European Spine Journal (2018) 27:1604–1613
https://doi.org/10.1007/s00586-018-5520-5

REVIEW

# Correlation between the Oswestry Disability Index and objective measurements of walking capacity and performance in patients with lumbar spinal stenosis: a systematic literature review

**Annette Bennedsgaard Jespersen**[1] · **Malin Eleonora av Kák Gustafsson**[2]

Received: 14 August 2017 / Revised: 31 January 2018 / Accepted: 10 February 2018 / Published online: 5 March 2018


## Abstract

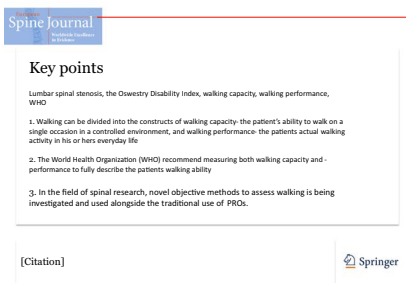
**Purpose** The Oswestry Disability Index (ODI) plays a significant role in lumbar spinal stenosis research and is used to assess patient's walking limitations. The World Health Organisation describes the constructs of walking capacity and performance and recommend measuring both to fully describe patient's walking ability. Objective methods to assess walking capacity and performance is being investigated and used alongside the traditional use of PROs. This review of the literature was made to provide an overview of relations between the ODI and outcome measures of walking capacity and performance in spinal stenosis research, and to provide a strategy for improving such measures in future research.

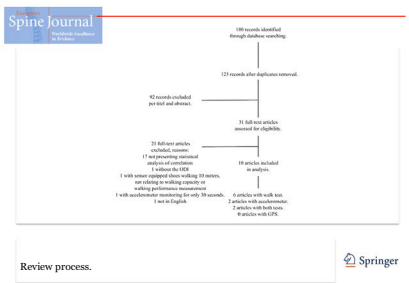
**Methods** The review was conducted according to the Prisma Statement. In February 2017, a search was performed in Pubmed, Embase and Cochrane database. Authors independently screened articles by title, abstract, and full text, and studies were included if both authors agreed. Articles with correlation analysis between the ODI, walking capacity and performance measures by accelerometer or GPS were included.

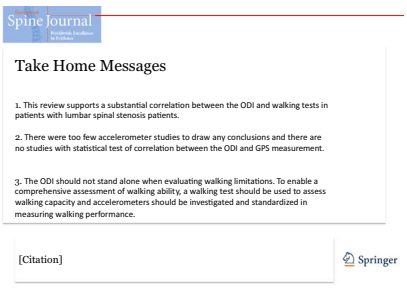
**Results** The results support a correlation between the ODI and walking capacity measures. The available studies using ODI and accelerometers were too few to reach a conclusion regarding correlation between ODI and walking performance. No articles with GPS measure were identified.

**Conclusions** The ODI should not stand alone when evaluating walking limitations in patients with lumbar spinal stenosis. To enable a comprehensive assessment of walking ability, a walking test should be used to assess walking capacity and accelerometers should be investigated and standardized in measuring walking performance.

**Graphical abstract** These slides can be retrieved under Electronic Supplementary Material.




**Keywords** Lumbar spinal stenosis · The Oswestry Disability Index · Walking capacity · Walking performance · WHO

**Electronic supplementary material** The online version of this article (https://doi.org/10.1007/s00586-018-5520-5) contains supplementary material, which is available to authorized users.

Extended author information available on the last page of the article

## Introduction

In addition to pain in the lower back and legs, limitations in walking is the primary complaint of patients suffering from lumbar spinal stenosis [1]. Not surprisingly then, much of the clinical research into lumbar stenosis is focused on such limitations in walking [2] and it follows that the appropriateness of outcome measures used to quantify walking has direct impact on the quality of the research findings [3, 4].

Walking can be divided into the constructs of walking capacity—the patient's ability to walk on a single occasion in a controlled environment, and walking performance—the patients actual walking activity in his or her everyday life [5]. The World Health Organization (WHO) describes walking performance as a construct built on a biopsychosocial model, as it is deeply linked with the patients unique social situation, psyche and environment. In other words, walking performance is not solely a measure of physical function. They recommend measuring both walking capacity and performance to fully describe the patients walking ability [6].

Walking capacity is often measured using the Self-Paced Walking Test (SPWT), which has been described as the gold standard of walking capacity measurement in patients with spinal stenosis [7]. Other walking tests used are the Motorized Treadmill Test (MTT) and Shuttle Walk Test (SWT). Both have been shown to be reproducible but to underestimate walking capacity [7–9]. These walking tests have been developed for lumbar spinal stenosis and produce objective and detailed continuous data, but are time consuming to perform. Quicker walking tests are available but have not been investigated for lumbar spinal stenosis [10–12].

Accelerometers are considered valid and reliable for measuring physical activity in older adults [13–16] and some studies have used accelerometers to monitor patients walking activity for several consecutive days, thus measuring walking performance [17–22]. There are also small scale attempts to monitor patients walking performance by GPS tracking [23–25].

Patients walking ability are also evaluated using Patient Reported Outcome measurements (PROs) [26–29]. Several scales are used for this purpose, the most common being the Oswestry Disability Index, measuring back specific function with reference to "today" [30]. It contains, among other questions about physical function, one question about walking ability, question four. The questionnaire is considered valid, responsive and reliable [31–35]. It is easy to use, economical and assesses several areas besides walking. Nevertheless, it is not specific for lumbar spinal stenosis, provides ordinal data, and gives only a crude approximation of walking disability. Being a subjective test it provides inherently uncertain data, due to psychological factors such as response shift and depression [3, 36, 37]. The ODI is an essential outcome measurement and is included in a core outcome set (COS) recommended to be reported in all clinical trials on low back pain (LOW) and non-specific low back pain [38]. When measuring a patient's walking ability with the ODI it is important to recognize that there is no consensus, whether the scale measures walking capacity, walking performance, neither of the two, or both.

