Journal of Bodywork & Movement Therapies 39 (2024) 201–208

Contents lists available at ScienceDirect

Journal of Bodywork & Movement Therapies

journal homepage: www.elsevier.com/jbmt

Evaluating the additive diagnostic value of DidRen LaserTest: Correlating temporal and kinematic predictors and patient-reported outcome measures in acute-subacute non-specific neck pain

Guillaume Hage [a], Fabien Buisseret [b,c], Jean-Michel Brismée [d], Frédéric Dierick [b,e,f], Christine Detrembleur [a], Renaud Hage [b,f,g,h,*]

[a] Laboratoire de Neuro Musculo Squelettique (NMSK), Institut de Recherche Expérimentale et Clinique (IREC), UCLouvain, 1200 Brussels, Belgium
[b] Centre de Recherche et de Formation de la HELHa (CeREF), Chaussée de Binche 159, 7000 Mons, Belgium
[c] Service de Physique Nucléaire et Subnucléaire, UMONS, Research Institute for Complex Systems, Place Du Parc 20, 7000 Mons, Belgium
[d] Center for Rehabilitation Research, Texas Tech University Health Sciences Center, Lubbock, TX, USA
[e] Laboratoire d'Analyse du Mouvement et de la Posture (LAMP), Centre National de Rééducation Fonctionnelle et de Réadaptation (Rehazenter), Rue André Vésale 1, 2674 Luxembourg, Luxembourg
[f] Faculté des Sciences de La Motricité, UCLouvain, Place Pierre de Coubertin 1-2, 1348 Louvain-la-Neuve, Belgium
[g] Traitement Formation Thérapie Manuelle (TFTM), Private Physiotherapy/Manual Therapy Center, Avenue des Cerisiers 211A, 1200 Brussels, Belgium
[h] Haute école Libre de Bruxelles Ilya Prigogine, Section Kinésithérapie, 808, Route de Lennik, Bâtiment P, 1070 Brussels, Belgium

ARTICLE INFO

Handling editor: Dr Jerrilyn Cambron

1. Introduction

Neck pain, a distressing sensory and emotional experience often linked to potential or actual tissue damage in the cervical region (Bogduk, 2011a), exhibits a substantial lifetime prevalence ranging from 22% to 70% (Blanpied et al., 2017; Fejer et al., 2006; Hoy et al., 2010). This condition tends to recur, with about 44% of patients developing chronic symptoms (Blanpied et al., 2017; Borghouts et al., 1998; Gore et al., 1987), thereby presenting significant personal and socioeconomic impacts (Borghouts et al., 1999; Cohen and Hooten, 2017; Ferrari and Russell, 2003).

The etiology of neck pain often remains elusive (Bogduk, 2011b), with most of cases classified as "non-specific" (Childs et al., 2008; Coulter et al., 2019). Acute or subacute non-specific neck pain (ANSP), characterized by pain duration of less than three months (Blanpied et al., 2017; Pool et al., 2010), presents unique challenges in diagnosis and management. Diagnosis is particularly challenging as neck pain is not directly linked to pathoanatomical sources (S. E. Anderson et al., 2012), leading to a reliance on classifications based on assessments of muscle, connective tissue, nerve functions, and visual observation of neck motion (Bier et al., 2018; Blanpied et al., 2017; Childs et al., 2008).

Deficiencies in movement kinematics, such as speed, fluidity, and range of motion (RoM), have been observed in patients with neck pain (Sarig Bahat, Sprecher, Sela and Treleaven, 2016; Sjolander et al., 2008). While assessing active cervical RoM is straightforward during clinical examinations (Williams et al., 2010), a more comprehensive understanding of kinematic movements in non-specific neck pain patients seems to be provided by cervical sensorimotor control assessment (de Zoete et al., 2017; Kristjansson and Treleaven, 2009; Bonnechere et al., 2014; R. Hage et al., 2021; Sarig Bahat, Weiss and Laufer, 2010b; Treleaven, 2017). Various tests, such as the "head repositioning test" (Chen and Treleaven, 2013), the "Virtual Reality Test" (Sarig Bahat, Weiss and Laufer, 2010a; Sarig-Bahat et al., 2010), and "The Fly" (Kristjansson et al., 2004), use a gold-standard tri-dimensional tracking system for this purpose.

In line with these developments, we have created the DidRen laser test, a valid and reliable test focusing on the cervical sensory and motor control systems and their connections to the proprioceptive, visual, and vestibular systems (R. Hage and Ancenay, 2009; R. Hage et al., 2021; R. Hage et al., 2019a,b; Kristjansson and Treleaven, 2009). This test specifically assesses axial head rotation, a common neck movement (Bible et al., 2010), by measuring performance time in a standardized

* Corresponding author. Centre de Recherche et de Formation de la HELHa (CeREF), Chaussée de Binche 159, 7000 Mons, Belgium.
E-mail address: renaudhage@gmail.com (R. Hage).

https://doi.org/10.1016/j.jbmt.2024.03.004
Received 17 February 2023; Received in revised form 28 February 2024; Accepted 3 March 2024
Available online 7 March 2024
1360-8592/

environment. Our test demonstrated that the sensorimotor performance is influenced by a speed-accuracy trade-off (Heitz, 2014; Liu and Watanabe, 2012), where faster completion times may lead to reduced accuracy (R. Hage et al., 2019b).

An enhanced version of the DidRen laser test incorporating an inertial motion unit (DYSKIMOT sensor) was recently developed (R. Hage et al., 2020), facilitating the computation of various kinematic parameters beyond total time directly in a clinical setting. As highlighted by Franov et al. (2022), this instrumented test significantly detected changes in kinematic parameters (R. Hage et al., 2021) in patients with ANSP patients compared to healthy control participants (HCP). However, our previous studies (R. Hage and Ancenay, 2009; R. Hage et al., 2021) did not explore which kinematic parameters were most discriminative. Investigating these significant kinematic parameters in ANSP patients is crucial for advancing clinical research.

Although several studies have examined the predictive value of kinematic parameters in ANSP patients (Roijezon et al., 2010; Sarig Bahat, Chen, Reznik, Kodesh and Treleaven, 2015; Treleaven et al., 2016), few have explored their relationship with patient-reported outcome measures (PROMs). These studies primarily emphasized the diagnostic value of cervical movement velocity in tri-dimensional head tracking tasks, showing a sensitivity of 76–85% and specificity of 78–100% (Roijezon et al., 2010; Sarig Bahat et al., 2015). Moreover, Bahat et al. established significant correlations between certain kinematic parameters and PROMs including pain intensity, disability of cervical function, and fear of motion (Sarig Bahat, Weiss, Sprecher, Krasovsky and Laufer, 2014).

This study aims to investigate the relationships between altered kinematic parameters, as assessed by the DidRen laser test, and PROMs. Using a multivariate logistic regression (LR) model, we sought to identify the best predictors for discriminating ANSP patients from HCP. We hypothesized that the DidRen laser test would reveal different relationships between kinematic parameters and PROMs compared to previous studies, considering its unique head-aiming pointing task (Franov et al., 2022) executed in the real-word instead of, in previous studies, an unconstrained task (Roijezon et al., 2010) or head-aiming pointing task in virtual reality (Sarig Bahat et al., 2014, 2015; Treleaven et al., 2016); and its focus on patients in the acute-subacute phase of their condition (Sarig Bahat et al., 2014; Treleaven et al., 2016).

