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ORIGINAL ARTICLE

Network analyses reveal the interaction between physical features, fear of movement and neck pain and disability in people with acute and chronic whiplash-associated disorders

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Abstract

Background and Objective: A network analysis can be used to quantitatively assess and graphically describe multiple interactions. This study applied network analyses to determine the interaction between physical and pain-related factors and fear of movement in people with whiplash-associated disorders (WAD) during periods of acute and chronic pain.

Methods: Physical measurements, including pressure pain-thresholds (PPT) over neural structures, cervical range of motion, neck flexor and extensor endurance and the cranio-cervical flexion test (CCFT), in addition to subjective reports including the Tampa Scale of Kinesiophobia (TSK-11), Neck Disability Index (NDI) and neck pain and headache intensity, were assessed at baseline in 47 participants with acute WAD. TSK-11, NDI and pain intensity were assessed for the same participants 6 months later ($n=45$). Two network analyses were conducted to estimate the associations between features at baseline and at 6 months and their centrality indices.

Results: Both network analyses revealed that the greatest weight indices were found for NDI and CCFT at baseline and for neck pain and headache intensity and NDI and TSK-11 at both time points. Associations were also found betweeen cervical muscle endurance and neck pain intensity in the acute phase. Cervical muscle endurance assesssed during the acute phase was also associated with NDI after 6 months - whereas PPT measured at baseline was associsated with headache intensity after 6 months.

Conclusion: The strongest associations were found for headache and neck pain intensity and neck disability and fear of movement, both during acute pain and when mesured 6 months later. The extent of neck endurance and measures of PPT at baseline may be associated with neck disability and headache, respectively, 6 months after a whiplash injury.

Significance: Through two network analyses, we evaluated the interaction between pain-related factors, fear of movement, neck disability and physical factors in people who had experienced a whiplash injury. We demonstrated that physical factors may be involved in the maintenance and development of chronic pain after a whiplash injury. Nevertheless, the strongest associations were found for headache and neck pain intensity and neck disability and fear of movement, both during acute and chronic phases.

1 | INTRODUCTION

Whiplash injuries are a global health problem and a significant financial burden for both health care and insurance systems (Connelly & Supangan, 2006; Godek, 2020); they are the most common non-hospitalized injury following a motor vehicle accident (Spitzer et al., 1995). Recovery after a whiplash injury is highly variable, with studies reporting between 19% and 60% of patients still suffering complaints 6 months after a whiplash injury (Scholten-Peeters et al., 2003; Stovner, 1996), and up to 50% of people with ongoing symptoms 1 year after the accident (Andersen et al., 2016; Sterling et al., 2010).

Several physical changes have been identified in patients with acute whiplash-associated disorders (WAD), such as altered neuromuscular control and changes in both the quantity and quality of neck movement (Alalawi et al., 2022; Baydal-Bertomeu et al., 2011; Falla et al., 2004; Jull et al., 2004; Sterling, Jull, Vicenzino, Kenardy, & Darnell, 2003; Woodhouse & Vasseljen, 2008). In addition, sensitization and hyperalgesia measured via lower pressure-pain thresholds (PPT) over local and remote sites have commonly been documented in people with acute WAD (Sterling, Jull, Vicenzino, & Kenardy, 2003; van Oosterwijck et al., 2013). Psychological factors such as pain catastrophizing and fear of movement are also commonly present (Carroll et al., 2008; Luque-Suarez et al., 2020; Sullivan et al., 2002; Vangronsveld et al., 2008). Given the wide range of signs and symptoms present in people with acute WAD and the numerous factors associated with poor recovery, several studies have attempted to understand the interactions between different factors, such as the association between different psychological factors (Anarte-Lazo et al., 2022) or between physical and psychological factors in the acute stage (Alalawi et al., 2022). Some of these factors, such as high neck pain intensity and headache or more severe initial disability (Côté et al., 2001; Nieto et al., 2013; Sterling et al., 2006), have been associated with ongoing pain and disability after a whiplash injury. In contrast, there is little evidence available investigating the role of neck physical function on prognosis following a whiplash injury, and currently there is inconclusive evidence on whether measures such as neck range of motion or neck muscle strength are predictive of outcome (Alalawi et al., 2021).

The association between single features, typically achieved by assessing simple correlations, may not capture the complexity of spinal pain, including WAD (Falla & Hodges, 2017; Ludvigsson et al., 2016). In contrast, a network analysis is an approach that can be applied to examine the interaction between multiple factors, including psychological features, measures of physical function and patient-reported outcome measures (PROMs), since it can be used to quantitatively assess and graphically describe multiple interactions (Devecchi et al., 2022). Indeed, the analysis of the interaction between physical and psychological factors has a stronger association with pain intensity and disability than the presence of either factor alone in people with neck pain (Johnston et al., 2010). Moreover, it was shown that disability was primarily driven by pain measures and fear-avoidance beliefs rather than by physical factors, which may suggest that the association between physical impairments and disability was influenced by other factors (Cai et al., 2007). Unravelling the interactions between physical and psychological features, disability and pain, which can be revealed via a network analysis, will further reveal the multidimensional nature of WAD and may provide insights into potential treatment strategies to optimize outcomes for people with WAD. No previous studies have assessed multiple interactions between physical impairments, such as range of motion, neck muscular function or sensitization and PROMs related to neck disability or pain-related factors in patients with WAD. Thus, a network analysis has the potential to identify and quantify interactions between various signs and symptoms in people with WAD, better exposing the potential complexity of these interactions. This type of analysis has been implemented to investigate other patient populations, such as those with tension-type headaches or other chronic pain conditions, providing evidence on the interaction between different variables and highlighting potential future targets for pain management (Devecchi et al., 2022; Fernández-de-Las-Peñas et al., 2022; Pedrero-Martin et al., 2021). However, there is an evident gap in the literature in relation to the use of this analysis in people with WAD.