In the field of spinal research, novel objective methods to assess walking is being investigated and used alongside the traditional use of PROs. There appears to be little agreement on how they should be applied and interpreted and no recommendations whether these outcome domains should be included in a COS for clinical trials or research in patients with spinal stenosis.

This review of the literature was made to provide an overview of outcome measurements of walking capacity and performance in spinal stenosis research, and to provide a strategy for improving such measures in future research. To this end the following questions are addressed (a) what is the relation of the ODI to spinal stenosis patients walking capacity and performance? and (b) what are the possibilities and benefits in the field of walking capacity and performance measurement?

## Materials and methods

### Design

This is a systematic critical literature review.

### Search

The review was conducted in accordance with the Prisma Statement [39]. The databases PudMed, Embase, and Cochrane were searched on the 2nd of February 2017. The search was performed by the authors, assisted by a research librarian, Johan Wallin, University of Southern Denmark. The search was focused strictly on spinal stenosis and the ODI combined with the three objective measures—walking tests, accelerometers and GPS. The exact search string in PubMed is provided in supplementary appendix I.

### Identifying articles

Authors independently screened all articles returned by the databases search by title and abstract. In cases where the authors reached different conclusions based on the initial screening, the article was read in full text. Articles retained

after initial screening were reviewed in full and included if both authors agreed. Articles were excluded if older than 1980, case-report, protocol, review or not in English.

The inclusion criteria were determined using the PICO system:

*Participants* Patients diagnosed with lumbar spinal stenosis (LSS).

*Intervention* Walking capacity measured by walk test in a clinical setting and walking performance measured by accelerometer or GPS (monitoring of activities of daily living and variables representing walking drawn from the accelerometer data).

*Comparison* Self-reported physical activity measured with the Oswestry Disability Index (ODI).

*Outcome* Studies performing a statistical analysis of correlation between intervention and comparison. The authors have chosen to use the cut points for interpreting correlation coefficients recommended by Munro et al. when interpreting correlation coefficients between essentially different outcome measures with different units: ± 0.1 weak to non-existent ± 0.3 moderate or typical ± 0.5 substantial [40–42].

## Definition of checklist items

Included articles were reviewed according to two checklists (A) descriptive and (B) quality. The article quality was quantified as a quality score. The quality items were defined by the authors and were considered essential for this review. No quality checklists appropriate for cross-sectional and cohort studies assessing objective outcome measurements were found, the authors therefore used the COSMIN checklist [43] and a critical appraisal tool for diagnostic studies from the University of Oxford [44], to decide on important sources of bias. Refer to Table 1 for the items of the quality checklist. Data were independently extracted by authors, reaching consensus on diverging items. The following were reviewed:

(A) Descriptive list

Study characteristics: objectives, design and setting.
Eligibility criteria
Objective measurements
Analysis
Results

(B) Quality list

Hypothesis
Appropriate study population
Measurements: valid ODI and clear description of objective measurements.
The authors defined the objective measurements as clearly described when all subheadings in the relevant descriptive list column could be filled out.
Blinding
Recording of data
Confounding
Statistical methods: non-parametric methods, appropriate for ordinal data, were considered as correct.

**Table 1** Quality checklist

| | |
|---|---|
| 1 | Were hypotheses regarding correlations formulated a priori? |
| 2 | Was diagnosis made with the help of MRI? |
| 3 | Was a valid version of the ODI stated as used? |
| 4 | Were the objective measurement(s) clearly described? |
| 5 | Was the test-assessor stated as blinded from the ODI results? |
| 6 | Were drop outs accounted for? |
| 7 | Did they consider confounding and moderating factors? |
| 8 | Was correct statistical method used to calculate the correlation between the ODI and the objective measurement? |

### Quality score

The authors decided on cutpoints for credibility as excellent (76–100%), good (51–75%), moderate (26–50%) and poor (0–25%).

# Results

## Search results

Database search yielded 180 articles, all of which were screened for eligibility and ten articles were included in the review. A flowchart of the search and the review process is provided in Fig. 1.

## Description of included studies

Six studies used walking test as the objective outcome measurement [45–50], two articles used accelerometers [51, 52] and two reported both [53, 54]. No articles with GPS measurement were identified. The included articles are summarized in supplementary appendix II.

### Population characteristics

Seven studies were from North America (Canada four [45, 46, 49, 51], three from USA [47, 53, 54]), one study from Germany [52]) and one from India [50]. Sample size ranged from 12 to 50 participants. One study had a mean age of 45.7 years [50]; the remaining had a mean age between 66 and 70 years. About half of the participants were male in

