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Identifying modifiable factors that influence walking in patients undergoing surgery for neurogenic claudication: a prospective longitudinal study

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Neurogenic claudication, caused by lumbar spinal stenosis, is the most common reason for spinal surgery in older adults, aiming to improve pain and walking. However, most people do not increase walking post-operatively. This study aimed to identify modifiable physical and psychosocial factors that could be targeted with rehabilitation. A prospective longitudinal study recruited 97 adults, aged > 50 years, awaiting surgery for neurogenic claudication. Walking measures (six-minute walk test, daily step count, self-rated maximum walking distance) were assessed pre-surgery and 12-weeks post-surgery. Modifiable variables, mapped to a behaviour change model (COM-B; e.g. falls, lower limb performance, fear of movement, illness perceptions), were evaluated using mixed-effects regression models. All walking measures demonstrated statistically significant improvements (p < .001). However, 50% did not achieve minimum clinically important differences. The strongest correlation with post-operative walking was pre-operative walking. Cross-sectionally, lower limb performance (b:.75; 95CI .64, .86 to b:.35; 95%CI .19, .52), pre-surgery history of falls (b:−.29; 95%CI−.44,−.13), fear of falling (b:−.55; 95%CI−.69,−.41 to b:−.32; 95%CI −.48, −.15), fear of movement (b:−.48; 95%CI−.63,−.33 to −.22; 95%CI −.40, −.03), coherence of condition (b:−.23; 95%CI −.41, −.05 to b:−.17; 95%CI−.33,−.01) and perceived personal control (b:.26; 95%CI .09, .43 to b:.14; 95%CI.02,.31), were significantly associated with pre-surgical walking (p < .05). Most pre-surgical variables were not longitudinally associated with change in walking post-surgery. Six-weeks post-surgery fear of falling (b:−.35; 95%CI −.57, −.13 to b:−.18; 95%CI−.33,−.02), fear of movement (b:−.32; 95%CI−.53,−.11 to b:−.19; 95%CI −.33, −.05), and emotional response (b−.24; 95%CI −.38, −.11 to b:−.22; 95%CI −.41, −.03) were significantly associated with less improvement in walking at 12-weeks post-surgery. Prehabilitation and post-operative rehabilitation targeting walking, balance, and psychosocial factors is recommended to optimise post-surgical walking.

Keywords Neurogenic claudication, Walking, Rehabilitation, Fear of movement, Fear of falling, Prognosis

Neurogenic claudication (NC) affects approximately 10% of the general population with incidence increasing with age[1,2]. It is caused by lumbar spinal stenosis (LSS), a degenerative condition that leads to narrowing around and compression of the nerves and blood vessels within the lumbar spine. NC is characterised by bilateral leg pain, paraesthesia, and/or weakness often accompanied by low back pain. It is exacerbated by standing and can cause substantial walking restriction[3], greater than that experienced by people with hip or knee osteoarthritis[4]. Additionally, it can lead to a substantial reduction in quality of life, comparable to that caused by stroke and heart disease[5].

Neurogenic claudication is the most common cause for lumbar surgery in older adults and the number of procedures performed annually is increasing worldwide[6]. Surgery aims to reduce pain and improve walking[7–9]. Yet, after surgery for NC, approximately 40% of people have ongoing pain and walking restriction[10] and the

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majority of people do not increase their daily step count and physical activity[11,12]. Walking is an accessible and acceptable form of physical activity in older people[13] and is associated with many health benefits including greater function and lower morbidity and mortality[14]. Thus, if people post-surgery are not increasing their walking, they remain at risk of the consequences of inactivity.

Identifying the factors associated with post-operative walking in patients undergoing surgery for NC is important because they could be targeted with rehabilitation to improve outcomes. To date, most of the research has focused on routinely collected and biological factors, for example sex, age, body mass index (BMI), comorbidities, and radiological parameters[15–19], as potential predictor variables whereas there has been limited investigation into the modifiable psychosocial variables of walking behaviour[20]. A systematic review of pre-operative factors (n = 34 studies, 9,973 patients) identified moderate quality of evidence that pre-operative walking capacity was positively associated with post-operative walking capacity; and spondylolisthesis and severity of stenosis was not found to be associated with post-operative walking capacity[20]. There was weak or inconclusive evidence that other factors were associated with post-operative walking: higher BMI, smoking, and previous lumbar surgery were negative prognostic factors; and higher income and better self-rated health were associated with better outcomes. However, age, sex, symptom severity and duration, fear avoidance, and social support were not found to be prognostic factors. Conflicting evidence emerged regarding comorbidities; musculoskeletal conditions and diabetes were identified as negative prognostic factors, while cardiovascular and respiratory comorbidities did not appear to influence post-operative walking capacity[20] Crucially, other than one study investigating fear avoidance beliefs[21], modifiable psychosocial variables of behaviour that may be addressed with rehabilitation, had not been studied.

Factors in the early post-operative period may also be important variables associated with long-term outcome. Studies in mixed lumbar-surgical populations have identified factors such as pain self-efficacy, fear of movement, illness perceptions and social support as being important[22–25]. However, these have not been thoroughly investigated in patients with NC.

Walking is a complex, multifaceted behaviour[26], behaviour change models can be used to comprehensively understand the behaviour and identify barriers and enabling factors, particularly those that might be most amenable to intervention. The Behaviour Change Wheel (BCW), a synthesis of 19 behaviour change models[27], provides a systematic framework for understanding the enabling factors of a target behaviour (e.g. walking) which can then be used to design an intervention (e.g. rehabilitation programme) targeting these factors. At the core of the BCW is the COM-B model. This specifies three drivers of behaviour: Capability (physical and psychological), Opportunity (social and physical), and Motivation (reflective and automatic). It further theorises that both Capability and Opportunity influence Motivation, making Motivation the central mediator within the COM-B model. The comprehensive coverage of the COM-B allows researchers to analyse the salient determinants specific to the population and behaviour of interest. Identifying the salient determinants is a crucial step in developing interventions and the COM-B and the BCW have been successfully utilised to develop interventions to increase physical activity in other populations[28,29], demonstrating its practical utility.

To date, no study has used a behavioural model to investigate the modifiable factors associated with walking in people undergoing surgery for NC. The aims of this study were to evaluate change in walking capacity and performance from pre-surgery to 12-weeks post-surgery; and to identify potentially modifiable physical and psychosocial determinants of walking capacity and performance in people undergoing surgery for NC that could be targeted with rehabilitation.

Materials and methods

Study design: A prospective multi-site observational study was conducted. The *Strengthening the Observational Report on Epidemiology* (STROBE) guidelines[30] were used to inform design and reporting of the study. The study was performed in accordance with the Declaration of Helsinki, written informed consent was provided by all participants. Ethical approval was obtained from the East Midlands—Nottingham 1 Research Ethics Committee (20/EM/0307). The study protocol was registered at Open Science Framework (https://doi.org/10.17605/OSF.IO/BHQJZ).

Participants: Participants were recruited from three NHS hospital trusts in England. Participants were eligible if they were ≥ 50 years old and due to have decompressive surgery for degenerative LSS with symptoms of NC. Neurogenic claudication symptoms were defined as leg or buttock pain and/or tingling, numbness or heaviness, made worse when standing or walking, and/or eased by sitting or bending forward. Symptoms may be present with or without low back pain[3,31]. Exclusion criteria consisted of LSS caused by tumour, fracture or significant deformity (> 15° lumbar scoliosis; ≥ grade II spondylolisthesis); patients requiring emergency surgery; > 1 level fusion surgery; or if they reported other conditions that were the primary cause of walking restriction. Patients with less than a week before their scheduled date for surgery were excluded as there was insufficient time for baseline data collection. Conversational level English or willingness to use an interpreter was also required.