2. Material and methods

2.1. Participants

This retrospective cross-sectional study included 80 adult participants, drawn from a registered clinical trial (R. Hage et al., 2021). HCP were recruited through a convenience sampling method, involving colleagues at Saint-Luc University Hospital (Brussels, Belgium) and acquaintances of the researchers who volunteered for the study. ANSP patients were recruited from a consecutive sample of patients diagnosed by general practitioners.

Inclusion criteria for ANSP patients were: acute-subacute non-specific neck pain lasting less than three months, a Neck Disability Index (NDI) greater than 8% (Vernon, 2008) and a Numeric Pain Rating Scale (NPRS) score exceeding 3/10 (Boonstra et al., 2016; Cleland et al., 2008a; Meisingset et al., 2016; Meisingset et al., 2015; Salaffi et al., 2004). ANSP patients were excluded if they had a history of neck surgery, experienced dizziness induced by neck or head movements (De Hertogh, Vaes, Vijverman, De Cordt and Duquet, 2007), or were diagnosed with cervical radiculopathy by a physician.

HCP inclusion criteria were an absence of neck symptoms, as indicated by an NDI score lower than 4% (Kato et al., 2012). HCPs were excluded if they reported dizziness or pain during active head rotation or during manual spinal assessment.

All participants signed an informed consent form prior to participation. The study received approval from the "Comité Académique de Bioéthique" (" https://www.a-e-c.eu", reference number B200-2018-103) and was conducted in line with the principles of the Declaration of Helsinki. The study was registered under the clinical trial number NCT02355301.

2.2. Protocol

The validity of the protocol for this study is outlined in our previous research (R. Hage et al., 2021). Both ANSP patients and HCP underwent a series of assessments, beginning with questionnaire completion, followed by the DidRen laser test (R. Hage et al., 2019a,b) for rapid axial head rotations, and concluding with a manual examination of the spine.

Specifically, the spinal manual examination comprised passive physiological intervertebral movements (PPIVMs) and passive accessory intervertebral movements (PAIVMs) (Grant and Niere, 2000; Maitland, 2013; Schneider et al., 2013). The primary objective of these tests was to elicit the patient's familiar pain. During the tests, participants were asked to report any pain provocation equal to or greater than 3 on the NPRS (1–10) (Schneider et al., 2014; Williamson and Hoggart, 2005) when the examiner detected resistance, subjectively categorized as mild, moderate, or marked (Uthaikhup et al., 2009). For HCP, passive manual examination, with its high sensitivity (92%), was employed to exclude participants who reported pain in any cervical spine level, thus confirming their status as "healthy" regarding the neck (Schneider et al., 2014). For ANSP patients, this examination was utilized to confirm the presence of familiar pain.

ANSP patients were asked to complete the French versions of the following PROMs: NDI (Wlodyka-Demaille et al., 2002), Bournemouth Questionnaire (BQ) (Martel et al., 2009), Tampa scale of Kinesiophobia (TSK) (Chaory et al., 2004), and NPRS. HCP completed NDI, BQ, and NPRS. The NDI has shown good to excellent clinometric properties in patients with neck pain (Vernon, 2008; Vernon and Mior, 1991; Wlodyka-Demaille et al., 2002). It is a self-rated questionnaire assessing disability due to neck pain, consisting of a series of 10 questions about activities of daily living, all scored on a 6-point scale. Each item is scored at 5 points, resulting in a maximum total score of 50 or a percentage of 100. The NDI score (in %) is interpreted as follows: 0–8 = none; 10–28 = mild; 30–48 = moderate; 50–68 = severe; more than 68 = complete (Vernon and Mior, 1991). The BQ evaluates several dimensions of neck including pain, disability, affective and cognitive aspects. It has shown good to excellent clinometric properties in patients with neck pain (Martel et al., 2009). Each question (7 items) is scored on an eleven-point (0–10) numeric rating scale. The maximum score for the BQ is 70 points and is the sum of the scores for each of the seven items. The TSK, which has demonstrated moderate clinometric properties in patients with neck pain (Cleland et al., 2008b), is a 17-item questionnaire assessing fear of movement or reinjury, in which participants are asked to rate their level of agreement with each item on a scale of 1 (strongly disagree) to 4 (strongly agree). A cut-off score of 39 is associated with risk for prolonged pain-related disability. The NPRS, which has shown excellent clinometric properties with neck pain patients (Bolton et al., 2010; Young et al., 2019), is commonly used to assess patients with neck pain. It uses an 11-point scale ranging from 0 (no pain) to 10 (worst pain imaginable) (Cleland et al., 2008a).

All participants then performed the DidRen laser test. This involved wearing a helmet with an attached laser, directing the laser beam onto three targets equipped with light-sensitive sensors The test requires standardized point-to-point horizontal rotational head motion around the vertical axis. Participants were instructed to rotate their head as fast as possible to align the laser beam with the three targets, positioned horizontally on a wooden board at 90 cm in front of the participants and 52 cm apart from the central target, to induce a 30° head rotation (R. Hage et al., 2021) (see Fig. 1A). The test consisted of 5 consecutive head rotations (cycles) to the left and right (see Fig. 1B) for an example of one complete cycle of head rotation.

Axial head rotation data were captured with a custom-made validated inertial motion unit, the DYSKIMOT sensor (R. Hage et al., 2021),