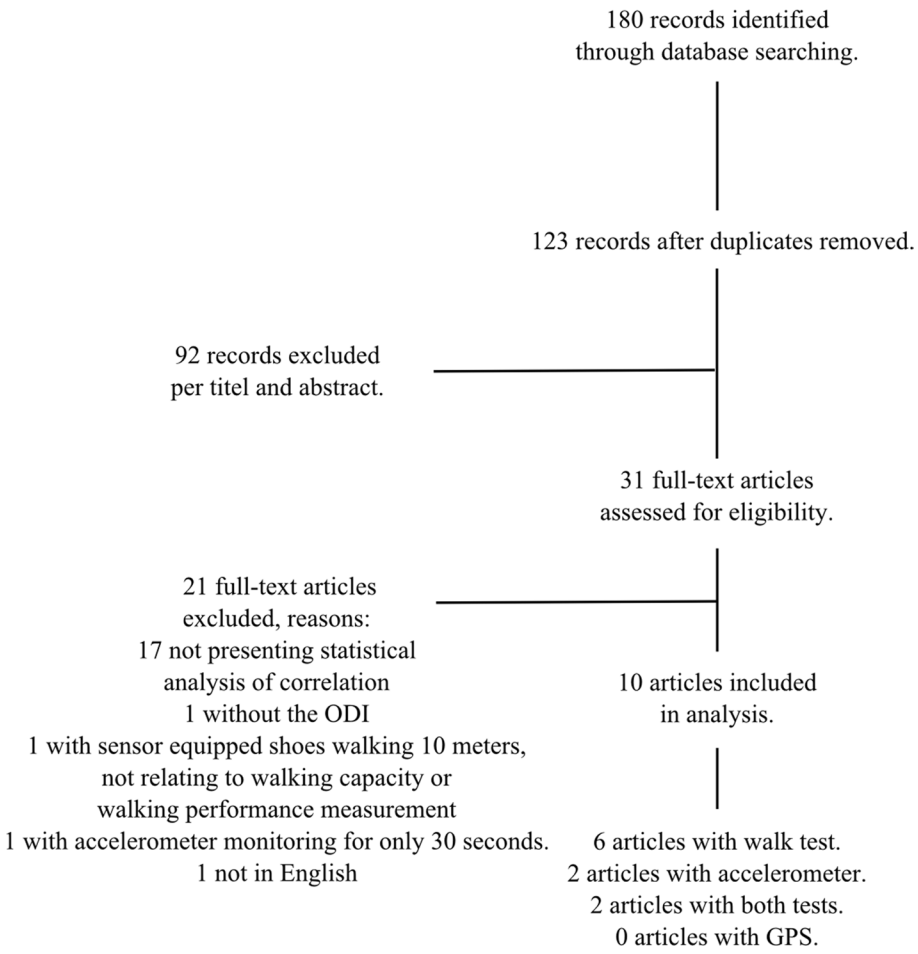



**Fig. 1** Review process

eight of the studies, the other studies had 35% [45], respectively, 75% [54] male participants.

## Outcome measurement characteristics

### ODI

Three articles did not clearly indicate which version of the ODI that was used [45, 50, 54] and one study used the revised ODI [51]. Two studies used version 1.0 [48, 49], two studies version 2.0 [46, 47] and one study a validated German version [52].

### Walking tests

Six studies performed the SPWT [45–47, 49, 53, 54] and three studies the MTT [47, 48, 50]. All SPWTs were conducted at self-selected pace, on a flat surface and discontinued when the participant were stopped by symptoms or after 30 min. One of the treadmill tests were done at desired pace [47], one at 0.5 m/s [48] and one at 2 km/h (0.56 m/s) [50]. When the MTT was discontinued were determined differently in the three studies.

### Accelerometer

Four accelerometer studies had a monitoring duration of 7 days in a community setting [51–54]. They used an Actigraph GT1M in two studies [53, 54]. The other studies used Biotrainer Pro [51] and StepWatch3 Activity Monitor [52]. All studies placed the accelerometer around the waist, except one which placed it on the ankle [52].

These four studies analyzed the raw accelerometer data using units per day, such as activity counts per day and gait cycles per day [51–54]. Three studies also performed analysis by registering continuous accelerometer activity in community setting, for example, maximum time of continuous activity per day [51, 53, 54].

### GPS

No studies were found with GPS monitoring.

## Quality assessment

Four studies used MRI to verify the diagnosis of spinal stenosis [48, 50, 53, 54]. The other six studies used CT instead

of MRI for some patients. One study described that the examiner did not influence the patient during the walk test; no other studies reported such procedures [48]. All studies considered confounders such as comorbidities and modifying factors, except a lack of information on gender in one study [51].

The most noted inadequacies related to unclear/lack of formulated hypothesis and uncertainty of blinding between the ODI results and objective measurements.

### Quality score

The quality score of each study is shown in Table 2. Five studies were classified as good [45, 48, 49, 52, 54] and five as moderate [46, 47, 50, 51, 53].

## Results of the review

A summary of the results is shown in Table 3. Three studies rated as being of good quality showed a substantial correlation between the ODI and walk tests [45, 48, 49], two of these were statistically significant and also showed a substantial statistically significant correlation between the walking distance item of the ODI and walking tests [45, 49].

One study showed substantial to moderate correlation between the ODI and walking tests, and weak to moderate correlation between multiple change scores [47]. The study was rated as being of moderate quality. Two more studies rated as being of moderate quality presented from substantial to weak, to non-existent correlation, between walking test and the ODI [46, 50].

One accelerometer study analyzing the data in units per day (acc. count/day) and continuous activity showed they had a weak to non-existent relationship with the ODI [54]. It was rated a good quality study.

A study analyzing gait cycles [52] showed a weak to non-existent correlation with the ODI, and a moderate correlation with the walking distance item of the ODI. It was rated a good quality study.

A study presented a substantial correlation between units per day (volume cal/kg/day) and the ODI, and moderate to substantial correlation between continuous activity (bout length) and the ODI. It was rated as being of moderate quality [51].

## Discussion

This review supports a substantial correlation between the ODI and walking tests in patients with lumbar spinal stenosis patients. There were too few accelerometer studies to draw any conclusions and there are no studies with statistical test of correlation between the ODI and GPS measurement.