The target sample size was set at 122 participants and calculated based on the objective to determine the factors that are associated with 12-week six-minute walk distance (6MWD) after controlling for clinical-demographic confounding variables. Specifically, 97 participants providing 80% power (alpha = 0.05) to detect a continuous predictor variable that explained an additional 5% of the variance in a linear regression model, including five control variables that combined explained 35% of the variance (i.e. $R^2_{change} = 0.05$, equivalent to d = 0.5). This number was inflated to account for 20% attrition resulting in the target of 122.

Procedures: Potentially eligible participants were invited to find out more about the study either in person during their surgical clinic appointment or via the telephone. They were invited to attend two, one hour assessments, one prior to their surgery and one 12-weeks following their surgery. If interested, they were posted the participant information sheet, consent form and a paper-based baseline questionnaire pack consisting of questions to collect demographic information and the self-reported measures. At the assessments, the questionnaire packs were checked for completion and the objective measures completed. Participants also completed a self-reported questionnaire pack at six weeks post-surgery which was returned by post.

Tests and measures

Walking capacity and performance: Walking capacity was assessed using the six-minute walk test. Participants were asked to walk as far as possible around two cones, placed 10m apart in a straight corridor, in 6 min. The total distance walked (in metres) in 6 min was recorded. The six-minute walk test is reliable and responsive to change in older people with long-term conditions[32]. The minimal clinically important difference (MCID) for the 6MWD has been calculated to be 50m[33]. Walking performance was measured in mean steps/day using a valid and reliable triaxial accelerometer (ActivPal3™, PAL Technologies Ltd., Glasgow, UK) which uses information about acceleration and thigh position to determine body posture, stepping, and cadence[4,12]. Each participant was fitted with an accelerometer on the mid-anterior thigh with a waterproof dressing. Initiation of the recording started at midnight of the day of assessment and participants were requested to wear it continuously for the following seven days. Three-dimensional acceleration data were collected over 60s epochs. Accelerometer data with at least 14-h of wear time per 24-h period and a minimum of 5 days of wear time was considered valid[34]. A minimum of 7000 steps/day is recommended for older adults to achieve health benefits[11,35]. The MCID for NC has not been defined, in its absence we have utilised the MCID for people with peripheral artery disease: 558 steps[36]. Maximum self-rated walking distance was assessed by asking "what is the maximum distance (in meters) you can walk at your usual pace on a flat surface before you have to stop?"[37]. No MCID has been defined, for the purpose of this study we set it at 250m. This was based on the MCID of the self-paced walking test which measures how far people with NC can walk for ≤ 30min before requiring a rest[38].

Clinical and demographic details: Clinical and demographic details collected included: age, body mass index (kg/m^2), sex, ethnicity, education, employment, indices of deprivation, social support, co-morbidities, smoking history, falls history. We collected the Oswestry Disability Index (ODI)[39] to assess back-pain related disability. The EuroQol five dimension, 5-level questionnaire (EQ5D-5L)[40] was used to assess quality of life. Average severity of back pain and average leg pain when resting and when walking over the last week was collected using an 11-item numerical rating scale[41].

Candidate predictor variables: Candidate predictor variables were selected by mapping measures and constructs onto the COM-B framework[27]. There is no standardised method or measurement tool to capture all the components of the COM-B. Therefore, to ensure we considered a range of potentially modifiable factors across the domains of the framework, that may be suitable to target in future rehabilitation,. we considered variables that had weak or inconclusive evidence from the previous systematic review e.g. fear of movement[20], factors associated with walking in older people e.g. balance[42,43,] and other conditions resulting in walking restriction e.g. illness perceptions in peripheral artery disease[44]. We included at least one measure for each of the six COM-B components, balancing the need for comprehensive assessment with minimising participant burden, sample size requirements, and risks of multiple testing. This approach ensured that the selected measures were both scientifically robust and feasible within the constraints of the study design.

Walking capacity (physical and psychological skills or knowledge required to perform the behaviour): Lower limb performance was measured with the Short Physical Performance Battery. This valid and reliable measure comprises three standing balance tests, gait speed over 2.44m and time to complete 5 sit-stands. A performance score between 0–12 is calculated and higher scores indicate better performance[45]. Maximum grip strength (kg) was assessed using a hand held Jamar Plus + Dynamometer[46]. Grip strength is widely used in the elderly to assess strength, lower scores are is associated with sarcopenia and frailty[46]. Participants perception that their condition is understandable, meaningful, and manageable was assessed using the coherence question from the Brief Illness Perceptions Questionnaire (B-IPQ). The BIPQ is a reliable and valid nine-item scale used to assess the cognitive and emotional representations of illness[47]. Ability to plan exercise was assessed using the action planning domain of the validated Self-Regulation questionnaire[48]. Higher scores indicated better ability to plan exercise.

Walking opportunity (social and physical environments that may enable or constrain the behaviour): Physical environment and suitability for walking was assessed using the valid and reliable self-reported physical activity-related environmental factors (ALPHA) scale[49]. A higher score indicates higher walkability. The social support and exercise survey was used to assess how much support family and friends provide to exercise[50,51]. Total scores range between −16 and 88 with higher scores indicating greater support.

Walking motivation (reflective and automatic processes driving the behaviour): Patient health questionnaire 4 (PHQ4) was used as an ultra-brief screening tool for depression and anxiety[52]. It requires participants to rate how often they have been bothered by thoughts and feelings on 4-items on a four-point Likert-type scale. Higher scores indicate greater severity. Beliefs about consequences, timeline, personal control, treatment control, identity, emotional representation, and illness concern were assessed with the B-IPQ[47]. Fear of falling was assessed using the valid and reliable Short Falls Efficacy Scale International (SFESI)[53]. A higher score indicates greater fear of falling. Fear of movement was assessed with the valid and reliable Tampa Scale of Kinesiophobia[54,55]. The total score of the scale range from 17–68. A higher score indicates greater fear of movement. Ability to monitor and regulate exercise behaviour was assessed using the action control domain of the Self-Regulation questionnaire[48]. Higher scores indicated better ability to regulate behaviour.

Analysis

Descriptive statistics were used to summarise participants' demographic and clinical characteristics. Means and standard deviations, or medians and interquartile ranges (IQR) for continuous variables are reported depending on skew; and frequencies and percentages for categorical variables. To compare walking capacity and performance and change in clinical characteristics pre- to post-operatively, we conducted two-tailed, paired t-tests. To determine factors associated with post-surgical walking capacity and performance, we assessed bivariate correlations and estimated multivariable linear mixed-effects regression coefficients, adjusted for key putative confounders. Regression models were estimated separately for each candidate predictor variable with walking measures at each post-surgery assessment as the outcome. A random-intercept accounted for the repeated measures nature of the data and a predictor-by-time interaction term was estimated to allow the estimation of different effects at each assessment. Models, controlled for age, gender, ethnicity, obesity, smoking and baseline score of the outcome. The maximum likelihood estimation approach allowed for the inclusion of all participants with at least one post-surgery assessment of the outcome, under the *missing at random* assumption. Predictor variables were the baseline scores of the COM-B domain factors described above plus the change from baseline to 12-weeks where this was recorded. To aid comparisons across predictor variables, standardised regression coefficients with 95% confidence intervals were estimated and presented in a forest plot. Given the exploratory nature of the study, statistical significance was set at 0.05 and no adjustment for multiple testing was made. Magnitude of regression coefficients was defined as strong ≥ 0.5; moderate ≥ 0.3; and weak ≥ 0.1[56]. This approach combined with the consideration of the distribution of the candidate predictor, to ensure they do not have floor/ceiling effects and are thus potentially modifiable, is recommended for selecting target variables for behavioural interventions[57]. All statistical analyses were conducted using STATA version 17 (Stata Corp, College Station Texas, USA).