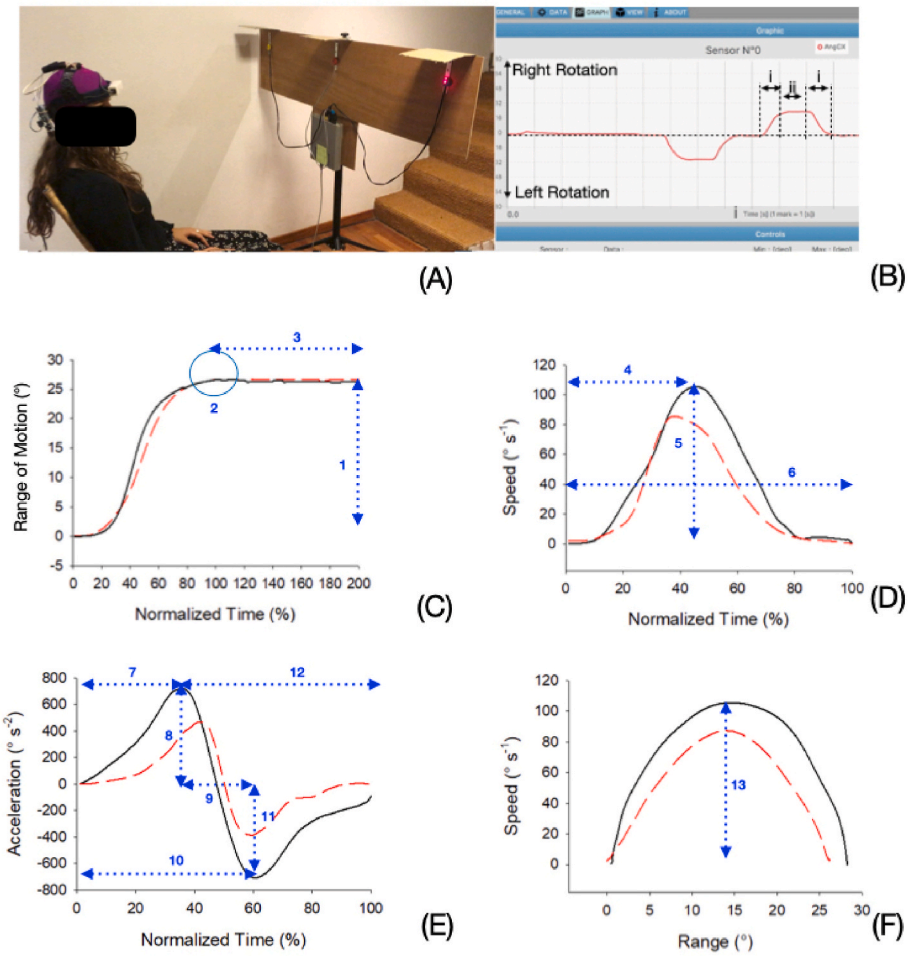

Fig. 1. Description of the DidRen laser test setup and the kinematic parameters analyzed during one head rotation to the right side. (A) Displays the DidRen laser setup, including the 3 light-sensitive sensors positioned in front of a participant and the adjustable helmet fitted on the participant's head. (B) Presents an example of data acquisition during the test. It shows a complete rotation cycle to the left and right (solid line) showing the fast dynamic/motor (i) and stabilization/sensorimotor phases (ii) with vertical dash lines. The head left and right rotations toward the target can be divided into one fast rotation phase when turning the head, called the dynamic phase which corresponds to a motor control phase (i) and another phase when stabilizing and adjusting the laser accurately during at least 0.5 s in the target, called the stabilization phase (ii) which corresponds to a sensorimotor control phase. These two phases were previously described in (Hage et al., 2019a). The kinematic analysis was performed during the head rotations (continuous up or down line) and the total time of the DidRen laser test was recorded during the whole test (5 cycles of right and left rotations). (C), (D), (E), (F) Show typical plots and parameters analyzed from the average of 5 head rotations to the right side of a DidRen laser test in a patient with ANSP (42 years, male, NDI = 20, NPRS = 4, red) and a HCP (52 years, male, NDI = 2, NPRS = 0, black). The kinematic parameters indicated by blue dotted arrows, were (1) range of motion during the test (RoM test, °); (2) overshoot (°s^{-1}) (it assesses the accuracy, and was computed as the difference between peak rotation amplitude and stabilized mean rotation amplitude); (3) stabilization time (s) (it was computed as the time elapsed between the end of one rotational movement and the start of the following one); (4) time to peak speed (s); (5) peak speed (°s^{-1}); (6) average speed (°s^{-1}); (7) time to peak acceleration (s); (8) peak acceleration (° s^{-2}); (9) time between peaks of acceleration and deceleration (s); (10) time to peak deceleration (s); (11) peak deceleration (°s^{-2}); (12) time from peak acceleration to end of rotation (s); and (13) angle at peak speed (°). These kinematic variables were previously described in (Hage et al., 2019a,b; Hage et al., 2021). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

attached to the front of the helmet. This sensor recorded head angular velocity at a sampling frequency of 100 Hz. Data collection occurred in the office of a manual physiotherapist (RH) to ensure a familiar environment for ANSP patients.

2.3. Kinematic variables

A total of 14 kinematic parameters, as detailed in our previous studies (R. Hage et al., 2019a,b; R. Hage et al., 2021), were calculated and are presented in Table 2. The total duration of the DidRen laser test (DidRen time, in s), encompassing both the "i + ii phases" (see Fig. 1 (B)), was derived from the DidRen laser software (R. Hage and Ancenay, 2009). The remaining 13 kinematic parameters were provided by the DYSKIMOT software (v.2) (R. Hage et al., 2020) and are detailed in Fig. 1C–F. All variables were calculated based on the average of 5 consecutives DidRen laser test cycles. Except for stabilization time and time from peak acceleration to end of rotation, the kinematic parameters were calculated during the "i phase", which is the head rotation phase (see Fig. 1(B)).

2.4. Statistical analysis

All statistical procedures were conducted using Sigma Plot software (version 13.0, Systat Software, Inc.). Based on our previous study (R. Hage et al., 2021), the sample size was calculated for average speed and DidRen time, set at 26 and 25 ANSP patients, respectively.

The statistical analysis was conducted in four stages. *Initial comparison:* DidRen laser test parameters exhibiting significant differences ($P < 0.05$) between the HCP and ANSP groups were identified using Student t-tests for normally distributed data or Mann-Whitney tests when normality (Shapiro-Wilk test) was not observed. *Correlation analysis:* A correlation matrix incorporating all DidRen laser test parameters, general participants' characteristics, and PROMs (excluding TSK) was generated to explore Spearman correlation coefficients (r) among variable pairs for all participants. With the intention of moving above the medium to moderate level (Chiu et al., 2005), a correlation was regarded as significant if $|r| > 0.6$. *Logistic regression models:* All parameters (PROMs and kinematic) that were significantly different between HCP and ANSP patients and not correlated were included in three multivariate LR models. As a reminder, logistic regression (LR) is used to estimate the association of various predictors (independent variables) with a dichotomous outcome (dependent variable), such as the presence or absence of a disease. Rather than the probability (or risk) of a given disease, the results of the LR are presented in terms of ratio between the probability of the outcome occurring and the probability of the outcome not occurring (R. P. Anderson et al., 2003). LR1 utilized only PROMs, LR2 only kinematic parameters, and LR3, combined PROMs from LR1 and kinematic parameters from LR2. Odds ratio (OR), sensitivity and specificity for each variable were computed in all three LR models. Their performances were judged by considering discrimination and calibration. *Discrimination and calibration assessment:* Discrimination was assessed with the Area Under Receiver Operating Characteristic (ROC) curve (AUROC) and calibration with the Hosmer-Lemeshow test (Meurer and Tolles, 2017). Cut-off scores for the PROMs and kinematic parameters were determined by their respective ROC curves. A correlogram was created using R software (version 4.2.1) with the *corrplot* package.

3. Results

Table 1 presents the comparisons between ANSP patients and HCP for general characteristics, PROMs, and DidRen parameters. The results indicate significant differences in all variables between the two groups, except for the males/female's proportion, angle at peak speed, overshoot, and RoM.

Fig. 2 features a correlogram that visually represents the correlations between each pair of variables. Following the elimination of significantly correlated variables, the remaining variables for inclusion in the LR equations (LREs) were identified as: BQ for the PROMs, DidRen time and average speed for the kinematic parameters.

Table 2 showcases the results of three LR models. The best performance of the LR3 model, which includes the BQ, DT, and AS predictors, was closely followed by that of the LR1 model (BQ only) and the LR2 model (DT and AS). However, for the LR3 model we can observe that only the p-value of BQ is significant, meaning that the two added kinematic variables have, as predictor, no significative influence. So, within our sample, LR3 has no significant added value with respect to LR1.

This was closely followed by the LR1 model (BQ only) and the LR2 model (DT and AS). Specifically, the LR3 model exhibited a Sensitivity of 98%, a Specificity of 95%, and an AUROC of 99%. Additionally, the regression coefficients (β_i) and OR for each variable in the models are presented.

Fig. 3 displays the ROC curve and AUROC results for all three LR models. The discrimination capability of LR1 and LR3 can be judged as excellent, while LR2 is deemed fair (Swets, 1988). The Hosmer-Lemeshow test results indicate no statistical difference in calibration across the three LR models (LR1: 3.509, $P = 0.899$; LR2: 9.281, $P = 0.319$; LR3: 1.993, $P = 0.981$), suggesting that all models were well-calibrated.