The results support the notion that the ODI relates to walking capacity. The total sum score of the ODI correlates remarkably strong with walking tests; from a theoretic perspective, it should be limited to correlation with the walking item of the questionnaire. Arguably, diminished walking capacity could be influencing the answer to several questions asked by the ODI, or a third factor is determining both. There are several confounding factors regarding outcome measurements of walking. Aalto et al. describes a negative effect of depression, cardiovascular comorbidity, disorder influencing walking ability, and scoliosis on walking ability [55]. It is not described how and which confounders affect the results of objective walk tests.

Would the ODI then be able to replace a walking test when measuring walking capacity? We cannot recommend that the ODI stand alone when measuring walking capacity. First, the evidence presented is not wholly conclusive, and second, the ODI only describes it in coarse subjective categories, negatively impacting the specificity and reliability of research results. As Rainville et al. writes, we believe that subjective and objective outcome measurements are different but of equal importance. Subjective outcome measurements

**Table 2** Quality assessment and quality score of the included articles

| Study | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | Score (%) | Classification |
|---|---|---|---|---|---|---|---|---|---|---|
| Barz et al. [48] | 0 | 1 | 1 | 1 | 0 | – | 1 | 1 | 71 | Good |
| Tomkins-Lane et al. [49] | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 75 | Good |
| Tomkins-Lane et al. [45] | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 63 | Good |
| Rainville et al. [47] | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 50 | Moderate |
| Prasad et al. [50] | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 50 | Moderate |
| Tomkins-Lane et al. [46] | 0 | 0 | 1 | 1 | 0 | – | 1 | 0 | 38 | Moderate |
| Conway et al. [54] | 1 | 1 | 0 | 1 | 0 | – | 1 | 1 | 71 | Good |
| Schulte et al. [52] | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 63 | Good |
| Tomkins-Lane et al. [53] | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 38 | Moderate |
| Pryce et al. [51] | 0 | 0 | 0 | 1 | 0 | – | 1[a] | 0 | 29 | Moderate |

[a]No gender

**Table 3** Summary of results

| Study | Objective outcome measurement | Quality | Correlation coefficients |
|---|---|---|---|
| Barz et al. [48] | Walk test (MTT) | Good | Correlation coefficient: treadmill—ODI: − 0.51 |
| Tomkins-Lane et al. [49] | Walk test (SPWT) | Good | Correlation coefficient: ODI-SPWT 0.52 ($P < 0.05$)<br>ODI walk-SPWT 0.83 ($P < 0.01$) |
| Tomkins-Lane et al. [45] | Walk test (SPWT) | Good | Correlation coefficients between changes: SPWT-ODI: − 0.70 (− 0.93 to − 0.25) ($P < 0.01$)<br>SPWT-ODI walking distance item: − 0.78 (− 1.04 to − 0.50) ($P < 0.01$) |
| Rainville et al. [47] | Walk test (SPWT) | Moderate | Correlation coefficients: SPWT time—ODI walk item: − 0.47<br>SPWT dist—ODI walk item: − 0.49<br>MTT time—ODI walk item: − 0.63<br>MTT dist—ODI walk item: − 0.54<br>($P < 0.01$)<br>Correlation coefficients of change score: SPWT time—ODI walk item: 0.17 ($P > 0.05$)<br>SPWT dist—ODI walk item: 0.23 ($P > 0.05$)<br>MTT time—ODI walk item: 0.48 ($P < 0.01$)<br>MTT dist—ODI walk item: 0.35 ($P > 0.05$) |
| Prasad et al. [50] | Walk test (MTT) | Moderate | Correlation coefficient: MWD—preoperative ODI: − 0.16<br>Measured walking distance—ODI score: − 0.21 preoperatively, − 0.32 postoperatively<br>*P* value not stated |
| Tomkins-Lane et al. [46] | Walk test (SPWT) | Moderate | Correlation coefficient: ODI-SPWT: 0.52 (− 0.26 to − 0.77) ($P < 0.01$) |
| Conway et al. [54] | Accelerometer and walk test (SPWT) | Good | Correlation coefficients: SPWT distance—maximum time of continuous activity: 0.629 ($P < 0.05$)<br>SPWT distance—activity count/day: 0.527<br>SPWT distance to first symptoms—activity count/day: − 0.075<br>ODI—SPWT dist: − 0.595 ($P < 0.05$)<br>ODI—SPWT distance to first symptoms: − 0.310<br>ODI—maximum time of continuous activity/day: − 0.07<br>ODI—acc. count/day: − 0.148 |
| Schulte et al. [52] | Accelerometer | Good | Correlation between accelerometer variables and the ODI<br>G.c/day<br>Baseline − 0.075<br>3 months − 0.284<br>12 months − 0.278<br>G.c/h<br>Baseline − 0.046<br>3 months − 0.214<br>12 months − 0.278<br>Gait intensity > 40 g.c/min<br>Baseline − 0.121<br>3 months − 0.223<br>12 months − 0.289 ($P < 0.05$)<br>Correlation between accelerometer variables and the ODI walking distance item<br>Gait cycles per day<br>Baseline: –<br>3 months: − 0.375 ($P < 0.017$)<br>12 months: − 0.444 ($P < 0.004$) |
| Tomkins-Lane et al. [53] | Accelerometer and walk test (SPWT) | Moderate | There were no significant relations between demographic variables (age, sex, height, weight, or body mass index) and change in performance or self-reported outcomes |