This study aimed to examine the interaction between physical factors and psychological features, as well as measures of pain, disability and headache, to understand if and to what extent these factors are related to each other, thereby obtaining a more comprehensive understanding of the interaction between different factors in the clinical presentation of WAD. Two network analyses were performed, at baseline during acute pain and 6 months later, in order to assess the interaction between physical features, pain-related factors and psychological features soon after a whiplash injury and to determine how a range of factors measured during the acute stage influence factors measured when people have developed chronic WAD. We hypothesized that the network analysis approach would provide a greater understanding of the complexity of presentation in people with WAD by taking into account physical features, pain-related factors and fear of movement and their interactions. Based on existing literature that suggests a greater role of psychological and/or pain-related factors on whiplash prognosis, we also hypothesized that pain-related features would be more strongly associated with kinesiophobia than with physical factors and that these findings would be even more evident at 6 months (Alalawi et al., 2021; Nieto et al., 2013).

2 | METHODS

2.1 | Study design

A prospective study was carried out involving patients with acute neck pain attributed to a whiplash injury due to a motor vehicle accident. Data were collected at a Traumatology Clinic in Madrid, Spain, from September 2020 to February 2021. The study was conducted according to the Declaration of Helsinki and is reported following STROBE guidelines (von Elm et al., 2014) and the reporting standards for network analyses (Burger et al., 2022). The study was approved by the Ethics Committee of the University Rey Juan Carlos, Madrid, Spain (Ref: 1003202108121).

2.2 | Sample size

This study was performed as a secondary analysis of a dataset that was adequately powered for the objectives of the primary study. In a network analysis, an a priori sample size calculation is challenging and still under discussion, given that for data-driven methods, there is no a priori single hypothesis (Epskamp et al., 2018; Epskamp & Fried, 2018). Nonetheless, based on achieving a desired level of stability on the results of a preliminary network, a post-hoc sample size estimation can be obtained (Epskamp et al., 2018). This is akin to determining sample size to achieve the desired precision of effect size rather than the magnitude of effect size (Bland, 2009). Thus, this study could inform the sample size for future network analyses.

2.3 | Participants

Consecutive patients arriving at the clinic were diagnosed by a physician and then referred to the Physiotherapy Department. Since over 90% of people with WAD are classified as WAD Grade II (Sterling, 2004), as defined by the Quebec Task Force on WAD (Spitzer et al., 1995), we selected to include only this subgroup of patients. Participants were included if they presented with WAD II, from 7 to 30 days after the accident and were aged between 18 and 65 years old. They were excluded if they had: a history of generalized pain; had experienced a previous whiplash injury; had a diagnosis of temporomandibular disorders, osteoporosis, cervical myelopathy, vertebral fractures and/or concussion or inflammatory/rheumatic diseases had a known psychological disorder or congenital disturbances; had undergone previous surgery in the cervical region or were not able to complete PROMs.

2.4 | Procedures

Individuals arriving at the clinic were invited to participate in the study. Before the evaluation, participants were advised that the physical measurements and questionnaires were not going to be considered for their final health report and therefore would not be reviewed as part of any insurance claim. All participants gave their written informed consent before being enrolled in the study.

For the data assessed at baseline, all participants completed questionnaires related to psychological features, neck pain, headache and disability, as detailed below. At this point, age and sex were documented, and weight and height were measured. Once the questionnaires were completed, a physical examination was then performed by a physical therapist who was blinded to the results of the PROMs assessment, although the assessor was not blind to the aims of the study. All measurements were collected twice in a single session conducted by the same examiner (EA) with more than

4 years of clinical experience and a Master's Degree in Orthopaedic Manual Therapy. The mean for each set of two measurements was used for the analysis. When tests were performed bilaterally, the mean of both sides was calculated.

In our prospective study, individuals included in our study received a multimodal treatment approach tailored to each participant's specific needs and presentation, including manual therapy, education/advice, exercise and electrotherapy. For the 6-month follow-up, only psychological factors, neck pain, headache and disability, were assessed as this was achieved remotely. Participants were contacted by email and provided with electronic copies of the questionnaires, which they were to complete and return via email.

2.5 | Outcome measures

2.5.1 | Physical measurements

Cervical Range of Motion (ROM): Flexion, extension, lateral flexion and rotation were assessed with the participant in a relaxed sitting position using a smartphone Xiaomi® MiA2. Participants were asked to sit comfortably on a chair with back support and both feet flat on the floor and their hips and knees at 90° (Fernández-de-las-Peñas et al., 2006). Smartphone apps (the Android Clinometer Application for the frontal plane and the Smartphone Compass Application for the horizontal plane) were used for this purpose, as previously described (Ghorbani et al., 2020; Tousignant-Laflamme et al., 2013). Flexion and extension were assessed with the phone placed on the left side of the head, aligned with the ear; left and right lateral flexion were measured with the phone on the contralateral side of the head, aligned with the eyes; and rotation measures were taken with the phone placed on the participant's head with the arrow aligned with the nose (Ghorbani et al., 2020; Tousignant-Laflamme et al., 2013). This device has excellent intra-rater reliability (ICC = 0.846–0.903), except for right rotation (ICC = 0.517) and left rotation (ICC = 0.131) (Ghorbani et al., 2020).