4. Discussion

This study aimed to identify the best discriminators among PROMs and kinematic parameters obtained from a sensorimotor test, the DidRen laser test in ANSP patients. This test, focusing on cervical sensory and motor control systems (R. Hage et al., 2019a,b; Kristjansson and Treleaven, 2009), was instrumental in our analysis. We found that the BQ (Martel et al., 2009), which evaluates several dimensions of participants' neck, including pain, disability, affective and cognitive

Table 1
General characteristics, PROMs, and DidRen laser test parameters for both ANSP and HCP groups, along with the *P*-values from the group comparisons. Results are presented as either mean ± SD or median [Q1-Q3], depending on whether a *t*-test or Mann-Whitney test was conducted. The variables in the table are organized in ascending order of *P*-value, from smallest to largest.

Total (n = 80)	ANSP (n = 38)	HCP (n = 42)	*P*-value
General characteristics			
Age (years)	46.2 ± 16.3	24.3 ± 6.8	<0.001*
BMI (kg m^{-2})	23.064 [20.941–25.188]	21.246 [20.330–23.715]	0.014*
Sex n (male/female) (%)	21 (55%)/17 (45%)	27 (64%)/15 (36%)	0.55†
PROMs			
NDI (0–100)	22.0 [15.5–33.0]	0 [0-0]	<0.001*
NPRS (0–10)	6 [4–7]	0 [0-0]	<0.001*
TSK (17–68)	38 [31–42]	Not applicable	Not applicable
BQ (0–70)	28.5 [14.8–46.3]	0 [0–3.25]	<0.001*
DidRen laser test parameters			
Average speed (° s^{-1})	40.34 ± 10.24	47.62 ± 7.96	<0.001*
Time to peak speed (s)	0.12 [0.10–0.16]	0.10 [0.097–0.11]	<0.001*
Time to peak acceleration (s)	0.20 [0.17–0.24]	0.16 [0.14–0.19]	0.001*
TimebetweenAccDecePeaks (s)	0.13 [0.11–0.15]	0.11 [0.088–0.13]	0.004*
Time to peak deceleration (s)	0.58 [0.55–0.81]	0.54 [0.53–0.58]	0.005*
Peak acceleration (° s^{-2})	630.62 [517.58–796.47]	821.70 [611.69–1050.54]	0.005*
Peak speed (° s^{-1})	88.06 [79.70–105.77]	110.48 [87.64–130.79]	0.006*
DidRen Time (s)	53.55 [46.95–61.61]	48.99 [44.92–52.66]	0.006*
Peak Deceleration (° s^{-2})	375.48 [268.93–493.27]	528.97 [372.73–719.49]	0.009*
TimeFroPeakAccToEndRot (s)	0.15 [0.13–0.18]	0.13 [0.12–0.16]	0.018*
StabilizationTime (s)	1.96 ± 0.37	1.82 ± 0.32	0.046*
Angle at peak speed (°)	14.07 [13.19–14.96]	14.37 [13.45–15.58]	0.300
OverShoot (°)	0.66 [0.52–0.84]	0.63 [0.51–0.78]	0.358
RoM test (°)	27.01 [26.30–27.94]	27.21 [26.24–27.92]	0.836

SD= Standard Deviation, Q1 = First Quartile, Q3 = Third Quartile, NDI=Neck Disability Index, BMI = Body Mass Index, NPRS=Numeric Pain Rating Scale. NDI= Neck Disability Index. TSK=Tampa Scale of Kinesiophobia. BQ=Bournemouth questionnaire. †Calculated with Chi2, * Indicates *P*-values with significant difference between ANSP and HCP groups. The DidRen laser test parameters are defined in Fig. 1. TimebetweenAccDecePeaks: Time between acceleration and deceleration peaks; TimeFroPeak AccToEndRot: Time from peak acceleration to end of rotation.

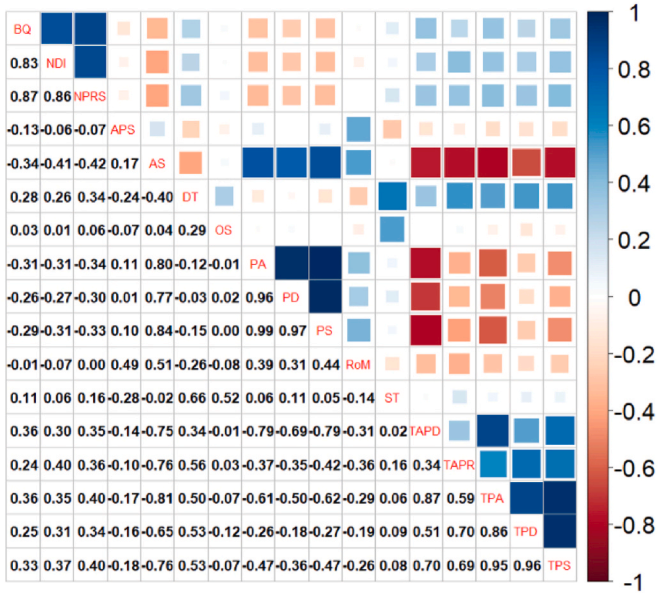

Fig. 2. Mixed correlogram between all DidRen laser test parameters, general characteristics of participants, and PROMs. The lower triangle givens the Spearman coefficient r values. The upper triangle translates them into squares of different sizes and colors. Positive correlations are reported in blue, whereas negative correlations are reported in red. The larger the square, the larger r. The diagonal of the correlogram show all the parameters (abbreviations in red). From top-left to down-right, PROMs are first given, and then DidRen laser test parameters. APS: Angle at peak speed, AS: average speed, BQ: Bournemouth questionnaire, DT: DidRen time, NDI: Neck Disability Index, NPRS: Numeric pain rating scale, OS: Overshoot, PA: Peak acceleration, PD: Peak deceleration, PS: Peak speed, RoM: Range of motion during test, ST: Stabilization time, TADP: Time between acceleration and deceleration peaks, TPAR: Time from peak acceleration to end of rotation, TPA: Time to peak acceleration, TPD: Time to peak deceleration, and TPS: Time to peak speed. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

aspects, emerged as the most effective PROM for identifying ANSP patients. More, the addition of DidRen time and average speed slightly improved its discriminating power, as evidenced in the LR3. The LR3 model proved to be a robust classifier, demonstrating good discrimination and calibration properties without overfitting. It achieved Specificity and Sensibility values above 95%, underscoring its remarkable performance. This multivariate LR model offers a novel way of handling kinematic variables obtained from the sensorimotor test and PROMs, revealing significant relationships, and identifying the most reliable predictors. Even if a study of R. Hage et al. (2022) demonstrated that a linear SVM algorithm is efficient in discriminating ANSP patients from HCP, we showed here that the diagnostic ability of LR can actually be seen as simple yet effective decision-making algorithm, i.e. a decision obtained by comparing the value of one parameter ($\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_m x_m$) to the zero threshold value. Looking ahead, we plan to integrate the LR model into a virtual reality version of the DidRen laser test, aiming to further refine the identification of ANSP patients.