**Table 3** (continued)

| Study | Objective outcome measurement | Quality | Correlation coefficients |
|---|---|---|---|
| Pryce et al. [51] | Accelerometer | Moderate | Correlation between the ODI and accelerometer variables<br>Physical intensity<br>Volume: − 0.52<br>Intensity: − 0.35<br>Duration: − 0.39<br>Meaningful intensity<br>Bout length: − 0.30<br>Maximum bout length: − 0.46<br>Moderate intensity<br>Bout length: − 0.49<br>Maximum bout length: − 0.55<br>Sedentary behavior:<br>Duration: − 0.14<br>Bout length: 0.25<br>Maximum bout length: 0.30<br>$P < 0.5 = r > 0.35$<br>$P < 0.01 = r > 0.45$ |

assess important areas such as pain. Aspects of function are best evaluated objectively when a feasible objective test is available, as is the case with walking capacity in walking tests. Out of the available evidence we recommend the SPWT. For future studies, one of the quicker walking tests should be validated against the SPWT to make walking capacity feasible to evaluate in clinical trials and clinical practice.

Some studies suggest that accelerometer outcomes also can relate to walking capacity. The accelerometer study of Papadakis et al. [56] resembles a test of walking capacity, and correlates substantially with the ODI, as the above-mentioned walking tests. Conway et al. [54] perform a correlation analysis between an accelerometer outcome and a walking test, and the result is a substantial correlation. The accelerometer thus shows promise as being able to assess both walking capacity and walking performance. The accelerometer could help to investigate whether the everyday environment has allowed the patient to walk better than what data about walking capacity would predict, or the other way around. The reviewed articles report a collection of accelerometer variables, each made to represent walking performance. We recommend that the accelerometer is further investigated and standardized for the purpose of measuring both walking performance and walking capacity in spinal stenosis patients.

## Quality of the review

This is the first systematic critical review regarding correlation between the ODI and objective outcome measurements of walking capacity and performance. The quality of the studies could be underestimated since authors were not contacted regarding missing quality items. There is heterogeneity of the studies and the study objectives which weakens the conclusions drawn from a summary of results. In an attempt, to provide a clear overview only the ODI were included leaving other potentially interesting PROs out, such as the Swiss Spinal Stenosis Questionnaire (SSSQ) and the Roland Morris Disability Questionnaire (RMDQ).

## Quality of the included studies

The review demonstrates methodological issues with most of the studies. These concern the attention to psychometric properties such as content and construct validity regarding the ODI and the objective measurements. Not all studies specify which version of the ODI is used. The absence of hypothesis regarding correlations indicates that construct validity have not been part of the study design. Blinding of data collectors is crucial to ensure unbiased assessment of outcomes. Since blinding appears to be non-existent in the included studies, reported correlation coefficients may be overestimated.

The quality of the studies may be too harshly scored. We included studies with patients clinically diagnosed with lumbar spinal stenosis, and chose to put MRI, the "golden standard" of imaging verification, as a quality item. CT is also frequently used, and how it performs in comparison to MRI is subject of discussion [57–60]. The impact of CT on the accuracy of the diagnosis may not have a big influence on the results of our review. The diagnoses in the studies were already quite certain, with the use of adequate inclusion and exclusion criteria.

## Perspective

The ODI plays a significant role in spinal stenosis research, as it have been used for almost four decades. But maybe it is time to develop new measurements of walking capacity

and performance to bring spinal stenosis research to the next level, guiding us on how best to help patients walk freely again. The accelerometer holds promise of being more than a walking performance measurement. Besides walking capacity measurement, it has been investigated as a motivational tool [61] and for assessing gait characteristics [62]. The latter could potentially be useful in the diagnosis of spinal stenosis and monitoring disease progression. For the same reasons, monitoring over several days could enable clinicians to identify variation of movement during the day, possibly distinguishing between the disease characteristics of, for example, spinal stenosis and hip arthrosis.

GPS technology has yet to be implemented in spinal stenosis research, but there is research on vascular claudication which experiments with GPS monitoring [63]. GPS technology gives a spatial dimension to monitoring [25, 64]. Studying walking performance in the light of spatial dimension enables us to objectively evaluate how far a patient's walking performance can carry them, whether they can participate fully in the community.

Sensors are becoming increasingly wearable. Accelerometers are being incorporated into plasters [65], and maybe a wearable device, such as a watch, could hold both an accelerometer and a GPS like today's mobile phones. Worn before a doctor visit and after treatment, it could aid in both diagnosis and follow up on walking ability.

We therefore encourage the COS developers to consider the objective outcome measurement tools that captures capacity and performance as a future standard in patients with spinal stenosis.

So how walking limitations should be evaluated in patients with lumbar spinal stenosis? The ODI should not stand alone when evaluating walking limitations. To enable a comprehensive assessment of walking ability, a walking test should be used to assess walking capacity and accelerometers should be investigated and standardized in measuring walking performance.

**Funding** This review has not received any funding.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no competing interests.