Results

Between April 2021 and July 2022, 288 patients were screened for eligibility. Of these, 221 met the inclusion criteria and 134 consented and underwent baseline assessment. Mean (SD) age was 70.2 (8.6) years, and 69 (51.5%) were female. As 17 people did not have surgery, in total 117 participants were recruited (Fig. 1, study flow). This was slightly below the target of 122, but as attrition was lower than anticipated, power remained at 80%. In total, 109 participants (93%) completed 12-week follow-up assessments, although objective measures were only collected on 97 (84%) participants. This was due to concerns about attending hospitals due to the perceived risk of COVID-19 infection or transport issues.

Table 1 presents baseline demographics and clinical details on all participants. The most common surgical procedure was laminectomy (n = 91), and most participants had one level operated on (n = 80). Median post-operative length of stay was one night (IQR 1 to 2; range 0–31). Thirteen (11%) had a hospital recorded complication (post-operative haematoma and required further surgery = 3, dural tear = 2; wound ooze = 2; acute urinary retention = 1, urinary infection = 1, delirium = 1, heart failure one-month post-operative = 1, COVID-19 = 1, hospital acquired pneumonia = 1). Twenty three (20%) received peri-operative (inpatient) physiotherapy and 43 (37%) received post-operative physiotherapy following discharge.

Change in walking measures after surgery

Table 2 and Fig. 2 illustrate the walking capacity and performance measures at baseline and follow-up. Changes in disability, quality of life and pain measures are presented in Supplementary Material 1. All walking measures demonstrated a statistically significant change post-operatively: mean increase in 6MWD was 61.38m (± 72.57) and daily step count 582.31 (± 1720.3), and median increase in maximum walking distance was 400m (IQR 15 to 1200) (all $p < 0.001$). Percentage achieving MCID were 49% for 6MWD; 58% for maximum walking distance; and 40% for daily step count. There was no statistically significant difference between the number of patients walking ≥ 7000 steps/day at baseline and follow-up assessment ($p = 0.250$).

Factors associated with change in walking

The pre-operative walking score for each of the walking measures explained 67% of the variance of the residualised change score in walking improvement for the 6MWD ($R^2 = 0.674$) and 75% of the variance in step count ($R^2 = 0.753$) and 38% of the variance of the self-rated maximum walking distance ($R^2 = 0.380$) (Supplementary Material 2).

The pre-operative and post-operative factors associated with pre-operative walking and change in post-operative walking are illustrated in the forest plots (Fig. 3) and Tables 3, 4, 5, 6. The unadjusted correlations between the candidate predictor variables and walking measures are reported in Supplementary Material 3.

Walking capability

In the analysis of the pre-operative capability factors, all the pre-operative capability variables were significantly associated cross sectionally with at least one of the pre-operative walking measures ($p < 0.05$, Table 3). Specifically, all variables were significantly associated with pre-operative 6MWD and number of falls, ability to plan exercise, and lower limb physical performance were significantly associated with all three walking measures. Lower limb physical performance had the strongest cross-sectional association with pre-operative walking measures, with a moderate to strong association. Pre-operative ability to plan exercise, and pre-operative grip strength were positively but weakly associated with all pre-operative walking measures. Pre-operative coherence and history of a fall had weak negative association with pre-operative 6MWD.

None of the pre-operative variables were significantly longitudinally associated with change in walking at 12-weeks post-operative (Table 3). Of the 6-weeks post-operative capability measures, only history of a fall post-operatively was statistically significant associated with change in walking at 12-weeks although the effect size was weak (Table 6).

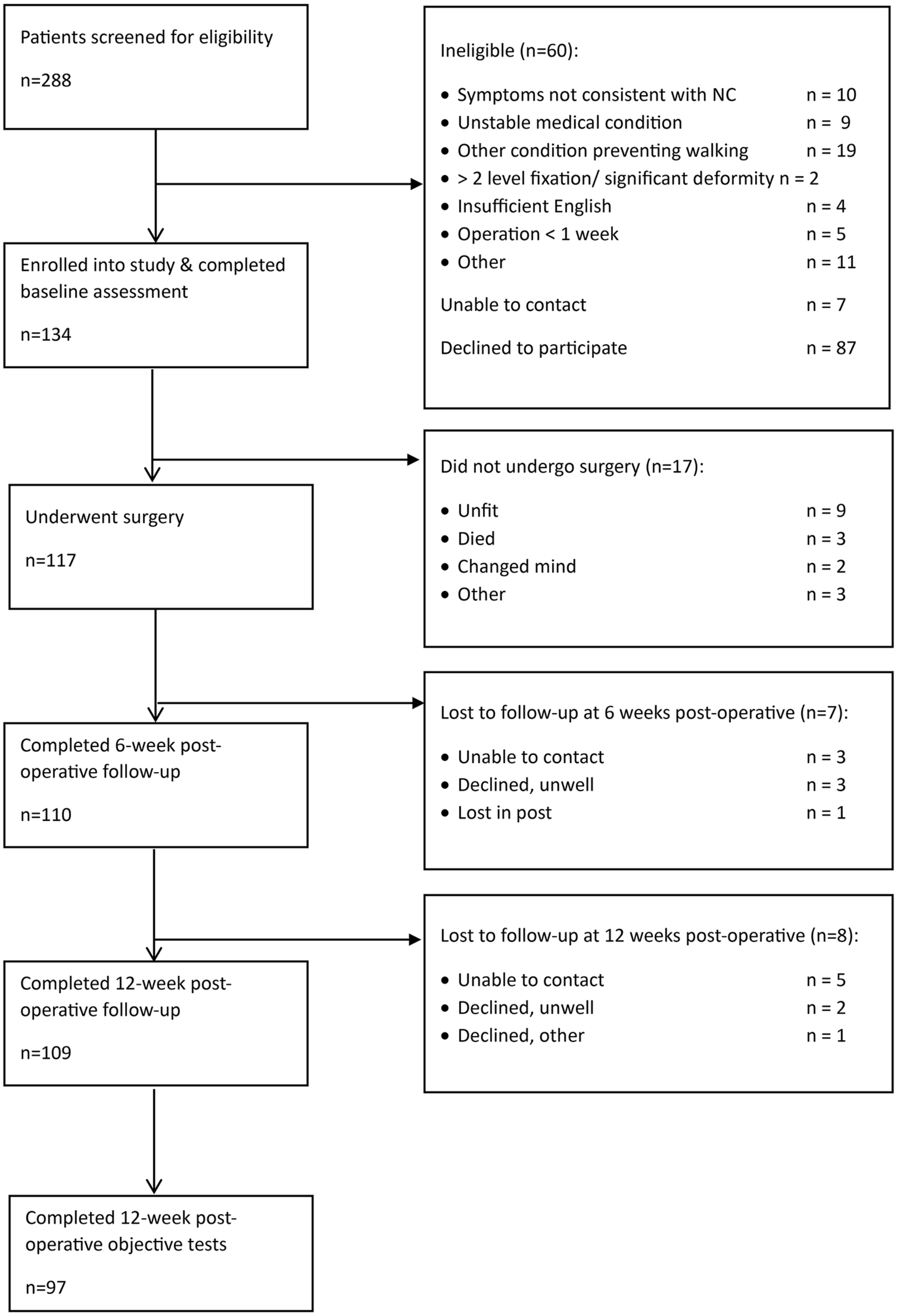

Fig. 1. Demonstrating flow of participants through the study.