The etiology of ANSP remains complex and multifactorial, making the study of correlations between DidRen parameters and PROMs clinically relevant. Our findings indicate that the correlations between these parameters were not strong ($|r| \leq 0.6$) in our study population. This supports the work of Treleaven et al. (2016), who reported a fair

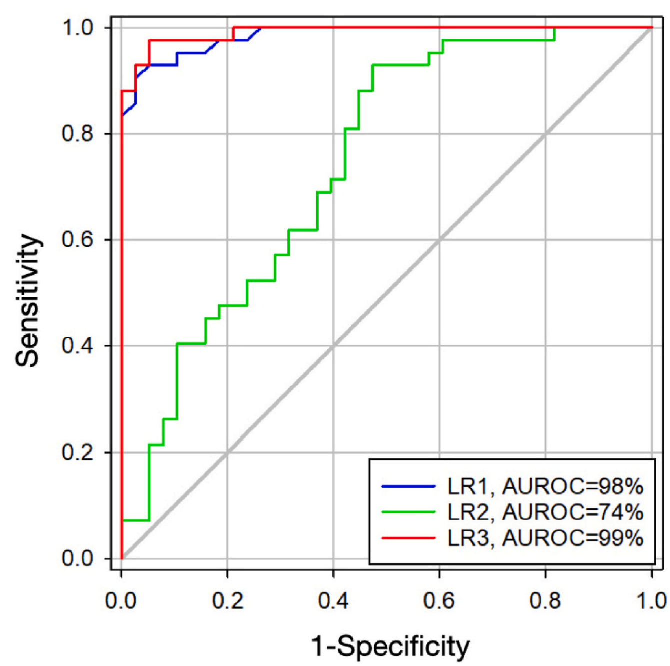

Fig. 3. ROC curves and AUROC values for LR1=BQ, LR2 = DidRen Time/average speed, LR3=BQ/DidRen Time/average speed.

Table 2
Detailed LR results. The coefficients β_i (β_1 to β_3) and their SE are given as well as their Wald statistic, and *P*-values. OR associated to each predictor (independent variable) are listed with their 95% CI. The specificity, sensitivity, and area under ROC curve (AUROC) of each LR equation are also given (LR1 to LR3).

LR (n)	Ind. variable	Coefficient (β_i)	SE	Wald	*P*-value	OR (95% CI)	Se/Sp/AUROC (%)
LR1 (80)	β_0	−4.21	1.09	14.85	<0.001	0.015 (0.002–0.126)	93/95/98
	BQ	0.45	0.12	14.34	<0.001	1.56 (1.24–1.97)	
LR2 (80)	β_0	−0.94	2.48	0.14	0.706	0.39 (0.003–50.62)	93/53/74
	DidRenTime	0.09	0.04	4.99	0.025	1.09 (1.01–1.18)	
	Average speed	−0,08	0.03	6.35	0.012	1091(1,01-1,18)	
LR3 (80)	β_0	−9.04	7.83	1.33	0.248	0,0001 (0–550.21)	98/95/99
	DidRenTime	0.19	0.12	2.44	0.118	1.21 (0.95–1.53)	
	Average speed	−0.13	0.09	2.03	0.154	0.88 (0.74–1.05)	
	BQ	0.48	0.15	10.16	0.001	1.61 (1.20–2.16)	

LR (N): logistic regression (number of data); Ind: independent; SE: standard error; OR: odds ratio; CI: confidence interval; Se: sensitivity; Sp: specificity; Each LR is of the form $logit\ (p) = \log(p/1-p) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_m x_m$, where p is the probability of the dependent variable (dichotomous condition), β_0 is a constant coefficient (intercept), and β_i is each coefficient (slope) for each independent variable x_i As a reminder, odds ratio are used to determine how a variable is a risk factor for a particular outcome, and to compare the importance of various risk factors for that outcome: OR>1 data is associated with a higher probability of outcome. OR<1 data is associated with a lower probability of outcome. BQ: Bournemouth Questionnaire.
The cut-offs are for DidRen Time: 52.6 (s), average speed: 49.72 ($^{\circ}s^{-1}$) and BQ: 8.5.

correlation between neck pain intensity and sensorimotor system kinematic variables during head rotation. Notably, the BQ was the most discriminative PROM, capturing a wide range of neck pain dimensions, including psychological factors that are crucial in the early phase of the condition. Persistent anxiety and depression at baseline might contribute to the transition to chronic pain (Ris et al., 2019; Wirth et al., 2016), but also pain intensity and the disability associated with neck pain. The BQ's effectiveness alone (LR1 model) in discrimination (AUROC >90%) highlights the importance of a multidimensional approach to pain management from the onset of treatment to improve outcomes (Wirth et al., 2016).

In our study, using the DidRen test's time and average speed as standalone measures yielded less effective results compared to those reported by Bahat et al. (Sarig Bahat et al., 2015), who conducted tests in a virtual reality environment with combined movements in all directions for chronic neck pain patients. This contrast highlights the complexity and variability in assessing neck pain and kinematics. Moreover, a systematic review by Luc et al. (Luc et al., 2022) underscores this complexity, indicating a very low certainty of evidence for distinct neck kinematic patterns between healthy individuals and chronic neck pain patients. Interestingly, the AUROC in our study using SVM and only kinematic parameters was 84% (R. Hage et al., 2022), which outperforms the LR2 model's 74%, but still falls short of the 99% achieved with the LR3 model. This finding signifies that incorporating a broader range of predictors, as done in the LR3 model, considerably enhances the discriminative power of the assessment.

Our methodological approach, emphasizing an integrated clinical picture based on clinical reasoning (Edwards et al., 2004), leverages the full spectrum of available predictors. This holistic strategy is reflected in the performance of the BQ and DidRen laser test kinematic parameters, which showed improved efficacy when used in combination. Such an integrative, heterogeneous cluster of tests aligns with the observations by Cook and Hegedus (2011), who suggested that isolated clinical tests offer limited diagnostic value and that future research should focus on clusters of clinical tests for more comprehensive assessments.

A primary limitation of our study is its retrospective design, which inherently restricts the ability to control for certain variables prospectively. However, its originality lies in the search for predictors of neck pain, which was not shown in our previous study which only showed the kinematic parameters that appeared to differ. Additionally, our healthy control group was not fully matched with the patient group in terms of age and BMI. However, our analysis revealed no significant correlation between age, BMI and the kinematic parameters (|r| maximum for age = 0.37; BMI = 0.39). These findings are consistent with our previous studies, which reported no age-related differences in sensorimotor control performances using the DidRen laser in healthy subjects aged 24 to 53 (R. Hage et al., 2019a,b). Therefore, we can be reasonably confident that age-related confounding factors did not significantly influence our results. It should be noted that a significant age difference between control and diseased subjects was previously found in a study to develop and determine the predictive performance of ML models to distinguish different subtypes of low back pain from healthy control subjects (Liew et al., 2020). Like in our study, they did not include age as a predictor in their model (Liew et al., 2020) Due to the cross-sectional design of our study and the focus on specific hypotheses, we consider that age was not a primary factor. The lower correlations observed in our study could be attributed to the variability in DidRen parameters between ANSP and HCP groups, the nature of the head pointing task used (±30° rotations that also does not cause pain), and the relatively small sample size calculated based solely on kinematic data. Additionally, the moderate effect of fear of movement observed in ANSP group (average near the cut-off of ±37 points) (Cleland et al., 2008a) may have also played a role. Also, we relied on a single training dataset to build our LR models. An assessment of independence of test data is now required and crucial to ensure external validity of our models. Furthermore, while regression analysis on kinematic parameters is valuable for understanding relationships within the data, this approach may not fully capture the subjective aspects inherent in self-report assessments. For example, factors such as a person's comfort level, satisfaction, or emotional experience during a task, which can significantly impact self-reported outcomes, are not directly measurable in kinematic data.