## References

1. Verbiest H (1980) Stenosis of the lumbar vertebral canal and sciatica. Neurosurg Rev 3:75–89
2. Ammendolia C, Stuber K, Tomkins-Lane C, Schneider M, Rampersaud YR, Furlan AD, Kennedy CA (2014) What interventions improve walking ability in neurogenic claudication with lumbar spinal stenosis? A systematic review. Eur Spine J Off Publ Eur Spine Soc Eur Spinal Deform Soc Eur Sect Cerv Spine Res Soc 23:1282–1301. https://doi.org/10.1007/s00586-014-3262-6
3. de Vet HCW, Terwee CB, Mokkink LB, Knol DJ (2011) Measurement in medicine. A practical guide. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511996214
4. Lassere MN (2006) A users guide to measurement in medicine. Osteoarthr Cartil 14(Suppl A):A10–A13. https://doi.org/10.1016/j.joca.2006.02.021
5. Organisation WH (2003) ICF Checklist. In: Version 21a, Clinician Form
6. Organisation WH (2002) Towards a Common Language for Functioning, Disability and Health ICF
7. Tomkins CC, Battie MC, Rogers T, Jiang H, Petersen S (2009) A criterion measure of walking capacity in lumbar spinal stenosis and its comparison with a treadmill protocol. Spine 34:2444–2449. https://doi.org/10.1097/BRS.0b013e3181b03fc8
8. Pratt RK, Fairbank JC, Virr A (2002) The reliability of the Shuttle Walking Test, the Swiss Spinal Stenosis Questionnaire, the Oxford Spinal Stenosis Score, and the Oswestry Disability Index in the assessment of patients with lumbar spinal stenosis. Spine 27:84–91
9. Deen HG Jr, Zimmerman RS, Lyons MK, McPhee MC, Verheijde JL, Lemens SM (2000) Test–retest reproducibility of the exercise treadmill examination in lumbar spinal stenosis. Mayo Clin Proc 75:1002–1007
10. Rossier P, Wade DT (2001) Validity and reliability comparison of 4 mobility measures in patients presenting with neurologic impairment. Arch Phys Med Rehabil 82:9–13. https://doi.org/10.1053/apmr.2001.9396
11. Singh A, Crockard HA (1999) Quantitative assessment of cervical spondylotic myelopathy by a simple walking test. Lancet (London, England) 354:370–373. https://doi.org/10.1016/s0140-6736(98)10199-x
12. Gibbons WJ, Fruchter N, Sloan S, Levy RD (2001) Reference values for a multiple repetition 6-min walk test in healthy adults older than 20 years. J Cardiopulm Rehabil 21:87–93
13. Tomkins-Lane CC, Haig AJ (2012) A review of activity monitors as a new technology for objectifying function in lumbar spinal stenosis. J Back Musculoskelet Rehabil 25:177–185. https://doi.org/10.3233/bmr-2012-0325
14. Welk GJ (2002) Physical activity assessments for health-related research. Human Kinetics, Champaign
15. Davis MG, Fox KR (2007) Physical activity patterns assessed by accelerometry in older people. Eur J Appl Physiol 100:581–589. https://doi.org/10.1007/s00421-006-0320-8
16. Cavanaugh JT, Coleman KL, Gaines JM, Laing L, Morey MC (2007) Using step activity monitoring to characterize ambulatory activity in community-dwelling older adults. J Am Geriatr Soc 55:120–124. https://doi.org/10.1111/j.1532-5415.2006.00997.x
17. Winter CC, Brandes M, Müller C, Schubert T, Ringling M, Hillmann A et al. (2010) Walking ability during daily life in patients with osteoarthritis of the knee or the hip and lumbar spinal stenosis: a cross sectional study. BMC Musculoskelet Disord 11:233
18. Gilmore S, McClelland JA, Davidson M (2016) Does walking after lumbar spinal surgery predict recovery of function at 6 months? Protocol for a prospective cohort study. BMC Musculoskelet Disord 17:472. https://doi.org/10.1186/s12891-016-1296-0
19. Skotte J, Korshoj M, Kristiansen J, Hanisch C, Holtermann A (2014) Detection of physical activity types using triaxial accelerometers. J Phys Act Health 11:76–84. https://doi.org/10.1123/jpah.2011-0347
20. Stemland I, Ingebrigtsen J, Christiansen CS, Jensen BR, Hanisch C, Skotte J, Holtermann A (2015) Validity of the Acti4 method for detection of physical activity types in free-living settings: comparison with video analysis. Ergonomics 58:953–965. https://doi.org/10.1080/00140139.2014.998724