Walking opportunity

In the analysis of the pre-operative opportunity factors, both social support to exercise, and physical environment suitability for walking, were significantly, yet weakly, positively associated cross sectionally with the pre-operative 6MWD but not the pre-operative step count or maximum walking distance (Table 4).

Neither of the pre-operative or post-operative opportunity variables were significantly longitudinally associated with change in walking at 12-weeks post-operative (Tables 4 and 6).

Walking motivation

In the analysis of the pre-operative motivation variables, the ability to self-regulate exercise, beliefs about the consequences of the condition, identity, fear of falling, and fear of movement were significantly associated cross-sectionally with all three walking measures. Fear of falling had a moderate-strong, negative cross-sectional

Demographic variable		Mean ± SD or N (%)		
		All participants	Did not receive surgery	Received surgery
		N = 134	N = 16	N = 118
Age (years)		70.2 (8.6)	72.1 (8.2)	69.9 (8.6)
Sex	Female, N (%)	69 (51.5%)	6 (37.5%)	63 (53.4%)
	Male, N (%)	65 (48.5%)	10 (62.5%)	55 (46.6%)
Body mass index		29.3 (5.2)	30.4 (8.3)	29.2 (4.6)
Education	Up to end secondary school N (%)	89 (66.4%)	12 (75.1%)	77 (65.2%)
	High professional or university N (%)	45 (33.6%)	4 (25.0%)	41 (34.7%)
Employment status	Working, N (%)	29 (21.6%)	1 (6.3%)	28 (23.7%)
	Retired, N (%)	95 (70.9%)	14 (87.5%)	81 (68.6%)
Ethnicity	White British, N (%)	97 (72.4%)	11 (68.8%)	86 (72.9%)
	White other, N (%)	8 (6.0%)	1 (6.3%)	7 (5.9%)
	Asian, N (%)	8 (6.0%)	3 (18.8%)	5 (4.2%)
	Black, N (%)	14 (10.4%)	1 (6.3%)	13 (11.0%)
	Mixed, N (%)	4 (3.0%)	0 (0.0%)	4 (3.4%)
	Other, N (%)	3 (2.2%)	0 (0.0%)	3 (2.5%)
Marital or civil status	In a relationship, N (%)	79 (59.0%)	5 (31.3%)	74 (62.7%)
Deprivation indices		6.0 (4.0–9.0)	4.0 (2.5–8.5)	6.0 (4.0–9.0)
Smoking history	Current smoker, N (%)	19 (14.2%)	1 (6.3%)	18 (15.3%)
	Previous smoker, N (%)	64 (47.8%)	6 (37.5%)	58 (49.2%)
Cumulative comorbidity score		8.0 (4.0)	10.9 (4.4)	7.6 (3.7)
PHQ4 score		2.1 (2.8)	2.6 (3.6)	2.0 (2.7)
Duration NC symptoms	months	48.0 (44.6)	60.6 (60.3)	46.2 (42.0)
Prior lumbar surgery		27 (20.1%)	4 (25.0%)	23 (19.5%)
Surgical procedure	Laminectomy			91
	Laminectomy & discectomy			9
	Laminectomy & excision synovial cyst			3
	Laminectomy & foraminotomy			7
	Laminotomy			6
	TLIF or XLIF			2
	No. of levels decompressed			1.4 (0.6)
Leg pain at rest	NRS	4.2 (2.9)	2.4 (2.1)	4.4 (2.9)
Leg pain when walking:	NRS	7.2 (2.4)	6.3 (2.5)	7.3 (2.3)
Back pain at rest	NRS	4.3 (2.8)	3.6 (2.6)	4.4 (2.9)
Back pain when walking	NRS	6.9 (2.8)	6.8 (3.1)	6.9 (2.8)
Disability	ODI	44.1 (15.4)	46.5 (14.8)	43.7 (15.5)
Fallen within last year		76 (57.1%)	12 (75.0%)	64 (54.7%)
No. of falls in last year		1.0 (0.0–4.0)	2.5 (0.5–5.0)	1.0 (0.0–3.0)

Table 1. Clinical and demographic characteristics of study participants. PHQ4: patient heath questionnaire; NC: neurogenic claudication; NRS: numerical rating scale; ODI: Oswestry Disability Index.

Variable	Baseline mean (± SD)	12 weeks post-operative mean (± SD)	Mean difference (± SD)	95% confidence intervals of mean difference	P value	Percentage achieving MCID
6MWD (m)	238.46 (112.70)	299.93 (104.12)	61.38 (72.57)	46.76, 76.0	< .001	49%
Log of maximum walking distance†	4.71 (1.71)	6.08 (1.85)	1.37 (1.82)	2.75, 1.74	< .001	58%
Daily step count	4878.97 (2502.30)	5461.28 (3042.50)	582.31 (1720.30)	219.93, 944.70	< .001	40.4%
Walking ≥ 7000 steps/day	19.38%	24.73%	5.35%	n/a	.250	n/a

Table 2. Walking measures at baseline and follow-up. Table demonstrating the walking capability and performance measures at baseline and 12-week follow up. 6MWD: six-minute walk distance; MCID: minimal clinically important difference. †log of data reported as data were skewed.