Future research should focus on the clinical utility of integrating DidRen temporal and kinematic parameters testing into the screening of ANSP patients. Incorporating these tests as a standard component of physical examinations could significantly aid clinicians in selecting the most effective exercise regimes or passive manual therapy modalities tailored to individual patient needs. The simplicity and affordability of motor control testing, based on a single inertial sensor, open new avenues for research, particularly in investigating the pathoanatomical basis of neck pain. Further studies are encouraged to explore how discriminative temporal kinematic parameters can serve as markers to evaluate the effectiveness of therapeutic interventions (Han et al., 2022). An innovative and practical method to improve therapeutic interventions could involve customizing therapeutic interventions based on specific neck motion impairments. This strategy, which differentiates between neck pain patients and those without pain, can lead to more targeted and effective treatment plans (Hesby et al., 2019; Spitzer, 1987). In clinical practice, this could translate into a "treat-what-you-find" approach, where rehabilitation exercises are tailored to the individual's specific impairments. For instance, using an audible signal from a metronome to guide the speed of exercise execution could provide a simple yet effective way to ensure patients perform rehabilitation exercises at an optimal pace.

In conclusion, the BQ emerged as the best PROM for discriminating ANSP patients, and the addition of two simple kinematic predictors via LR may enhance its effectiveness, though a definitive answer is out of the scope of the present study. We recommend incorporating these kinematic predictors, easily measured in sensorimotor control tests, in future clinical trials involving ANSP patients to enhance the discriminative power of established PROMs. Our LR3 model offers a promising tool for clinicians in diagnosing ANSP, and we aim to further explore its application in guiding and assessing therapeutic interventions.

CRediT authorship contribution statement

Guillaume Hage: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Fabien Buisseret:** Writing – review & editing. **Jean-Michel Brismée:** Writing – review & editing. **Frédéric Dierick:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Christine Detrembleur:** Writing – review & editing, Validation, Software, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Renaud Hage:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

None.

References

Anderson, R.P., Jin, R., Grunkemeier, G.L., 2003. Understanding logistic regression analysis in clinical reports: an introduction. Ann. Thorac. Surg. 75 (3), 753–757. https://doi.org/10.1016/s0003-4975(02)04683-0.

Anderson, S.E., Boesch, C., Zimmermann, H., Busato, A., Hodler, J., Bingisser, R., Sturzenegger, M., 2012. Are there cervical spine findings at MR imaging that are specific to acute symptomatic whiplash injury? A prospective controlled study with four experienced blinded readers. Radiology 262 (2), 567–575. https://doi.org/10.1148/radiol.11102115.

Bible, J.E., Biswas, D., Miller, C.P., Whang, P.G., Grauer, J.N., 2010. Normal functional range of motion of the cervical spine during 15 activities of daily living. J. Spinal Disord. Tech. 23 (1), 15–21. https://doi.org/10.1097/BSD.0b013e3181981632.

Bier, J.D., Scholten-Peeters, W.G.M., Staal, J.B., Pool, J., van Tulder, M.W., Beekman, E., Verhagen, A.P., 2018. Clinical practice guideline for physical therapy assessment and treatment in patients with nonspecific neck pain. Phys. Ther. 98 (3), 162–171. https://doi.org/10.1093/ptj/pzx118.

Blanpied, P.R., Gross, A.R., Elliott, J.M., Devaney, L.L., Clewley, D., Walton, D.M., Robertson, E.K., 2017. Neck pain: revision 2017. J. Orthop. Sports Phys. Ther. 47 (7), A1–a83. https://doi.org/10.2519/jospt.2017.0302.

Bogduk, N., 2011a. The anatomy and pathophysiology of neck pain. Phys. Med. Rehabil. Clin 22 (3), 367–382. https://doi.org/10.1016/j.pmr.2011.03.008 vii.

Bogduk, N., 2011b. On cervical zygapophysial joint pain after whiplash. Spine 36 (25 Suppl. l), S194–S199. https://doi.org/10.1097/BRS.0b013e3182387f1d.

Bolton, J.E., Humphreys, B.K., van Hedel, H.J., 2010. Validity of weekly recall ratings of average pain intensity in neck pain patients. J. Manip. Physiol. Ther. 33 (8), 612–617. https://doi.org/10.1016/j.jmpt.2010.08.009.

Bonnechere, B., Salvia, P., Dugailly, P.M., Maroye, L., Van Geyt, B., Feipel, V., 2014. Influence of movement speed on cervical range of motion. Eur. Spine J. 23 (8), 1688–1693. https://doi.org/10.1007/s00586-014-3249-3.

Boonstra, A.M., Stewart, R.E., Köke, A.J., Oosterwijk, R.F., Swaan, J.L., Schreurs, K.M., Schiphorst Preuper, H.R., 2016. Cut-off points for mild, moderate, and severe pain on the numeric rating scale for pain in patients with chronic musculoskeletal pain: variability and influence of sex and catastrophizing. Front. Psychol. 7, 1466. https://doi.org/10.3389/fpsyg.2016.01466.

Borghouts, J.A.J., Koes, B.W., Bouter, L.M., 1998. The clinical course and prognostic factors of non-specific neck pain: a systematic review. Pain 77 (1), 1–13. https://doi.org/10.1016/s0304-3959(98)00058-x.

Borghouts, J.A.J., Koes, B.W., Vondeling, H., Bouter, L.M., 1999. Cost-of-illness of neck pain in The Netherlands in 1996. Pain 80 (3), 629–636. https://doi.org/10.1016/s0304-3959(98)00268-1.

Chaory, K., Fayad, F., Rannou, F., Lefevre-Colau, M.M., Fermanian, J., Revel, M., Poiraudeau, S., 2004. Validation of the French version of the fear avoidance belief questionnaire. Spine 29 (8), 908–913. https://doi.org/10.1097/00007632-200404150-00018.

Chen, X., Treleaven, J., 2013. The effect of neck torsion on joint position error in subjects with chronic neck pain. Man. Ther. 18 (6), 562–567. https://doi.org/10.1016/j.math.2013.05.015.

Childs, J.D., Cleland, J.A., Elliott, J.M., Teyhen, D.S., Wainner, R.S., Whitman, J.M., Flynn, T.W., 2008. Neck pain: clinical practice guidelines linked to the international classification of functioning, disability, and health from the orthopedic section of the American physical therapy association. J. Orthop. Sports Phys. Ther. 38 (9), A1–a34. https://doi.org/10.2519/jospt.2008.0303.

Chiu, T.T., Lam, T.H., Hedley, A.J., 2005. Correlation among physical impairments, pain, disability, and patient satisfaction in patients with chronic neck pain. Arch. Phys. Med. Rehabil. 86 (3), 534–540. https://doi.org/10.1016/j.apmr.2004.02.030.

Cleland, J.A., Childs, J.D., Whitman, J.M., 2008a. Psychometric properties of the neck disability index and numeric pain rating scale in patients with mechanical neck pain. Arch. Phys. Med. Rehabil. 89 (1), 69–74. https://doi.org/10.1016/j.apmr.2007.08.126.

Cleland, J.A., Fritz, J.M., Childs, J.D., 2008b. Psychometric properties of the fear-avoidance beliefs questionnaire and Tampa scale of kinesiophobia in patients with neck pain. Am. J. Phys. Med. Rehabil. 87 (2), 109–117. https://doi.org/10.1097/PHM.0b013e31815b61f1.

Cohen, S.P., Hooten, W.M., 2017. Advances in the diagnosis and management of neck pain. BMJ 358, j3221. https://doi.org/10.1136/bmj.j3221.

Cook, C., Hegedus, E., 2011. Diagnostic utility of clinical tests for spinal dysfunction. Man. Ther. 16 (1), 21–25. https://doi.org/10.1016/j.math.2010.07.004.

