disclosure statement

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Notes on contributors

Alexandre Luc, OMT, MSc, is an orthopaedic manual therapist and a PhD student at the Institute of Experimental and Clinical Research (Université Catholique de Louvain, Belgium). His research focuses on neck pain rehabilitation using immersive virtual reality.

Stephany Tamer, PT, MSc, is a physical therapist graduated from the Université Catholique de Louvain. She is a clinician with a great interest in musculoskeletal physical therapy research.

Renaud Hage, OMT, PhD, is an orthopaedic manual therapist and a researcher specialized in neck pain. His research focuses on the sensorimotor control assessment of the cervical spine.

Christine Detrembleur, PT, PhD, is a researcher at the Institute of Experimental and Clinical Research and a professor at the Faculty of Motricity Sciences, at the Université Catholique de Louvain. She has a great interest in kinematics and its assessment in physical therapy.

Laurent Pitance, OMT, PhD, is an orthopaedic manual therapist, a researcher at the Institute of Experimental and Clinical Research, and a professor at the Faculty of Motricity Sciences, at the Université Catholique de Louvain. His research focuses on neck pain and temporomandibular disorders.

ORCID

Alexandre Luc http://orcid.org/0000-0003-1031-6490

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Appendix

PubMed: (((‘neck pain’[MeSH Terms]) OR (neck pain*[Title/Abstract] OR neckache*[Title/Abstract] OR neck ache*[Title/Abstract] OR cervicalgia*[Title/Abstract] OR cervical pain*[Title/Abstract]))) AND (((‘virtual reality’[MeSH Terms]) OR (‘virtual reality’[Title/Abstract] OR game*[Title/Abstract] OR gaming[Title/Abstract] OR computer game*[Title/Abstract] OR ‘virtual environment’[Title/Abstract] OR Exergam*[Title/Abstract] OR Computer simulation[Title/Abstract] OR interactive gam*[Title/Abstract] OR active video gam*[Title/Abstract] OR ‘video gam*’[Title/Abstract] OR ‘computer-interface’[Title/Abstract] OR ‘simulator’[Title/Abstract])) OR VR[Title/Abstract] OR ‘Virtual Reality Exposure Therapy’[MeSH Terms] OR ‘virtual reality simulator’[Title/Abstract] OR ‘headset’[Title/Abstract] OR ‘head-mounted’[Title/Abstract] OR ‘imaging software’[Title/Abstract])

Scopus: (TITLE-ABS-KEY (‘neck pain*’ OR ‘neck ache*’ OR ‘neckache*’ OR ‘cervicalgia*’ OR ‘cervical pain*’) AND TITLE-ABS-KEY ({virtual reality} OR ‘game*’ OR gaming OR ‘computer game*’ OR {virtual environment} OR ‘exergam*’ OR computer AND simulation OR ‘interactive gam*’ OR ‘active video gam*’ OR ‘video gam*’ OR {computer-interface} OR {simulator} OR vr OR {virtual reality exposure therapy} OR {virtual reality simulator} OR {headset} OR {head-mounted} OR {imaging software}))

Embase: (’neck pain’/exp OR ’neck pain’:ti,ab OR ’cervicalgia’/exp OR ’cervical pain’/exp OR ’neckache’:ti,ab OR ’neck ache’:ti,ab) AND (’virtual reality’/exp OR ’virtual reality’:ti,ab OR ’video game’/exp OR ’computer game’:ti,ab OR ’computergame’:ti,ab OR ’video game’:ti,ab OR ’video games’:ti,ab OR ’videogame’:ti,ab OR ’videogames’:ti,ab OR ’exergame’/exp OR ’exergaming’/exp OR ’virtual reality exposure therapy’/exp OR ’simulator’/exp OR ’simulator’:ti,ab OR ’computer simulation’/exp OR ’computer simulation’:ti,ab OR ’virtual reality simulator’/exp OR ’virtual environment’/exp OR ’imaging software’/exp OR ’computer interface’/exp OR ’head-mounted’:ti,ab OR ’game’:ti,ab OR ’gaming’:ti,ab OR ’vr’:ti,ab OR ’headset’:ti,ab)

Google Scholar: (‘neck pain’ OR cervicalgia) AND (exergame OR exergaming OR ‘head-mounted’ OR ‘headset’ OR ‘virtual reality’)