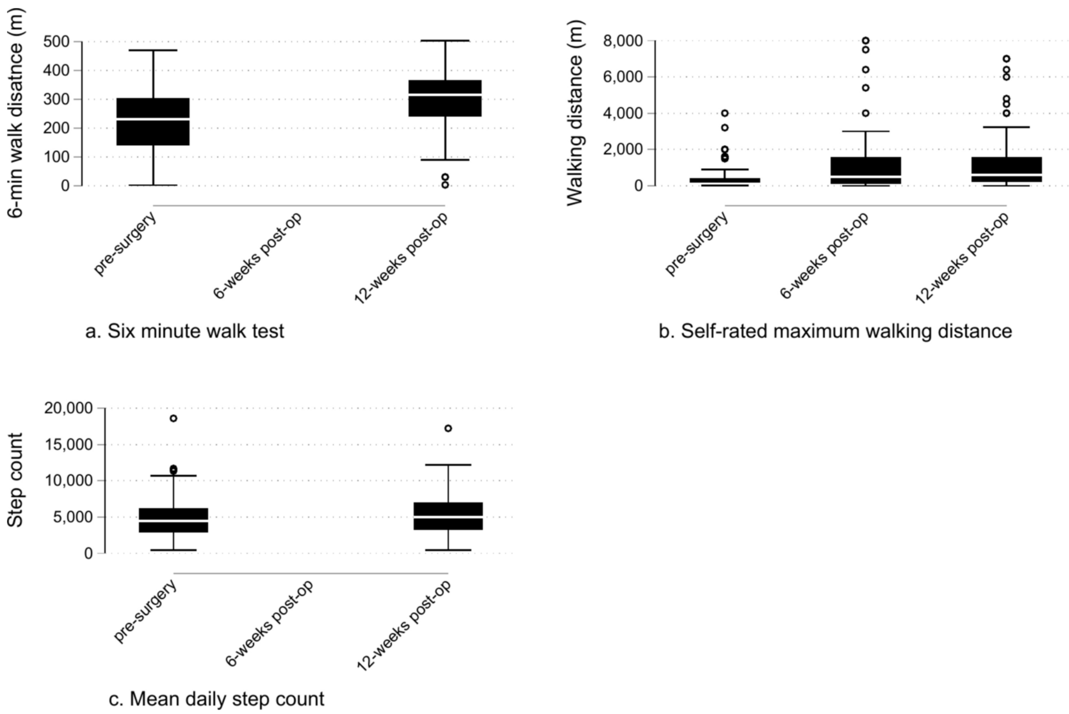

Fig. 2. Boxplots illustrating the walking capacity and performance measures at baseline and follow-up.

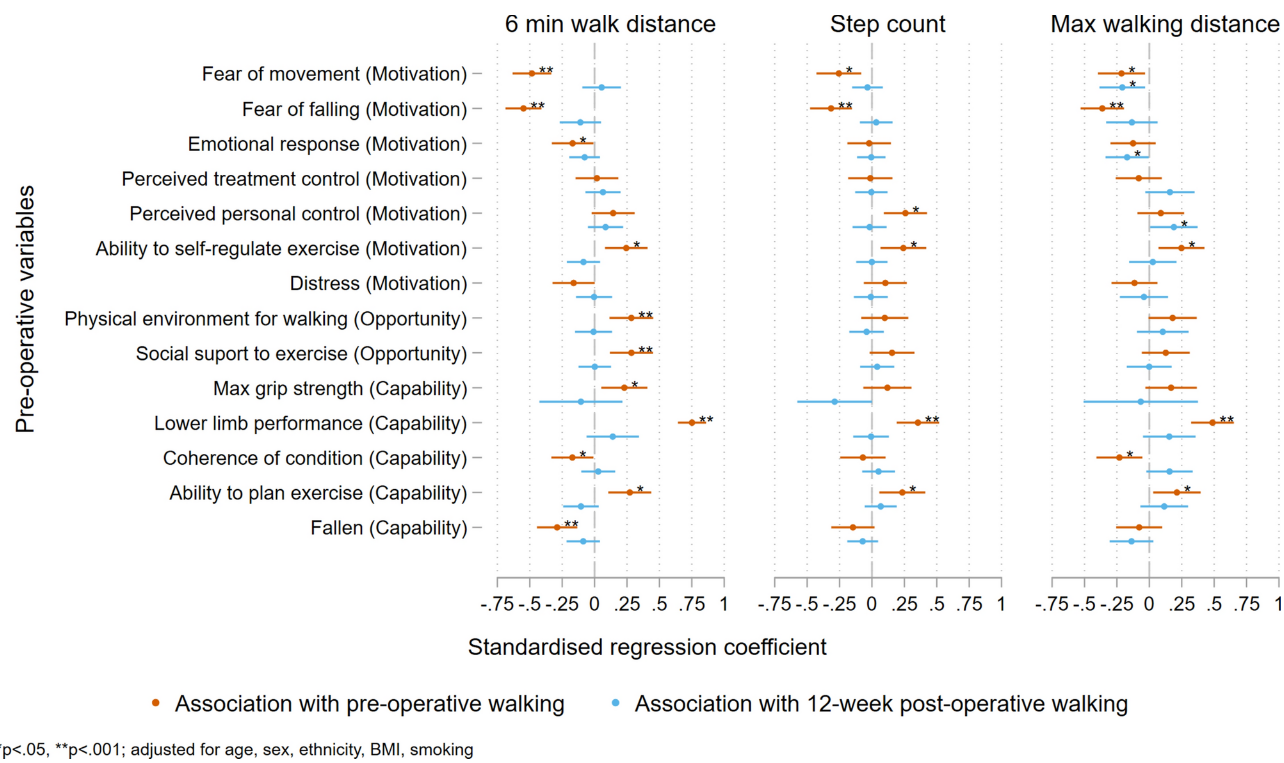

Fig. 3. A forest plot illustrating the associations between the pre-operative factors with pre-operative walking and change in post-operative walking at 12-weeks post-operative.

Capability candidate pre-operative predictor variable	Time point	6 min walk distance						Step count						Max walking distance					
		b	se	z	p	95% CI LL	95% CI UL	b	se	z	p	95% CI LL	95% CI UL	b	se	z	p	95% CI LL	95% CI UL
Fallen in last year	Pre-op	−0.289	0.079	−3.644	0.000**	−0.445	−0.134	−0.147	0.085	−1.723	0.085	−0.313	0.020	−0.078	0.091	−0.861	0.389	−0.255	0.100
Fallen in last year	12-weeks	−0.087	0.066	−1.330	0.183	−0.216	0.041	−0.071	0.061	−1.178	0.239	−0.190	0.047	−0.137	0.086	−1.596	0.111	−0.306	0.031
No. of falls	Pre-op	−0.314	0.079	−3.984	0.000**	−0.469	−0.160	−0.167	0.083	−2.018	0.044*	−0.328	−0.005	−0.200	0.088	−2.277	0.023*	−0.372	−0.028
No. of falls	12-weeks	−0.234	0.127	−1.845	0.065	−0.482	0.014	0.008	0.108	0.076	0.939	−0.203	0.219	−0.153	0.173	−0.885	0.376	−0.493	0.186
Ability to plan exercise	Pre-op	0.272	0.085	3.210	0.001**	0.106	0.437	0.234	0.090	2.588	0.010*	0.057	0.411	0.213	0.093	2.279	0.023*	0.030	0.396
Ability to plan exercise	12-weeks	−0.105	0.070	−1.502	0.133	−0.242	0.032	0.068	0.063	1.072	0.284	−0.056	0.191	0.115	0.094	1.224	0.221	−0.069	0.299
Coherence of condition	Pre-op	−0.171	0.083	−2.067	0.039*	−0.334	−0.009	−0.070	0.089	−0.783	0.434	−0.245	0.105	−0.231	0.090	−2.552	0.011*	−0.408	−0.054
Coherence of condition	12-weeks	0.028	0.067	0.420	0.674	−0.103	0.159	0.051	0.064	0.790	0.430	−0.075	0.177	0.156	0.091	1.708	0.088	−0.023	0.335
Lower limb performance: SPPB	Pre-op	0.752	0.055	13.565	0.000**	0.643	0.860	0.354	0.083	4.245	0.000**	0.191	0.518	0.487	0.084	5.790	0.000**	0.322	0.652
Lower limb performance: SPPB	12-weeks	0.140	0.103	1.360	0.174	−0.062	0.342	−0.007	0.070	−0.099	0.921	−0.144	0.131	0.154	0.103	1.489	0.137	−0.049	0.357
Max grip strength	Pre-op	0.229	0.091	2.527	0.011*	0.051	0.407	0.119	0.095	1.259	0.208	−0.067	0.305	0.168	0.101	1.658	0.097	−0.031	0.366
Max grip strength	12-weeks	−0.105	0.163	−0.645	0.519	−0.426	0.215	−0.288	0.147	−1.956	0.051	−0.576	0.001	−0.066	0.225	−0.293	0.769	−0.508	0.375

Table 3. Regression coefficients for pre-operative capability variables with pre and post-operative walking measures. Regression coefficients for pre-operative variables with pre and post-operative walking measures. Estimates are from separate mixed-effects regression models, adjusting for age, sex, ethnicity, BMI, smoking and pre-operative scores. Key: SPPB: short physical performance battery; 12-weeks: 12-weeks post-operative walking; LL: lower limit; UL: upper limit *p ≤ .05; **p ≤ 001.