Coulter, I.D., Crawford, C., Vernon, H., Hurwitz, E.L., Khorsan, R., Booth, M.S., Herman, P.M., 2019. Manipulation and mobilization for treating chronic nonspecific neck pain: a systematic review and meta-analysis for an appropriateness panel. Pain Physician 22 (2), E55–e70.

De Hertogh, W.J., Vaes, P.H., Vijverman, V., De Cordt, A., Duquet, W., 2007. The clinical examination of neck pain patients: the validity of a group of tests. Man. Ther. 12 (1), 50–55.

de Zoete, R.M.J., Osmotherly, P.G., Rivett, D.A., Farrell, S.F., Snodgrass, S.J., 2017. Sensorimotor control in individuals with idiopathic neck pain and healthy individuals: a systematic review and meta-analysis. Arch. Phys. Med. Rehabil. 98 (6), 1257–1271. https://doi.org/10.1016/j.apmr.2016.09.121.

Edwards, I., Jones, M., Carr, J., Braunack-Mayer, A., Jensen, G.M., 2004. Clinical reasoning strategies in physical therapy. Phys. Ther. 84 (4), 312–330.

Fejer, R., Kyvik, K.O., Hartvigsen, J., 2006. The prevalence of neck pain in the world population: a systematic critical review of the literature. Eur. Spine J. 15 (6), 834–848. https://doi.org/10.1007/s00586-004-0864-4.

Ferrari, R., Russell, A.S., 2003. Regional musculoskeletal conditions: neck pain. Best Pract. Res. Clin. Rheumatol. 17 (1), 57–70. https://doi.org/10.1016/s1521-6942(02)00097-9.

Franov, E., Straub, M., Bauer, C.M., Ernst, M.J., 2022. Head kinematics in patients with neck pain compared to asymptomatic controls: a systematic review. BMC Muscoskel. Disord. 23 (1), 156. https://doi.org/10.1186/s12891-022-05097-z.

Gore, D.R., Sepic, S.B., Gardner, G.M., Murray, M.P., 1987. Neck pain: a long-term follow-up of 205 patients. Spine 12 (1), 1–5. https://doi.org/10.1097/00007632-198701000-00001.

Grant, T., Niere, K., 2000. Techniques used by manipulative physiotherapists in the management of headaches. Aust. J. Physiother. 46 (3), 215–222. https://doi.org/10.1016/s0004-9514(14)60330-5.

Hage, R., Ancenay, E., 2009. Identification of a relationship between cervical spine function and rotational movement control. Ann Phys Rehabil Med 52 (9), 653–667. https://doi.org/10.1016/j.rehab.2009.04.003.

Hage, R., Buisseret, F., Houry, M., Dierick, F., 2022. Head pitch angular velocity discriminates (Sub-)Acute neck pain patients and controls assessed with the DidRen laser test. Sensors 22 (7). https://doi.org/10.3390/s22072805.

Hage, R., Buisseret, F., Pitance, L., Brismee, J.M., Detrembleur, C., Dierick, F., 2019a. Head-neck rotational movements using DidRen laser test indicate children and seniors' lower performance. PLoS One 14 (7), e0219515. https://doi.org/10.1371/journal.pone.0219515.

Hage, R., Detrembleur, C., Dierick, F., Brismée, J.M., Roussel, N., Pitance, L., 2021. Sensorimotor performance in acute-subacute non-specific neck pain: a non-randomized prospective clinical trial with intervention. BMC Muscoskel. Disord. 22 (1), 1017. https://doi.org/10.1186/s12891-021-04876-4.

Hage, R., Detrembleur, C., Dierick, F., Pitance, L., Jojczyk, L., Estievenart, W., Buisseret, F., 2020. DYSKIMOT: an ultra-low-cost inertial sensor to assess head's rotational kinematics in adults during the didren-laser test. Sensors 20 (3). https://doi.org/10.3390/s20030833.

Hage, R., Dierick, F., Roussel, N., Pitance, L., Detrembleur, C., 2019b. Age-related kinematic performance should be considered during fast head-neck rotation target task in individuals aged from 8 to 85 years old. PeerJ 7. https://doi.org/10.7717/peerj.7095.

Han, C.S., Hancock, P.M., Maher, P.C., 2022. Reconsidering non-specific low back pain: where to from here? Spine J. https://doi.org/10.1016/j.spinee.2022.08.001.

Heitz, R.P., 2014. The speed-accuracy tradeoff: history, physiology, methodology, and behavior. Front. Neurosci. 8, 150. https://doi.org/10.3389/fnins.2014.00150.

Hesby, B.B., Hartvigsen, J., Rasmussen, H., Kjaer, P., 2019. Electronic measures of movement impairment, repositioning, and posture in people with and without neck pain-a systematic review. Syst. Rev. 8 (1), 220. https://doi.org/10.1186/s13643-019-1125-2.

Hoy, D.G., Protani, M., De, R., Buchbinder, R., 2010. The epidemiology of neck pain. Best Pract. Res. Clin. Rheumatol. 24 (6), 783–792. https://doi.org/10.1016/j.berh.2011.01.019.

Kato, S., Takeshita, K., Matsudaira, K., Tonosu, J., Hara, N., Chikuda, H., 2012. Normative score and cut-off value of the neck disability index. J. Orthop. Sci. 17 (6), 687–693. https://doi.org/10.1007/s00776-012-0276-y.

Kristjansson, E., Hardardottir, L., Asmundardottir, M., Gudmundsson, K., 2004. A new clinical test for cervicocephalic kinesthetic sensibility: "the fly". Arch. Phys. Med. Rehabil. 85 (3), 490–495.

Kristjansson, E., Treleaven, J., 2009. Sensorimotor function and dizziness in neck pain: implications for assessment and management. J. Orthop. Sports Phys. Ther. 39 (5), 364–377. https://doi.org/10.2519/jospt.2009.2834.

Liew, B.X.W., Rugamer, D., De Nunzio, A.M., Falla, D., 2020. Interpretable machine learning models for classifying low back pain status using functional physiological variables. Eur. Spine J. 29 (8), 1845–1859. https://doi.org/10.1007/s00586-020-06356-0.

Liu, C.C., Watanabe, T., 2012. Accounting for speed-accuracy tradeoff in perceptual learning. Vis. Res. 61, 107–114. https://doi.org/10.1016/j.visres.2011.09.007.

Luc, A., Tamer, S., Hage, R., Detrembleur, C., Pitance, L., 2022. 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. Phys. Ther. Rev. 27 (6), 430–443. https://doi.org/10.1080/10833196.2022.2143211.

Maitland, G.D., 2013. Vertebral Manipulation. Butterworth-Heinemann.

Martel, J., Dugas, C., Lafond, D., Descarreaux, M., 2009. Validation of the French version of the Bournemouth questionnaire. J. Can. Chiropr. Assoc. 53 (2), 102–120.

Meisingset, I., Stensdotter, A.K., Woodhouse, A., Vasseljen, O., 2016. Neck motion, motor control, pain and disability: a longitudinal study of associations in neck pain patients in physiotherapy treatment. Man. Ther. 22, 94–100. https://doi.org/10.1016/j.math.2015.10.013.

Meisingset, I., Woodhouse, A., Stensdotter, A.K., Stavdahl, O., Loras, H., Gismervik, S., Vasseljen, O., 2015. Evidence for a general stiffening motor control pattern in neck pain: a cross sectional study. BMC Muscoskel. Disord. 16, 56. https://doi.org/10.1186/s12891-015-0517-2.