21. Allet L, Knols RH, Shirato K, de Bruin ED (2010) Wearable systems for monitoring mobility-related activities in chronic disease: a systematic review. Sensors (Basel, Switzerland) 10:9026–9052. https://doi.org/10.3390/s101009026
22. Granat M, Clarke C, Holdsworth R, Stansfield B, Dall P (2015) Quantifying the cadence of free-living walking using event-based analysis. Gait Posture 42:85–90. https://doi.org/10.1016/j.gaitpost.2015.04.012
23. Barzilay Y, Noam S, Meir L, Gail A, Amit B, Michal I, Vaccaro AR, Leon K (2011) Assessing the outcomes of spine surgery using global positioning systems. Spine 36:E263–E267. https://doi.org/10.1097/BRS.0b013e3181da3737
24. Maddison R, Jiang Y, Vander Hoorn S, Exeter D, Mhurchu CN, Dorey E (2010) Describing patterns of physical activity in adolescents using global positioning systems and accelerometry. Pediatr Exerc Sci 22:392–407
25. Maddison R, Ni Mhurchu C (2009) Global positioning system: a new opportunity in physical activity measurement. Int J Behav Nutr Phys Act 6:73. https://doi.org/10.1186/1479-5868-6-73
26. Roland M, Fairbank J (2000) The Roland–Morris disability questionnaire and the Oswestry disability questionnaire. Spine 25:3115–3124
27. Stucki G, Daltroy L, Liang MH, Lipson SJ, Fossel AH, Katz JN (1996) Measurement properties of a self-administered outcome measure in lumbar spinal stenosis. Spine 21:796–803
28. Tomkins CC, Battie MC, Hu R (2007) Construct validity of the physical function scale of the Swiss spinal stenosis questionnaire for the measurement of walking capacity. Spine 32:1896–1901. https://doi.org/10.1097/BRS.0b013e31811328eb
29. Roland M, Morris R (1983) A study of the natural history of back pain. Part I: development of a reliable and sensitive measure of disability in low-back pain. Spine 8:141–144
30. Heinemann A, Raad J, Akuthota V, Segal N, Nitsch KP, Rho M, Chan L, Casey E, Press J, Sowa G, Moore J (2017) Scoping review to develop common data elements for lumbar spinal stenosis. Spine J Off J N Am Spine Soc. https://doi.org/10.1016/j.spinee.2017.04.005
31. Chapman JR, Norvell DC, Hermsmeyer JT, Bransford RJ, DeVine J, McGirt MJ, Lee MJ (2011) Evaluating common outcomes for measuring treatment success for chronic low back pain. Spine 36:S54–S68. https://doi.org/10.1097/BRS.0b013e31822ef74d
32. Fairbank JCCJDJ et al (1980) The Oswestry low back pain disability questionnaire. Physiotherapy 66:271–273
33. Fairbank JC, Pynsent PB (2000) The Oswestry Disability Index. Spine 25:2940–2952 **(discussion 2952)**
34. Copay AG, Glassman SD, Subach BR, Berven S, Schuler TC, Carreon LY (2008) Minimum clinically important difference in lumbar spine surgery patients: a choice of methods using the Oswestry Disability Index, medical outcomes study questionnaire short form 36, and pain scales. Spine J Off J N Am Spine Soc 8:968–974. https://doi.org/10.1016/j.spinee.2007.11.006
35. Fairbank JC (2014) Why are there different versions of the Oswestry Disability Index? J Neurosurg Spine 20:83–86. https://doi.org/10.3171/2013.9.spine13344
36. Sinikallio S, Aalto T, Airaksinen O, Herno A, Kroger H, Savolainen S, Turunen V, Viinamaki H (2007) Lumbar spinal stenosis patients are satisfied with short-term results of surgery—younger age, symptom severity, disability and depression decrease satisfaction. Disabil Rehabil 29:537–544. https://doi.org/10.1080/09638280600902646
37. Okoro T, Qureshi A, Sell B, Sell P (2010) The accuracy of assessment of walking distance in the elective spinal outpatients setting. Eur Spine J Off Publ Eur Spine Soc Eur Spinal Deform Soc Eur Sect Cerv Spine Res Soc 19:279–282. https://doi.org/10.1007/s00586-009-1152-0
38. Werneke M (2016) A proposed set of metrics for standardized outcome reporting in the management of low back pain. Acta Orthop 87:88. https://doi.org/10.3109/17453674.2015.1120127
39. Moher D, Liberati A, Tetzlaff J, Altman DG (2010) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Int J Surg (London, England) 8:336–341. https://doi.org/10.1016/j.ijsu.2010.02.007
40. Kellar SP, Kelvin EA, Munro BH (2012) Munro's statistical methods for health care research. Wolters Kluwer Health/Lippincott Williams & Wilkins, Philadelphia
41. Domholdt E (1993) Physical therapy research: principles and applications. W. B. Saunders, Philadelphia
42. Gross DP, Battie MC (2003) Construct validity of a kinesiophysical functional capacity evaluation administered within a worker's compensation environment. J Occup Rehabil 13:287–295
43. Mokkink LB, Terwee CB, Patrick DL, Alonso J, Stratford PW, Knol DL, Bouter LM, de Vet HC (2010) The COSMIN checklist for assessing the methodological quality of studies on measurement properties of health status measurement instruments: an international Delphi study. Qual Life Res Int J Qual Life Asp Treat Care Rehabil 19:539–549. https://doi.org/10.1007/s11136-010-9606-8
44. Centre for Evidence Based Medicine (2017) Diagnostic study appraisal worksheet. https://www.cebm.net/wp-content/uploads/2014/06/CEBM_Diagnostic-study-appraisal-worksheet.doc. Accessed 14 Aug 2017
45. Tomkins-Lane CC, Battie MC, Macedo LG (2014) Longitudinal construct validity and responsiveness of measures of walking capacity in individuals with lumbar spinal stenosis. Spine J Off J N Am Spine Soc 14:1936–1943. https://doi.org/10.1016/j.spinee.2013.11.030
46. Tomkins-Lane CC, Battie MC (2013) Predictors of objectively measured walking capacity in people with degenerative lumbar spinal stenosis. J Back Musculoskelet Rehabil 26:345–352. https://doi.org/10.3233/bmr-130390
47. Rainville J, Childs LA, Pena EB, Suri P, Limke JC, Jouve C, Hunter DJ (2012) Quantification of walking ability in subjects with neurogenic claudication from lumbar spinal stenosis—a comparative study. Spine J Off J N Am Spine Soc 12:101–109. https://doi.org/10.1016/j.spinee.2011.12.006
48. Barz T, Melloh M, Staub L, Roeder C, Lange J, Smiszek FG, Theis JC, Merk HR (2008) The diagnostic value of a treadmill test in predicting lumbar spinal stenosis. Eur Spine J Off Publ Eur Spine Soc Eur Spinal Deform Soc Eur Sect Cerv Spine Res Soc 17:686–690. https://doi.org/10.1007/s00586-008-0593-1
49. Tomkins-Lane CC, Battie MC (2010) Validity and reproducibility of self-report measures of walking capacity in lumbar spinal stenosis. Spine 35:2097–2102. https://doi.org/10.1097/BRS.0b013e3181f5e13b
50. Prasad BC, Ramesh Chandra VV, Devi BV, Chivukula SS, Pundarikakshaiah K (2016) Clinical, radiological, and functional evaluation of surgical treatment in degenerative lumbar canal stenosis. BioMed Res Int 64:677–683. https://doi.org/10.1155/2016/9074257. https://doi.org/10.4103/0028-3886.185378
51. Pryce R, Johnson M, Goytan M, Passmore S, Berrington N, Kriellaars D (2012) Relationship between ambulatory performance and self-rated disability in patients with lumbar spinal stenosis. Spine 37:1316–1323. https://doi.org/10.1097/BRS.0b013e31824a8314
52. Schulte TL, Schubert T, Winter C, Brandes M, Hackenberg L, Wassmann H, Liem D, Rosenbaum D, Bullmann V (2010) Step activity monitoring in lumbar stenosis patients undergoing decompressive surgery. Eur Spine J Off Publ Eur Spine Soc Eur Spinal Deform Soc Eur Sect Cerv Spine Res Soc 19:1855–1864. https://doi.org/10.1007/s00586-010-1324-y
53. Tomkins-Lane CC, Conway J, Hepler C, Haig AJ (2012) Changes in objectively measured physical activity (performance)