Cranio-Cervical Flexion Test (CCFT): The participant lay supine with the neck in a neutral position, with their head supported by towels as needed. An uninflated pressure cuff (Chattanooga Stabilizer Group Inc., USA) was placed behind the neck so that it abutted the occiput and was then inflated to a stable baseline pressure of 20 mmHg, filling the space between the testing surface and the neck without pushing the neck into a lordosis (Jull et al., 2008). The highest level of the five stages of the CCFT (22–30 mmHg) that was held for 10 s, without substitution using excessive superficial neck muscle activity, was recorded as described previously (Jull et al., 2008). The highest level they achieved over the two repetitions of the test was used for analysis. Higher scores imply better performance on the test. This outcome measure has moderate intra-rater reliability (ICC ≥ 0.69) and excellent inter-rater reliability (ICC ≥ 0.85) (Juul et al., 2013).

Neck flexor endurance: The test was performed with the participant positioned supine on the plinth. The participant's head was positioned in slight upper cervical flexion by the examiner, who placed his left hand on the table just below the participant's occiput. The participant was then asked to gently flex his/her upper neck and lift his/her head off the examiner's hand while retaining upper cervical flexion. Verbal feedback ('tuck your chin in' or 'hold your head up') was given to the participant when their head touched the examiner's hand during the test. The test was terminated if the participant was unable to maintain the position of their head off the examiner's hand despite verbal encouragement or if they reached the maximum holding time of 30 s (Edmondston et al., 2008). This test has excellent reliability, with an ICC (95% CI) = 0.93 (0.86–0.97) (Edmondston et al., 2008).

Neck extensor endurance: This test measured the time, in seconds, to keep the head steady while lying in a prone position with the head over the edge of the plinth in a neutral position (Juul et al., 2013). This test was terminated if the participant lost the position despite verbal encouragement or reached a maximum holding time of 30 s. This test has excellent reliability, with an ICC (95% CI) = 0.75 (0.55–0.87) (Jørgensen et al., 2014).

Pain-Pressure Thresholds (PPT): PPT were taken over the median, radial, ulnar, supra-orbital and greater occipital nerve. They were measured bilaterally using a digital algometer (Force Ten™-Model FDX, Wagner) with a surface area of a round tip of 1 cm^2 and were recorded in N/cm^2. The supra-orbital nerve was tested over the supra-orbital notch (at the junction between the medial third and the two lateral thirds of the upper part of the margin of the orbit); the median nerve was located over the cubital fossa medial to and adjacent to the biceps tendon; the radial nerve was marked where it passes through the lateral intermuscular septum between the medial and lateral heads of the triceps brachii to enter the mid to lower third of the humerus; the ulnar nerve was located in the groove between the medial epicondyle and the olecranon; and the greater occipital nerve was assessed approximately 2 cm medial to the greater occipital protuberance (Fernández-de-Las-Peñas et al., 2011; Szikszay et al., 2018). A lower PPT implies increased sensitivity. These tests have ICCs (95% CI) ranging from 0.90 to 0.96 (Jørgensen et al., 2014) in asymptomatic people and excellent reliability [ICC (95% CI) = 0.81–0.94] in people with acute neck pain (Walton et al., 2011).

2.5.2 | Pain intensity, neck disability and fear of movement

The following outcomes were measured both at baseline and 6 months after the baseline assessment.

Visual Analogue Scale (VAS): Neck pain and headache intensity were assessed using the VAS, with a score varying from 0 to 100 (0 = no pain; 100 = worst pain imaginable) (Rodero et al., 2013), which has established good reliability (Huskisson, 1983). VAS0 represents this outcome at baseline, and VAS6 indicates the VAS score at the 6-month follow-up. In the figures, neck pain has been expressed as 'neckp' and headache as 'headp'. For baseline measures, 0 has been added after 'neckp' or 'headp', whereas for the 6-month follow-up, the number 6 is included.

Neck Disability Index (NDI): The Spanish version of the NDI was used to evaluate neck disability (internal consistency Chronbach's alpha 0.80; excellent reliability ICC (95% CI) = 0.88 [0.63 to 0–95]; The NDI has good construct validity when compared to the Global Rating of Change [$p < 0.001$]) and is commonly used to assess disability in people with WAD (Andrade Ortega et al., 2010; Merrick & Stålnacke, 2010; Young et al., 2019). Both in the article and in the figures, NDI0 represents this outcome at baseline, and NDI6 indicates the NDI at the 6-month follow-up.

Tampa Scale Kinesiophobia-11 (TSK-11): The Spanish version of the TSK-11 was used to measure fear of movement (internal consistency, Chronbach's alpha 0.79). This tool is composed of 11 items, and scores range from 1 (strongly disagree) to 4 (completely agree). The total score can range from 11 to 44, with higher scores reflecting greater kinesiophobia. The TSK-11 has good test–retest reliability (ICC [95% CI] 0.81 [0.71–0.88]) and a highly significant correlation with change scores on the TSK ($r = 0.93$, $p < 0.001$) (Gómez et al., 2011; Woby et al., 2005). Both in the article and in the figures, TSK0 represents the TSK-11 score at baseline, and TSK6 indicates the TSK-11 score at the 6-month follow-up.