Meurer, W.J., Tolles, J., 2017. Logistic regression diagnostics: understanding how well a model predicts outcomes. JAMA 317 (10), 1068–1069. https://doi.org/10.1001/jama.2016.20441.

Pool, J.J., Ostelo, R.W., Knol, D., Bouter, L.M., de Vet, H.C., 2010. Are psychological factors prognostic indicators of outcome in patients with sub-acute neck pain? Man. Ther. 15 (1), 111–116. https://doi.org/10.1016/j.math.2009.08.001.

Ris, I., Barbero, M., Falla, D., Larsen, M.H., Kraft, M.N., Søgaard, K., Juul-Kristensen, B., 2019. Pain extent is more strongly associated with disability, psychological factors, and neck muscle function in people with non-traumatic versus traumatic chronic neck pain: a cross sectional study. Eur. J. Phys. Rehabil. Med. 55 (1), 71–78. https://doi.org/10.23736/s1973-9087.18.04977-8.

Roijezon, U., Djupsjobacka, M., Bjorklund, M., Hager-Ross, C., Grip, H., Liebermann, D. G., 2010. Kinematics of fast cervical rotations in persons with chronic neck pain: a cross-sectional and reliability study. BMC Muscoskel. Disord. 11, 222. https://doi.org/10.1186/1471-2474-11-222.

Salaffi, F., Stancati, A., Silvestri, C.A., Ciapetti, A., Grassi, W., 2004. Minimal clinically important changes in chronic musculoskeletal pain intensity measured on a numerical rating scale. Eur. J. Pain 8 (4), 283–291. https://doi.org/10.1016/j.ejpain.2003.09.004.

Sarig Bahat, H., Chen, X., Reznik, D., Kodesh, E., Treleaven, J., 2015. Interactive cervical motion kinematics: sensitivity, specificity and clinically significant values for identifying kinematic impairments in patients with chronic neck pain. Man. Ther. 20 (2), 295–302. https://doi.org/10.1016/j.math.2014.10.002.

Sarig Bahat, H., Sprecher, E., Sela, I., Treleaven, J., 2016. Neck motion kinematics: an inter-tester reliability study using an interactive neck VR assessment in asymptomatic individuals. Eur. Spine J. 25 (7), 2139–2148. https://doi.org/10.1007/s00586-016-4388-5.

Sarig Bahat, H., Weiss, P.L., Laufer, Y., 2010a. The effect of neck pain on cervical kinematics, as assessed in a virtual environment. Arch. Phys. Med. Rehabil. 91 (12), 1884–1890. https://doi.org/10.1016/j.apmr.2010.09.007.

Sarig Bahat, H., Weiss, P.L., Laufer, Y., 2010b. Neck pain assessment in a virtual environment. Spine 35 (4), E105–E112. https://doi.org/10.1097/BRS.0b013e3181b79358.

Sarig Bahat, H., Weiss, P.L., Sprecher, E., Krasovsky, A., Laufer, Y., 2014. Do neck kinematics correlate with pain intensity, neck disability or with fear of motion? Man. Ther. 19 (3), 252–258. https://doi.org/10.1016/j.math.2013.10.006.

Sarig-Bahat, H., Weiss, P.L., Laufer, Y., 2010. Neck pain assessment in a virtual environment. Spine 35 (4), E105–E112. https://doi.org/10.1097/BRS.0b013e3181b79358.

Schneider, G.M., Jull, G., Thomas, K., Smith, A., Emery, C., Faris, P., Salo, P., 2014. Derivation of a clinical decision guide in the diagnosis of cervical facet joint pain. Arch. Phys. Med. Rehabil. 95 (9), 1695–1701. https://doi.org/10.1016/j.apmr.2014.02.026.

Schneider, G.M., Jull, G., Thomas, K., Smith, A., Emery, C., Faris, P., Salo, P., 2013. Intrarater and interrater reliability of select clinical tests in patients referred for diagnostic facet joint blocks in the cervical spine. Arch. Phys. Med. Rehabil. 94 (8), 1628–1634. https://doi.org/10.1016/j.apmr.2013.02.015.

Sjolander, P., Michaelson, P., Jaric, S., Djupsjobacka, M., 2008. Sensorimotor disturbances in chronic neck pain–range of motion, peak velocity, smoothness of movement, and repositioning acuity. Man. Ther. 13 (2), 122–131. https://doi.org/10.1016/j.math.2006.10.002.

Spitzer, W.L.R.D.M., 1987. Scientific approach to the assessment and management of activity-related spinal disorders. A monograph for clinicians. Report of the Quebec Task Force on Spinal Disorders. Spine 12 (7 Suppl. l), S1–S59.

Swets, J.A., 1988. Measuring the accuracy of diagnostic systems. Science 240 (4857), 1285–1293. https://doi.org/10.1126/science.3287615.

Treleaven, J., 2017. Dizziness, unsteadiness, visual disturbances, and sensorimotor control in traumatic neck pain. J. Orthop. Sports Phys. Ther. 47 (7), 492–502. https://doi.org/10.2519/jospt.2017.7052.

Treleaven, J., Chen, X., Sarig Bahat, H., 2016. Factors associated with cervical kinematic impairments in patients with neck pain. Man. Ther. 22, 109–115. https://doi.org/10.1016/j.math.2015.10.015.

Uthaikhup, S., Sterling, M., Jull, G., 2009. Cervical musculoskeletal impairment is common in elders with headache. Man. Ther. 14 (6), 636–641. https://doi.org/10.1016/j.math.2008.12.008.

Vernon, H., 2008. The neck disability index: state-of-the-art, 1991-2008. J. Manip. Physiol. Ther. 31 (7), 491–502. https://doi.org/10.1016/j.jmpt.2008.08.006.

Vernon, H., Mior, S., 1991. The Neck Disability Index: a study of reliability and validity. J. Manip. Physiol. Ther. 14 (7), 409–415.

Williams, M.A., McCarthy, C.J., Chorti, A., Cooke, M.W., Gates, S., 2010. A systematic review of reliability and validity studies of methods for measuring active and passive cervical range of motion. J. Manip. Physiol. Ther. 33 (2), 138–155. https://doi.org/10.1016/j.jmpt.2009.12.009.

Williamson, A., Hoggart, B., 2005. Pain: a review of three commonly used pain rating scales. J. Clin. Nurs. 14 (7), 798–804. https://doi.org/10.1111/j.1365-2702.2005.01121.x.

Wirth, B., Humphreys, B.K., Peterson, C., 2016. Importance of psychological factors for the recovery from a first episode of acute non-specific neck pain - a longitudinal observational study. Chiropr. Man. Ther. 24, 9. https://doi.org/10.1186/s12998-016-0090-2.

Wlodyka-Demaille, S., Poiraudeau, S., Catanzariti, J.F., Rannou, F., Fermanian, J., Revel, M., 2002. French translation and validation of 3 functional disability scales for neck pain. Arch. Phys. Med. Rehabil. 83 (3), 376–382. https://doi.org/10.1053/apmr.2002.30623.

Young Ia Pt, D., Dunning, J Pt, D, P.T., Butts R Pt, P., Mourad, F Pt, D, P.T., Cleland Ja Pt, P., 2019. Reliability, construct validity, and responsiveness of the neck disability index and numeric pain rating scale in patients with mechanical neck pain without upper extremity symptoms. Physiother. Theory Pract. 35 (12), 1328–1335. https://doi.org/10.1080/09593985.2018.1471763.