Opportunity candidate pre-operative predictor variable	Time point	6 min walk distance						Step count						Max walking distance					
		b	se	z	p	95% CI LL	95% CI UL	b	se	z	p	95% CI LL	95% CI UL	b	se	z	p	95% CI LL	95% CI UL
Social support for exercise	Pre-op	0.284	0.085	3.349	0.001**	0.118	0.451	0.155	0.088	1.755	0.079	−0.018	0.328	0.127	0.094	1.347	0.178	−0.058	0.312
Social support for exercise	12-weeks	0.001	0.064	0.020	0.984	−0.124	0.127	0.040	0.067	0.602	0.548	−0.091	0.172	−0.001	0.089	−0.009	0.993	−0.174	0.173
Physical environment suitability for walking	Pre-op	0.284	0.086	3.295	0.001**	0.115	0.452	0.099	0.093	1.065	0.287	−0.083	0.280	0.180	0.095	1.891	0.059	−0.007	0.366
Physical environment suitability for walking	12-weeks	−0.008	0.073	−0.109	0.913	−0.151	0.135	−0.042	0.068	−0.613	0.540	−0.174	0.091	0.104	0.102	1.020	0.308	−0.096	0.303

Table 4. Regression coefficients for pre-operative opportunity variables with pre and post-operative walking measures. Regression coefficients for pre-operative variables with pre and post-operative walking measures. Estimates are from separate mixed-effects regression models, adjusting for age, sex, ethnicity, BMI, smoking and pre-operative scores. Key: 12-weeks: 12-weeks post-operative walking; LL: lower limit; UL: upper limit $^*p \leq .05$; $^{**}p \leq 001$.

association with pre-operative walking measures. Pre-operative fear of movement, and consequences had moderate negative associations with pre-operative walking measures. Pre-operative identity (symptom severity) and ability to self-regulate exercise had weak negative associations with pre-operative walking measures. Pre-operative emotional response had a weak negative association with pre-operative 6MWD, and perceived personal control had a weak positive association with pre-operative step count. Longitudinally, pre-operative perceived personal control, emotional response and fear of movement were significantly, albeit weakly, associated with change in maximum walking distance at 12-weeks post-operatively (Table 5).

Of the post-operative motivation measures collected 6-weeks post-operatively consequences, identity, illness concern, emotional response, and fear of falling were significantly associated with changes in all walking measures at 12-weeks post-operatively (<0.05, Table 6). Distress and fear of movement were significantly associated with change in 6MWD and maximum walking distance. The strengths of the associations were moderate-weak for fear of movement and fear of falling, and weak for the remaining variables.

Discussion

This study aimed to identify the salient, modifiable physical and psychosocial factors associated with walking in people undergoing surgery for NC. There were statistically significant changes in walking outcomes after surgery, but these changes were not clinically meaningful for many participants. In addition, there was no statistically significant change in the number of people walking at least the recommended 7000 steps/day for older adults[35]. This means that their health may be at risk of the consequences of inactivity. Consistent with previous studies, the strongest predictor of change in walking after surgery was pre-operative walking[20], due to the strength of the association, there was little scope for the other candidate pre-operative variables to be statistically important. Therefore, scrutiny of variables associated with pre-operative walking was required. Biopsychosocial factors from all domains of the COM-B framework were associated with pre-operative walking but only a few pre-operative measures, from the motivation domain, were longitudinally associated with change in post-operative walking.

The pre-operative factors associated with change in walking at 12-weeks post-operatively were associated with self-reported maximum walking distance but not objective walking measures. This discrepancy may be because maximum walking distance assesses an individuals' perception of their walking capacity, and this aligns more closely with the motivation domain of the COM-B model. It may also be due to the known discordance between subjective and objective measures of physical activity[58]. While motivation is theorised as the central mediator in COM-B, our study identified associations between these factors, but they do not necessarily imply causation.

A greater number of candidate predictor variables collected at 6-weeks post-operatively were longitudinally associated with changes in walking at 12-weeks compared to those collected pre-operatively. Additionally, factors were associated with all walking measures. Since most healing and recovery occur within the first 6–12 weeks post-surgery[59,60], these findings likely reflect the early effects of surgery, as improvements and differences in outcomes between individuals with good and poor recovery become apparent. Thus, early post-operative variables are crucial for understanding post-operative changes, alongside pre-operative factors.

Fear of falling pre-operatively and at 6-weeks post-operatively was associated with pre-operative walking capacity and change in walking respectively. 57% of participants reported a fall within the last year, this is approximately twice the prevalence of community dwelling older adults[61] and higher than a non-surgical cohort of older people with NC where prevalence of falling was found to 40%[1]. As falls are a leading cause of injury related deaths in older people, in addition to being associated with walking, balance and fear of falling is an important area for rehabilitation for patients prior and after lumbar surgery. Additionally, physical performance tests (grip strength and lower limb physical performance (individual items and composite score), physical capability) were associated cross-sectionally with pre-operative and post-operative walking but not with change in walking post-operatively. Our findings are consistent with previous studies of lumbar surgical patients[62,63] and thus suggest that physical capability needs to be targeted with rehabilitation pre-operatively to maximise pre-operative walking.

Beliefs regarding the consequences of pain can result in fear of movement and fear-avoidance behaviours and ultimately less treatment benefit[64]. Pre-operative fear of movement has been found to be associated with reduced quality of life and increased pain and disability 6–12 months after lumbar disc surgery[65,66] and 2 years after lumbar surgery for mixed indications[67]. High fear of movement 6-weeks after lumbar surgery has been found to have a small mediating effect on step count 12-months after lumbar laminectomy[68]. Our findings which show that pre-operative fear of movement is associated with pre-operative walking, and that post-operative fear of movement to be associated with less improvement in post-operative walking are consistent with the previous studies. Therefore, our study adds to the growing body of evidence that fear of movement needs to be addressed in patients undergoing surgery for NC to optimise surgical outcomes.

Further beliefs and cognitions were assessed by the Brief Illness Perception Questionnaire[47], with most of the constructs associated with walking pre-operatively cross-sectionally, and 6-week post-operative measures longitudinally, albeit weakly. This questionnaire is based on the self-regulatory model by Leventhal, which proposes that illness representations influence coping behaviours through a continuous appraisal loop[69]. There is consistent evidence that illness representations are correlated with health and treatment outcomes, including low back pain, although have not been explicitly studied in lumbar surgery[70]. Thus, by identifying pertinent beliefs we may understand how people undergoing surgery for NC perceive their condition and treatment. This in turn may help explain adopted coping mechanisms, treatment responses and outcome to surgery, and should be explored and addressed with people undergoing surgery for NC.