2.6 | Statistical analysis

All statistical analyses were conducted using R software (version 4.2.2.) (R Core Team, 2021). The Shapiro–Wilk test was used to assess the distribution of the data. Demographic characteristics and outcome measures are descriptively reported using the mean and standard deviation. Demographic features and physical examination findings are reported at baseline, whereas neck pain intensity and disability, headache intensity and kinesiophobia are presented at baseline and for the 6-month follow-up. Comparisons between baseline and 6-month follow-up data for neck pain and headache intensity, neck disability and kinesiophobia were performed with the Student's *t*-test for continuous variables.

2.6.1 | Network analysis

Before conducting the network analysis, cervical ROM was averaged across all movement directions and collapsed into one variable representing average cervical ROM. The same approach was conducted for endurance (average of flexor and extensor muscle endurance) and PPT (average across all testing sites). Thus, potential features included in the network were ROM, endurance, PPT, CCFT, neck pain intensity, headache intensity, TSK-11 and NDI.

Network analysis was performed with the R package *bootnet* (R Core Team, 2021). In a network, features are graphically represented as nodes, and the partial correlation coefficients that define the interactions among them are represented by edges (Costantini et al., 2015; Epskamp et al., 2018). Partial correlations are also defined as conditional (in)dependence associations because they are computed after conditioning all other nodes (Costantini et al., 2015). Hence, the presence or absence of an edge between the two nodes indicates a conditional dependency or independency, respectively (Costantini et al., 2015). Edges in a network are graphically reported with different colours to represent positive versus negative correlations, and their thickness depends on the strength of the correlation (edge weight).

A nonparanormal transformation was applied to ensure that the variables were multivariate normally distributed (Liu et al., 2009), a requirement to estimate a Gaussian Graphical Model (GGM) (Lauritzen & Wermuth, 1989). The graphical least absolute shrinkage and selection operator (LASSO) was used for the network analysis (Friedman et al., 2014). The LASSO uses a tuning parameter to control the sparsity of the network, which we chose by minimizing the Extended Bayesian Information Criterion (EBIC) (Foygel & Drton, 2010). This methodology is explained in more detail in previous tutorial papers (Costantini et al., 2015; Epskamp & Fried, 2018). The importance of each note within the network, termed centrality, was quantified using three indices: Strength, Closeness and Betweenness (Costantini et al., 2015).

We assessed the variability of the edge weights using bootstrapping ($B = 1000$) (Epskamp et al., 2018) to estimate the 95% confidence interval of the estimated edge weights (i.e. the partial correlations). To gain an estimate on the variability of the found centrality indices (CS-coefficient)—meaning if the order of centrality indices remains the same after re-estimating the network with fewer participants, we applied the participant-dropping subset bootstrap ($B = 1000$) (Epskamp et al., 2018). This procedure drops a percentage of participants, re-estimates the network and re-calculates the three centrality indices. The CS-coefficient reflects the maximum proportion of participants that can be dropped, such that with 95% probability, the correlation (of the centrality value of the bootstrapped sample vs. that of the original) would reach a certain value (0.7 in the current study, $CS_{cor}=0.7$). It is suggested that $CS_{cor}=0.7$ should be >0.25, and it is better if it is >0.5 (Epskamp et al., 2018).

2.6.2 | Post-hoc sample size analysis

Using the netSimulator function of the bootnet package and based on the estimated network, six performance indices were calculated: (1) correlation between the edge weights; (2) sensitivity—the proportion of edges present; (3) specificity—proportion of missing edges; correlation between (4) Strength, (5) Closeness and (6) Betweenness centrality measures of the given network against those of the re-estimated network using different sample sizes (Epskamp & Fried, 2018). To achieve these indices and follow a priori network structure and edge weights, the *netSimulator* function simulates data in a similar way that a standard statistical power simulation study simulates new data following a hypothesized effect size being detected. Thus, based on our original network and edge weights, simulation of data was performed with varying sample sizes, n, across these values: 50, 100, 150, 200, 250 and 500. For each sample, 1000 bootstrap samples with replacement were performed to re-estimate the network and calculate the six performance indices.

3 | RESULTS

Data from 47 participants were analysed at baseline. Two participants did not provide feedback from our request by email and were lost to follow-up, therefore the 6-month follow-up data is based on 45 participants. The sociodemographic characteristics of the participants are presented in Table 1. The sample recruited had a mean age of 38.94 years (SD: 10.99), a mean height of 175.93 cm (SD: 9.23), a mean weight of 73.11 kg (SD: 10.52) and 12.70 (SD: 4.1) mean days from the accident until the baseline evaluation. The participants presented with a mean cervical ROM of 44.07° (SD: 8.43), a mean neck muscle endurance of 13.42 s (SD: 5.10), a mean PPT of 15.96 kg/cm^2 (SD: 3.87) and a mean score of 24.81 mmHg (SD: 1.85) on the CCFT. From baseline to the 6-month follow-up, there were significant reductions in neck pain intensity ($p<0.001$), headache intensity ($p=0.003$), NDI ($p<0.001$) and TSK-11 ($p<0.001$) (Supplementary Material 1).