after epidural steroid injection for lumbar spinal stenosis. Arch Phys Med Rehabil 93:2008–2014. https://doi.org/10.1016/j.apmr.2012.05.014
54. Conway J, Tomkins CC, Haig AJ (2011) Walking assessment in people with lumbar spinal stenosis: capacity, performance, and self-report measures. Spine J Off J N Am Spine Soc 11:816–823. https://doi.org/10.1016/j.spinee.2010.10.019
55. Aalto TJ, Malmivaara A, Kovacs F, Herno A, Alen M, Salmi L, Kroger H, Andrade J, Jimenez R, Tapaninaho A, Turunen V, Savolainen S, Airaksinen O (2006) Preoperative predictors for postoperative clinical outcome in lumbar spinal stenosis: systematic review. Spine 31:E648–E663. https://doi.org/10.1097/01.brs.0000231727.88477.da
56. Papadakis NC, Christakis DG, Tzagarakis GN, Chlouverakis GI, Kampanis NA, Stergiopoulos KN, Katonis PG (2009) Gait variability measurements in lumbar spinal stenosis patients: part A. Comparison with healthy subjects. Physiol Meas 30:1171–1186. https://doi.org/10.1088/0967-3334/30/11/003
57. Lee GY, Lee JW, Choi HS, Oh KJ, Kang HS (2011) A new grading system of lumbar central canal stenosis on MRI: an easy and reliable method. Skelet Radiol 40:1033–1039. https://doi.org/10.1007/s00256-011-1102-x
58. Lurie J, Tomkins-Lane C (2016) Management of lumbar spinal stenosis. BMJ (Clinical research ed) 352:h6234. https://doi.org/10.1136/bmj.h6234
59. de Schepper EIT, Overdevest GM, Suri P, Peul WC, Oei EHG, Koes BW, Bierma-Zeinstra SMA, Luijsterburg PAJ (2013) Diagnosis of lumbar spinal stenosis: an updated systematic review of the accuracy of diagnostic tests. Spine 38:E469–E481. https://doi.org/10.1097/BRS.0b013e31828935ac
60. Lee S, Lee JW, Yeom JS, Kim KJ, Kim HJ, Chung SK, Kang HS (2010) A practical MRI grading system for lumbar foraminal stenosis. AJR Am J Roentgenol 194:1095–1098. https://doi.org/10.2214/ajr.09.2772
61. Normahani P, Kwasnicki R, Bicknell C, Allen L, Jenkins MP, Gibbs R, Cheshire N, Darzi A, Riga C (2017) Wearable sensor technology efficacy in peripheral vascular disease (wSTEP): a randomized controlled trial. Ann Surg. https://doi.org/10.1097/sla.0000000000002300
62. Del Din S, Godfrey A, Rochester L (2016) Validation of an accelerometer to quantify a comprehensive battery of gait characteristics in healthy older adults and Parkinson's disease: toward clinical and at home use. IEEE J Biomed Health Inform 20:838–847. https://doi.org/10.1109/jbhi.2015.2419317
63. Gernigon M, Le Faucheur A, Fradin D, Noury-Desvaux B, Landron C, Mahe G, Abraham P (2015) Global positioning system use in the community to evaluate improvements in walking after revascularization: a prospective multicenter study with 6-month follow-up in patients with peripheral arterial disease. Medicine 94:e838. https://doi.org/10.1097/md.0000000000000838
64. Krenn PJ, Titze S, Oja P, Jones A, Ogilvie D (2011) Use of global positioning systems to study physical activity and the environment: a systematic review. Am J Prev Med 41:508–515. https://doi.org/10.1016/j.amepre.2011.06.046
65. Schneller MB, Bentsen P, Nielsen G, Brond JC, Ried-Larsen M, Mygind E, Schipperijn J (2017) Measuring children's physical activity: compliance using skin-taped accelerometers. Med Sci Sports Exerc 49:1261–1269. https://doi.org/10.1249/mss.0000000000001222

## Affiliations

**Annette Bennedsgaard Jespersen[1] · Malin Eleonora av Kák Gustafsson[2]**

✉ Annette Bennedsgaard Jespersen
annette.bennedsgaard.jespersen@rsyd.dk

[1] Department of Regional Health Research, Center for Spine Surgery and Research, Middelfart, Region of Southern Denmark, P V Tuxensvej 12, 5500 Middelfart, Denmark

[2] Department of Regional Health Research, Center for Spine Surgery and Research, Middelfart, Region of Southern Denmark, Faaborgvej 237, 5250 Odense, Denmark