The results of this study have important clinical implications for pre-operative and postoperative care. The findings can be used for risk stratification and to guide rehabilitation. Where previous interventions have investigated prehabilitation *or* post-operative rehabilitation[71–74] we propose that patients require rehabilitation

Motivation candidate pre-operative predictor variable	Time point	6 min walk distance						Step count						Max walking distance					
		b	se	z	p	95% CI LL	95% CI UL	b	se	z	p	95% CI LL	95% CI UL	b	se	z	p	95% CI LL	95% CI UL
Distress	Pre-op	−0.162	0.083	−1.944	0.052	−0.325	0.001	0.103	0.085	1.222	0.222	−0.062	0.269	−0.115	0.090	−1.268	0.205	−0.292	0.063
Distress	12-weeks	−0.004	0.071	−0.058	0.953	−0.144	0.135	−0.009	0.067	−0.133	0.894	−0.140	0.122	−0.041	0.095	−0.437	0.662	−0.227	0.144
Ability to self-regulate exercise	Pre-op	0.244	0.084	2.921	0.004*	0.080	0.408	0.242	0.090	2.689	0.007*	0.066	0.419	0.248	0.090	2.741	0.006*	0.071	0.425
Ability to self-regulate exercise	12-weeks	−0.086	0.065	−1.308	0.191	−0.214	0.043	−0.001	0.062	−0.014	0.989	−0.122	0.120	0.027	0.093	0.290	0.772	−0.156	0.210
Consequences of condition	Pre-op	−0.358	0.079	−4.498	0.000**	−0.513	−0.202	−0.304	0.084	−3.603	0.000**	−0.469	−0.138	−0.411	0.085	−4.857	0.000**	−0.577	−0.245
Consequences of condition	12-weeks	0.104	0.070	1.487	0.137	−0.033	0.242	0.044	0.065	0.683	0.494	−0.083	0.172	0.084	0.095	0.891	0.373	−0.101	0.270
Timeline beliefs	Pre-op	−0.161	0.087	−1.845	0.065	−0.331	0.010	−0.087	0.090	−0.964	0.335	−0.264	0.090	0.002	0.097	0.019	0.985	−0.188	0.192
Timeline beliefs	12-weeks	0.012	0.065	0.191	0.848	−0.115	0.140	0.041	0.060	0.684	0.494	−0.076	0.158	−0.073	0.091	−0.796	0.426	−0.252	0.106
Perceived personal control	Pre-op	0.143	0.085	1.692	0.091	−0.023	0.309	0.258	0.085	3.036	0.002*	0.091	0.425	0.088	0.092	0.962	0.336	−0.092	0.269
Perceived personal control	12-weeks	0.084	0.069	1.218	0.223	−0.051	0.220	−0.018	0.067	−0.268	0.788	−0.149	0.113	0.189	0.093	2.028	0.043*	0.006	0.372
Perceived treatment control	Pre-op	0.018	0.084	0.216	0.829	−0.147	0.183	−0.013	0.087	−0.146	0.884	−0.184	0.158	−0.082	0.091	−0.899	0.369	−0.259	0.096
Perceived treatment control	12-weeks	0.065	0.069	0.937	0.349	−0.071	0.200	−0.005	0.064	−0.075	0.941	−0.130	0.120	0.159	0.097	1.638	0.101	−0.031	0.349
Identity (symptom severity)	Pre-op	−0.272	0.080	−3.424	0.001**	−0.428	−0.116	−0.214	0.084	−2.543	0.011*	−0.378	−0.049	−0.297	0.086	−3.444	0.001**	−0.465	−0.128
Identity (symptom severity)	12-weeks	0.095	0.061	1.557	0.120	−0.025	0.216	0.050	0.057	0.869	0.385	−0.062	0.161	−0.048	0.089	−0.541	0.589	−0.223	0.126
Illness concern	Pre-op	−0.075	0.083	−0.903	0.366	−0.237	0.088	−0.063	0.084	−0.752	0.452	−0.228	0.102	−0.047	0.089	−0.524	0.600	−0.222	0.129
Illness concern	12-weeks	0.097	0.056	1.712	0.087	−0.014	0.207	0.007	0.052	0.126	0.900	−0.096	0.109	−0.060	0.081	−0.740	0.460	−0.219	0.099
Emotional response	Pre-op	−0.170	0.082	−2.074	0.038*	−0.330	−0.009	−0.022	0.086	−0.253	0.800	−0.190	0.146	−0.125	0.089	−1.408	0.159	−0.300	0.049
Emotional response	12-weeks	−0.077	0.060	−1.269	0.204	−0.195	0.042	−0.005	0.056	−0.094	0.925	−0.115	0.104	−0.171	0.085	−2.014	0.044*	−0.338	−0.005
Fear of falling	Pre-op	−0.549	0.071	−7.747	0.000**	−0.687	−0.410	−0.315	0.082	−3.829	0.000**	−0.477	−0.154	−0.363	0.086	−4.243	0.000**	−0.530	−0.195
Fear of falling	12-weeks	−0.110	0.081	−1.351	0.177	−0.269	0.049	0.033	0.064	0.511	0.609	−0.093	0.159	−0.134	0.101	−1.327	0.184	−0.333	0.064
Fear of movement	Pre-op	−0.483	0.076	−6.345	0.000**	−0.633	−0.334	−0.256	0.088	−2.900	0.004*	−0.428	−0.083	−0.215	0.093	−2.312	0.021*	−0.396	−0.033
Fear of movement	12-weeks	0.055	0.076	0.718	0.473	−0.094	0.203	−0.035	0.061	−0.571	0.568	−0.153	0.084	−0.208	0.090	−2.322	0.020*	−0.384	−0.032

Table 5. Regression coefficients for pre-operative motivation variables with pre and post-operative walking measures. Regression coefficients for pre-operative variables with pre and post-operative walking measures. Estimates are from separate mixed-effects regression models, adjusting for age, sex, ethnicity, BMI, smoking and pre-operative scores. Key: 12-weeks: 12-weeks post-operative walking; LL: lower limit; UL: upper limit *p ≤ .05; **p ≤ 001.