TABLE 1 Sociodemographic features and physical measurements obtained at baseline.

Variables	Mean ± SD
Age (years)	38.94 ± 10.99
Gender (male/female)	16/21
Height (cm)	175.93 ± 9.23
Weight (kg)	73.11 ± 10.52
Days from the accident	12.70 ± 4.1
ROM (°)	44.07 ± 8.43
END (s)	13.42 ± 5.10
PPT (kg/cm^2)	15.96 ± 3.87
CCFT (mmHg)	24.81 ± 1.85

Note: Data expressed on mean ± SD ($n=47$).

Abbreviations: CCFT, cranio-cervical flexion test; END, muscle endurance; PPT, pressure-pain threshold; ROM, range of motion.

For the network analysis performed on the baseline data, the three edges with the greatest weight magnitudes were between NDI0-TSK0 (0.36 [95% CI 0.13–0.51]), neck pain and headache intensity (0.34 [95% CI 0.11–0.56]) and CCFT-NDI0 scores (−0.33 [95% CI −0.48 to −0.11]) (Figures 1a and 2a).

For the network analysis incorporating the follow-up data, the three edges with the greatest weight magnitudes were between NDI6-TSK6 (0.54 [95% CI 0.38–0.65]), neck pain and headache intensity both at 6 months (0.50 [95% CI 0.34–0.61]) and CCFT-NDI at baseline (−0.33 [95% CI −0.47 to −0.09]) (Figures 1b and 2b).

From the analysis of baseline data, baseline NDI, neck pain intensity and muscle endurance had the greatest relative Strength, Closeness and Betweenness measures (Supplementary Material 2a). The stability of the centrality measures, $CS_{cor}=0.7$, of Strength, Closeness and Betweenness were 0.128, 0.128 and 0, respectively, for the baseline network analysis (Supplementary Material 3a). For the network analysis incorporating the longitudinal data, NDI0, baseline TSK0 and headache intensity at 6 months had the greatest relative Strength, Closeness and Betweenness measures (Supplementary Material 2b). The stability of the centrality measures, $CS_{cor}=0.7$, of Strength, Closeness and Betweenness were 0.277, 0.043 and 0, respectively (Supplementary Material 3b).

From Supplemental Material 4 it can be seen that the correlation of the estimated edge weights increased $r>0.70$ when the sample size increased from $n=50$ to $n=100$, suggesting that assuming our estimated was true, a sample size of at least $n=100$ is required for both networks. The correlation between the presently estimated Strength index and the re-estimated values increased beyond $r>0.70$ with a sample size of $n=250$. However, the precision of our Closeness and Betweenness indices did

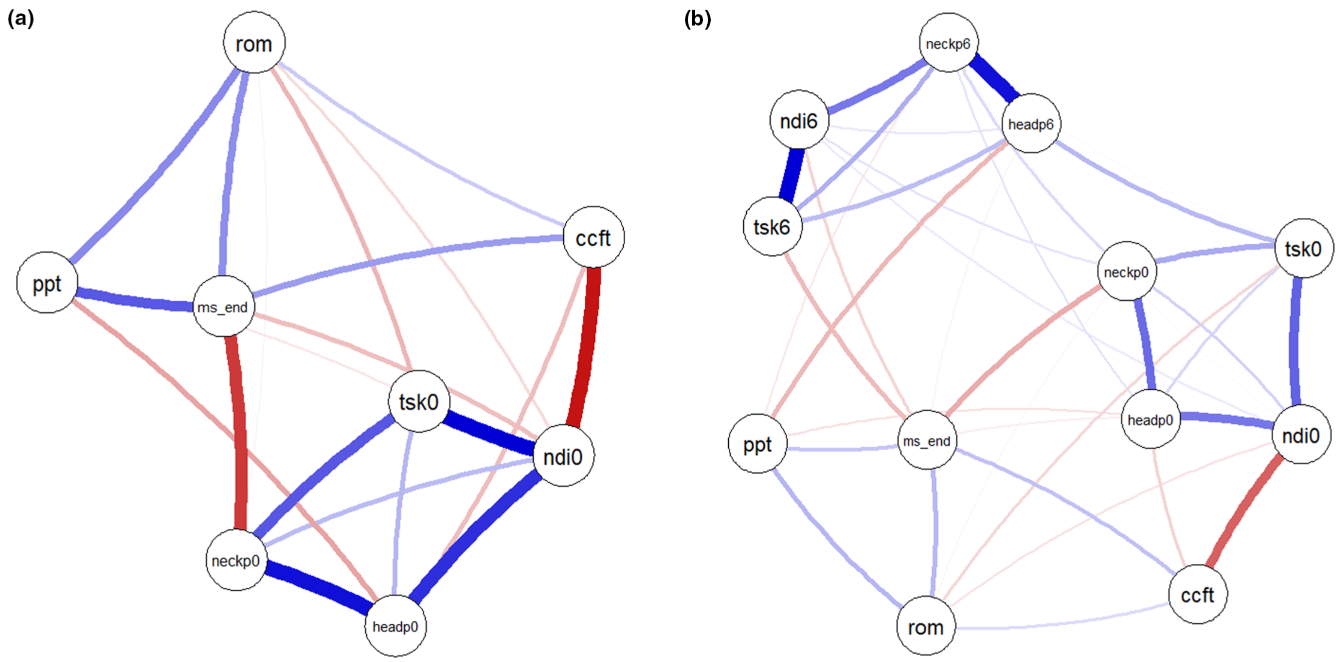


FIGURE 1 Network analyses including all variables. (a) Network analysis only including variables measured at baseline. (b) Network analysis including variables measured both at baseline and at the 6-month follow-up. ccft, cranio-cervical flexion test; ms_end, muscle endurance; ndi, Neck Disability Index; neckp, neck pain intensity; ppt, pressure-pain threshold; Rom, range of motion; tsk, Tampa Scale of Kinesiophobia. When the number 0 accompanies a variable it refers to 'at baseline'; when the number 6 accompanies a variable it refers to the '6-month follow-up'.

not improve substantially across the sample size (Supplementary Material 4).

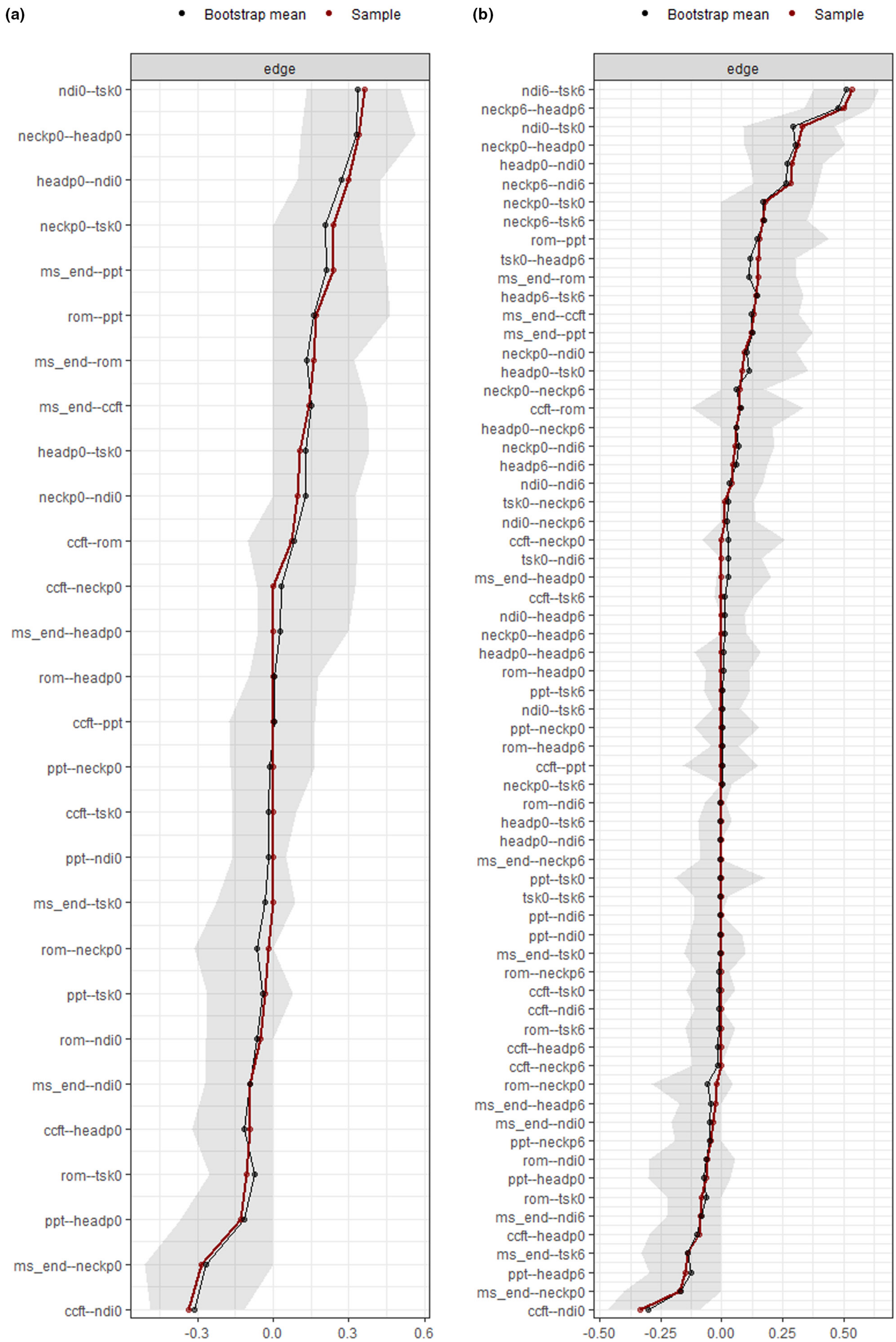
4 | DISCUSSION

In the present study, we performed two network analyses to evaluate the interactions between different physical and psychological features, disability and neck pain and headache intensity in people with acute WAD and when measured and 6 months later. Through these network analyses, this study revealed that fear of movement, perceived neck disability and pain intensity showed the strongest interaction both at baseline and at a 6-month follow-up, which is in line with our hypothesis. We also found a relationship between physical impairments and neck pain and disability, namely neck endurance and CCFT performance. Moreover, an association between fear of movement and cervical ROM and between PPT and headache was found at baseline. However, the associations between physical impairments at baseline and pain intensity, disability and fear of movement at 6 months were only found for neck endurance and PPT at 6 months and were not strongly sustained, as hypothesized. The identification and quantification of these interactions between physical and psychological features, disability and neck pain and headache intensity underscore the multidimensional nature of WAD and provide insights into potential treatment strategies for optimizing outcomes in people with WAD.