Post-operative candidate predictor variable	6 min walk distance						Step count						Max walking distance					
	b	se	z	p	95% CI LL	95% CI UL	b	se	z	p	95% CI LL	95% CI UL	b	se	z	p	95% CI LL	95% CI UL
Walking capability																		
Fallen in last 6 weeks	−0.140	0.065	−2.143	0.032*	−0.268	−0.012	0.023	0.061	0.378	0.705	−0.096	0.142	−0.075	0.100	−0.742	0.458	−0.271	0.122
Ability to plan exercise	−0.035	0.070	−0.495	0.621	−0.172	0.102	0.012	0.067	0.179	0.858	−0.120	0.144	−0.029	0.087	−0.333	0.739	−0.199	0.141
Coherence of condition	0.088	0.072	1.211	0.226	−0.054	0.230	0.031	0.069	0.457	0.647	−0.103	0.166	0.057	0.097	0.584	0.559	−0.133	0.246
Walking opportunity																		
Social support to exercise	0.050	0.080	0.619	0.536	−0.108	0.207	0.101	0.089	1.131	0.258	−0.074	0.276	0.164	0.121	1.356	0.175	−0.073	0.401
Walking motivation																		
Distress	−0.252	0.063	−4.020	0.000**	−0.375	−0.129	−0.084	0.065	−1.285	0.199	−0.212	0.044	−0.270	0.092	−2.944	0.003*	−0.449	−0.090
Ability to self-regulate exercise	−0.014	0.075	−0.186	0.852	−0.160	0.132	0.018	0.068	0.261	0.794	−0.116	0.152	0.062	0.096	0.641	0.522	−0.127	0.250
Consequences of condition	−0.133	0.062	−2.162	0.031*	−0.254	−0.012	−0.155	0.056	−2.765	0.006*	−0.265	−0.045	−0.233	0.086	−2.712	0.007*	−0.402	−0.065
Timeline beliefs	−0.192	0.069	−2.789	0.005*	−0.326	−0.057	−0.112	0.066	−1.694	0.090	−0.242	0.018	−0.153	0.099	−1.548	0.122	−0.346	0.041
Perceived personal control	0.045	0.068	0.672	0.501	−0.087	0.178	−0.013	0.062	−0.213	0.831	−0.134	0.108	0.038	0.096	0.394	0.693	−0.151	0.227
Perceived treatment control	0.146	0.067	2.179	0.029*	0.015	0.278	0.041	0.066	0.617	0.537	−0.088	0.169	0.178	0.092	1.933	0.053	−0.002	0.358
Identity (Symptom severity)	−0.243	0.061	−4.000	0.000**	−0.362	−0.124	−0.197	0.058	−3.399	0.001**	−0.310	−0.083	−0.232	0.087	−2.667	0.008*	−0.402	−0.061
Illness concern	−0.227	0.064	−3.576	0.000**	−0.352	−0.103	−0.142	0.061	−2.313	0.021*	−0.262	−0.022	−0.270	0.086	−3.130	0.002*	−0.439	−0.101
Emotional response	−0.241	0.074	−3.246	0.001**	−0.386	−0.095	−0.243	0.067	−3.618	0.000**	−0.375	−0.111	−0.220	0.098	−2.234	0.025*	−0.413	−0.027
Fear of falling	−0.178	0.079	−2.252	0.024*	−0.333	−0.023	−0.191	0.073	−2.639	0.008*	−0.333	−0.049	−0.354	0.112	−3.156	0.002*	−0.573	−0.134
Fear of movement	−0.230	0.086	−2.679	0.007*	−0.398	−0.062	−0.123	0.077	−1.594	0.111	−0.274	0.028	−0.317	0.107	−2.961	0.003*	−0.527	−0.107

Table 6. Regression coefficients for variables collected 6-week post-surgery with change in walking at 12-weeks post-surgery. Regression coefficients for variables collected 6-weeks post-surgery with change in walking at 12-weeks post-surgery. Estimates are from separate mixed-effects regression models, adjusting for age, gender, ethnicity, BMI, smoking and baseline score. Key: LL: lower limit; UL: upper limit *p ≤ .05; **p ≤ 001.

before *and* after surgery. Prehabilitation is required to optimise patient's pre-operative walking capacity and performance, and this should be provided in combination with behaviour change strategies aiming to increase walking and psychological preparation for surgery. Evidence for prehabilitation and psychological preparation is mixed[71,72,75]. A recent meta-analysis of prehabilitation programmes for patients undergoing lumbar surgery (15 studies, predominantly for lumbar fusion surgery) suggested that there was low to very low certainty evidence that there were no additional benefits of psychoeducational interventions on post-operative physical functioning and pain[71]. Although a randomised controlled trial of 197 patients with LSS demonstrated that a 9-week multi-modal prehabilitation programme delivered with a behavioural approach, increased pre-operative walking capacity, and was associated with physical activity levels one-year post-surgery[72]. This suggest that a complex, systematically developed, multi-modal intervention, targeting the salient factors identified in this study, specifically for this surgical population, requires development.

Our results indicate that post-operative rehabilitation targeting ongoing fear of falling and movement is also required. Indeed, only a small proportion of our cohort received any form of post-operative rehabilitation. Archer et al.[74] demonstrated that in patients with high pre-operative fear of movement undergoing lumbar laminectomy, 6 weekly sessions of post-operative cognitive-behavioural-based physical therapy resulted in clinically meaningful improvements in pain, disability, and physical performance tests 6-month after surgery. This adds credibility to our recommendations and provides a promising direction for improving outcomes in people with NC.

With our results demonstrating that greater pre-operative walking and physical capacity are associated with greater improvement after surgery, it could be argued that earlier surgical intervention, before significant functional decline, might be beneficial. International guidelines for NC recommend a stepped approach to care, prioritising non-surgical treatments as the first-line approach with surgical decompression reserved for patients with persistent, severe, or debilitating leg pain[76,77]. The natural history of NC indicates that rapid progression to severe neurological deficits is uncommon, and long-term studies show that one-third to half of patients improve without surgery[78–80]. Prognostic indicators for spontaneous improvement remain unclear although, patients with very tight dural sac areas (< 0.5 cm^2) and severe symptoms are less likely to improve significantly[78–80]. Given these considerations, treatment decisions regarding whether to seek surgical opinion, should adhere to shared decision-making principles, incorporating patient preferences and clinical circumstances. Regardless of the chosen treatment pathway, healthcare professionals should emphasise walking and physical activity as essential components of care.

Strength and limitations

Strengths of this study include the use of objective and self-rated measures of walking capacity and performance which has ensured a comprehensive assessment of different walking constructs[81]. Our focused approach of only including patients with NC, reduced heterogeneity in the study population, ensuring that the potentially modifiable factors are identified in a manner maximising the chance of generalisability. To our knowledge, this is the first study within lumbar surgery to use a behaviour change framework to select a comprehensive battery of candidate predictor variables with a focus on modifiable factors and therefore the results can be used to inform rehabilitation. Due to constraints in the study design, it was not feasible to investigate an exhaustive list of candidate predictor variables, meaning some factors influencing post-operative walking may not have been identified. However, as pre-operative walking explains a substantial proportion of the change in post-operative walking, it is unlikely that other factors will substantially explain walking outcomes. Further limitations include the relatively short follow-up period of three months. However, previous studies have demonstrated that outcomes between three and 12-months post-surgery are relatively stable[59]. Not all patients were able to attend for their post-operative objective measures due to COVID-19 restrictions and some accelerometers were lost in the post resulting in some missing data however, sufficient data was collected to achieve planned statistical power. Finally, whilst we identified associations between variables and walking, we are not able to identify the causal mechanism. Future work should consider whether the same factors are causal mediators.

Conclusions

Using a comprehensive battery of biopsychosocial measures, mapped to a behaviour change framework, we aimed to identify modifiable factors associated with walking in people undergoing surgery for NC. Surgery resulted in statistically significant improvements in walking capacity and performance, however, for approximately 50% of the sample the changes were not clinically meaningful. The strongest predictor of change in walking after surgery was pre-operative walking, the greater the walking before surgery, the greater the improvement after surgery. Several physical and psychosocial factors were associated with pre-operative walking. The results indicate that prehabilitation targeting walking, balance and psychosocial factors combined with post-operative rehabilitation targeting ongoing fear of falling and movement, and unhelpful beliefs may be required to optimise surgical outcomes in patients undergoing surgery for neurogenic claudication.

Data availability

De-identified data from this study are not available in a public archive. De-identified data from this study may be made available, on reasonable request, by emailing the corresponding author.

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Declarations

Competing interests
The authors declare no competing interests.

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