4.1 | Network analysis at baseline

Previous studies have assessed the role of physical factors in people with acute WAD and their relationship with psychological features (e.g., Alalawi et al., 2022; Fernández-Pérez et al., 2012). In our network analysis, we observed that kinesiophobia was strongly associated with pain and disability, but also with physical measures such as cervical ROM. It has previously been

FIGURE 2 Magnitude of the correlation between variables. (a) Network analysis only including variables measured at baseline. (b) Network analysis including variables measured both at baseline and at the 6-month follow-up. ccft, cranio-cervical flexion test; ms_end, muscle endurance; ndi, Neck Disability Index; neckp, neck pain intensity; ppt, pressure-pain threshold; Rom, range of motion; tsk, Tampa Scale of Kinesiophobia. When the number 0 accompanies a variable it refers to 'at baseline'; when the number 6 accompanies a variable it refers to the '6-month follow-up'.


(a)
Bootstrap mean
Sample
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ndi0--tsk0
neckp0--headp0
headp0--ndi0
neckp0--tsk0
ms_end--ppt
rom--ppt
ms_end--rom
ms_end--ccft
headp0--tsk0
neckp0--ndi0
ccft--rom
ccft--neckp0
ms_end--headp0
rom--headp0
ccft--ppt
ppt--neckp0
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ppt--tsk0
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ccft--headp0
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ppt--headp0
ms_end--neckp0
ccft--ndi0
-0.3
0.0
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(b)
Bootstrap mean
Sample
edge
ndi6--tsk6
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rom--ppt
tsk0--headp6
ms_end--rom
headp6--tsk6
ms_end--ccft
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ms_end--tsk0
rom--neckp6
ccft--tsk0
ccft--ndi6
rom--tsk6
ccft--headp6
ccft--neckp6
rom--neckp0
ms_end--headp6
ms_end--ndi0
ppt--neckp6
rom--ndi0
ppt--headp0
rom--tsk0
ms_end--ndi6
ccft--headp0
ms_end--tsk6
ppt--headp6
ms_end--neckp0
ccft--ndi0
-0.50
-0.25
0.00
0.25
0.50

demonstrated that altered cervical kinematics are associated with increased levels of kinesiophobia in people with chronic neck pain (Devecchi et al., 2022; Sarig Bahat et al., 2014), in line with our findings in participants with acute WAD, suggesting that fear of movement could be influencing neck ROM in both acute and chronic stages. Conversely, a recent study performed on people with acute WAD found that fear of movement was not associated with reduced ROM (Alalawi et al., 2022). These differences may reflect the large heterogeneity of psychological and physical features between individuals with WAD. Indeed, the difference may be explained by differences in ROM and TSK-11 values, which differ between studies. For example, considering the level of kinesiophobia, our sample had a mean value at baseline of 25.34 ± 8.23, while the study by Alalawi et al., (2022) had a sample with a higher average score on the TSK-11 of 33.4 ± 9.6. Therefore, this relationship between physical features and psychological features such as kinesiophobia may not be present in some situations, such as those with more severe levels of kinesiophobia or when kinesiophobia is not present at all. Kinesiophobia was not strongly associated with other physical features such as CCFT performance or neck endurance; this may again be explained by the relatively low levels of kinesiophobia in our sample compared to previous studies and/or the fact that these tests involved little movement of the neck.

According to our network analysis, neck endurance and the CCFT are physical factors strongly associated with other variables. In accordance with previous findings, we found that reduced levels of endurance of the neck musculature, as well as impaired performance on the CCFT, are associated with higher neck disability (Elliott et al., 2009; Kahlaee et al., 2017). According to the network analysis, the strength of the association with neck disability at baseline was greater for the CCFT than for neck endurance. These findings confirm previous reports that altered neuromuscular control of the neck is evident soon after the onset of pain/injury (Sterling, Jull, Vicenzino, Kenardy, & Darnell, 2003). In addition, we found that endurance played an important role in our network in terms of high levels of Betweenness, Strength and Closeness. In other words, a change in muscle endurance was associated with changes in other features, including pain intensity, disability and kinesiophobia. To the best of our knowledge, this is the first study demonstrating the importance of neck endurance and its interaction with a number of clinical features in people with acute WAD. Nonetheless, it has been previously demonstrated that neck muscle endurance mediates the relationship between neck-specific exercise and neck pain dynamics in people with chronic WAD, reinforcing the relevance of neck endurance in exercise prescription in people with WAD (Liew et al., 2019) and the importance of neck-specific exercises to improve neck endurance and patient satisfaction (Peterson et al., 2015). In addition, neck-specific exercises significantly reduce neck pain intensity and improve neck endurance, but changes in kinesiophobia are small when assessed at 6 months (Peterson et al., 2015).

The most important characteristic of our network analysis comes from the strong interaction between neck pain, headache intensity, kinesiophobia and neck disability. Previous work has shown a moderate mediation of fear of movement in the relationship between pain and disability soon after a whiplash injury (Kamper et al., 2012) and an increased presence of psychological factors when symptoms are more severe (Sterling et al., 2004). Therefore, the network analysis suggests that addressing fear of movement may also be of great importance in the management of neck pain and headache in people with WAD in the acute stage.

4.2 | Network analysis at 6 months

In the network analysis which included the follow-up at 6 months, NDI was not strongly associated with CCFT at baseline but was associated with neck endurance, suggesting that neck endurance could be influencing longer-term disability. To the best of our knowledge, no previous studies have assessed the ability of neck endurance measures to predict disability in the longer term in people with WAD (Alalawi et al., 2021). Another relevant interaction related to neck endurance revealed by our second network analysis is that it still remained in a central position, reinforcing the notion that endurance may be important to address in the early management of people with WAD. Nonetheless, according to our findings, the association between NDI and TSK-11 at 6 months show that fear of movement could be conditioning neck disability, which would be supported by the fear-avoidance model (Vlaeyen & Linton, 2012).

In line with previous findings (Sterling et al., 2005), PPT was not associated with disability at 6 months. However, the current results suggest that pain sensitivity, measured via the PPT over neural structures in the cranio-cervical region and upper limbs, is related to the intensity of headache when assessed 6 months later. A previous study found that increased sensitization was present in people with chronic WAD and headache (Watson & Drummond, 2016). However, no measures were taken during the acute stage. Our study is the first to demonstrate that reduced PPT over neural structures measured soon after the whiplash injury and higher headache intensity 6 months later are conditionally dependent, therefore suggesting that sensitization may be present early after a whiplash trauma and that this has relevance for the longer-term persistence of headache.

The main relationships with higher levels of neck pain and headache intensity at 6 months were higher neck pain and headache intensity at baseline and higher TSK-11 and NDI at baseline. These findings are in accordance with previous findings, since pain intensity, neck disability and psychological factors have been identified as predictors of poor prognosis (Carroll et al., 2008; Sullivan et al., 2002). Indeed, we observed that the interactions with greater strengths were similar at baseline and 6 months later; the structure of association between nodes concerning headache, NDI, neck pain intensity and TSK-11 continued to be strongly related.

4.3 | Methodological considerations

A strength of this work is the analysis that we have applied, which has helped to appreciate the multidimensional nature of WAD by revealing the important role of neck endurance, the relationship between reduced PPT and chronic whiplash-associated headache, and the strong correlation between neck pain and headache intensity, neck disability and kinesiophobia. The importance of our results is based on the fact that these are not bivariate correlations but relationships coming from two network analyses considering different variables and their interactions. In addition, our study was performed in a clinical setting, which allowed us to understand the evolution of interactions between different variables while patients were being treated according to each person's needs.

A possible limitation that partially affects the interpretability of the network analysis is represented by the reduction of features into a single node: range of motion was a result of collapsing ROM for rotation, flexion, extension and lateral flexion; PPT was the result of collapsing assessments over the radial, median, ulnar, supraorbitaire and greater occipital nerves; and muscle endurance was the result of collapsing flexor and extensor endurance. However, feature reduction was necessary since the number of nodes influences the estimation of a network. Additionally, it should be noted that the intra-rater reliability of assessing cervical rotation ROM using the Smartphone Compass Application is low (Fernández-de-las-Peñas et al., 2006). Given that rotation is commonly restricted in people with WAD (de Rosario et al., 2018; Stenneberg et al., 2022), we chose to retain this measure within the total ROM.

Another limitation of the present study is the relatively small sample size. No sample size calculation was performed for this network analysis, as this was performed as a secondary analysis. In addition, an a priori sample size calculation is not frequently possible without the presence of a prior network on similar variables to provide an approximate expectation of the network structure and weights (Burger et al., 2022). However, we performed a post-hoc power calculation, revealing that with a sample of 50, there was a correlation of over 0.70 between our findings and bootstrapped data, particularly in relation to association weights. This power calculation will be useful for future studies.

It must be noted that causality cannot be established based on the current results since the network analysis only establishes relationships but not the direction of these relationships. Nonetheless, identified associations can promote the generation of hypotheses and indicate potential features and relationships to be investigated in the future. Furthermore, physical impairments were not assessed at the follow-up as data were collected remotely. Additionally, some variables that are predictive of poor prognosis, such as cold hyperalgesia or acute posttraumatic stress, were not included in this study.

4.4 | Future research

The findings from this study provide directions for future research. First, it would be valuable to explore strategies to address fear of movement in individuals with acute WAD, considering its strong association with headache, neck pain intensity and disability, and evaluating if these strategies improve pain-related features and disability. Additionally, the predictive ability of neck endurance and other physical features on long-term prognosis should be examined to understand whether these features should become early treatment targets. The relationship between reduced PPT over neural structures and the persistence of headache at 6 months also warrants further investigation.

5 | CONCLUSION

Findings from network analyses show that the strongest interactions were neck pain intensity and headache, and neck disability and kinesiophobia, both in the acute stage and a 6-month follow-up in people with WAD. Moreover, important conditional dependencies were found between CCFT and NDI at baseline, neck endurance and NDI in the longer term, PPT and headache both in the short term and longer term, and between reduced cervical ROM and increased levels of kinesiophobia.

AUTHOR CONTRIBUTIONS

EAL performed data collection. BLW performed data analysis, with the support of VD. EAL, CBU, CRB and DF conceptualized the study. EAL, VD, BLW and DF developed the manuscript, which was then approved by all authors. CBU, CRB and DF supervised the overall study.

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CONFLICT OF INTEREST STATEMENT

Authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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