Review Article on Objective Monitoring and Wearable Technologies including Sensor-Based Accelerometers and Mobile Health Applications for the Spine Patient

Analysing gait patterns in degenerative lumbar spine diseases: a literature review

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Objectives: To collate the current state of knowledge and explore differences in the spatiotemporal gait patterns of degenerative lumbar spine diseases: lumbar spinal stenosis (LSS), lumbar disc herniation (LDH) and low back pain (LBP).

Background: LBP is common presenting complaint with degenerative lumbar spine disease being a common cause. In particular, the gait patterns of LSS, LDH and mechanical-type (facetogenic and discogenic) LBP is not established.

Methods: A search of the literature was conducted to determine the changes in spatial and temporal gait metrics involved with each type of degenerative lumbar spine disease. A search of databases including Medline, Embase and PubMed from their date of inception to April 18th, 2021 was performed to screen, review and identify relevant studies for qualitative synthesis. Seventeen relevant studies were identified for inclusion in the present review. Of these, 5 studies investigated gait patterns in LSS, 10 studies investigated LBP and 2 studies investigated LDH. Of these, 4 studies employed wearable accelerometry in LSS (2 studies) and LBP (2 studies).

Conclusions: Previous studies suggest degenerative diseases of the lumbar spine have unique patterns of gait deterioration. LSS is characterised by asymmetry and variability. Spatiotemporal gait deterioration in gait velocity, cadence with increased double-support duration and gait variability are distinguishing features in LDH. LBP involves marginal abnormalities in temporal and spatial gait metrics. Previous studies suggest degenerative diseases of the lumbar spine have unique patterns of gait deterioration. Gait asymmetry and variability, may be relevant metrics for distinguishing between the gait profiles of lumbar spine diseases.

Keywords: Degenerative disease; disc herniation; spinal stenosis; lumbar spine, gait patterns

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Introduction

Low back pain (LBP) is a common health problem that accounts for a substantial clinical and socioeconomic global health burden incurring a total measured burden of approximately 83 million disability-adjusted life years (1). Most cases of LBP (other than non-specific causes) involve well-defined pathoanatomical causes (pain generators) and are typically associated with degenerative diseases of the lumbar spine (2,3).

Degenerative lumbar spine diseases affect 266 million people worldwide and includes diagnoses such as lumbar spinal stenosis (LSS), lumbar disc herniation (LDH) and

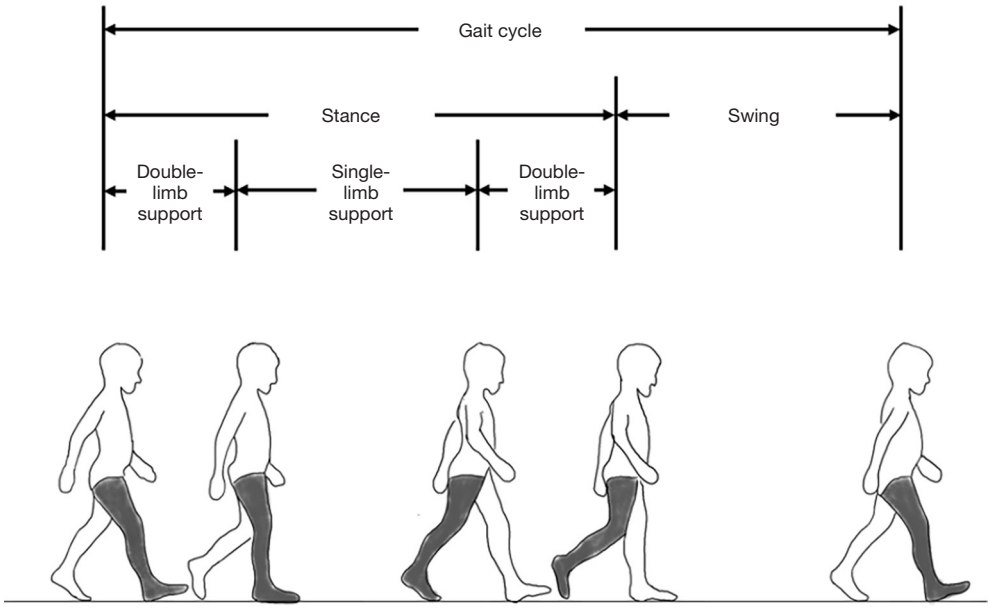

Figure 1 Gait phases for one gait cycle of right (shaded) leg illustrating stance, swing, single-limb support, double-limb support.

mechanical-type (discogenic or facetogenic) LBP (4). These diseases can present with a range of symptoms such as sciatica, neurogenic intermittent claudication and mechanical-type onset of LBP respectively (4). Although varying in symptoms and severity, degenerative lumbar diseases are theorised to be associated with biomechanical impairments of spinal muscles resulting in energy-inefficient gait patterns (5) and therefore a deterioration to walking quality and capacity (6,7).

Gait is a clinically important biomarker for the identification and evaluation of disease-states (8). Performance-oriented functional tests of gait such as the 10-meter walk (10MW) test, 6-minute walking (6MWT) test, or Timed Up and Go (TUG) typically focus on a single quantitative parameter of gait (6,7), overlooking other important aspects such as quality of gait (9). They also do not reveal specifically which aspects of gait differ from healthy gait. Previously, several quantitative gait analysis studies have investigated the walking patterns of lumbar degenerative diseases, quantifying the spatial and temporal aspects of gait deterioration (10-12).

To the best of the authors' knowledge however, a review of literature has not been undertaken to compare the gait patterns in these lumbar degenerative diseases including LSS, LDH and chronic mechanical-type LBP. Non-specific causes of LBP were not considered in the present review with LBP referring to chronic mechanical-type onset and presence of patho-anatomical (facetogenic or discogenic) pain generators. Analysing gait patterns in lumbar spine diseases, may pave the way for the creation of a disease-specific gait profiles to aid clinical identification of disease-states. We present the following article in accordance with the Narrative Review reporting checklist (available at https://jss.amegroups.com/article/view/10.21037/jss-21-91/rc).

Methods

Spatial and temporal gait parameters

During a bout of walking, two successive steps such that a foot returns to its initial position is considered a 'stride' or a 'gait cycle' (*Figure 1*). Within a gait cycle the two distinct phases of a foot can be considered: stance (foot is in contact with ground) and swing (foot is lifted and moved forwards) (13). Moreover, the time that both feet touch the ground (double support time) and only one foot touches the ground (single support time) can also be analysed. These gait phases can be analysed as a proportion of gait cycle and compared to normative values: stance (60%), swing (40%) and double support time ratios (20%).

The walking bout itself may quantitatively analysed (*Table 1*) considering spatial (step and stride length) and temporal parameters (step and stride time) and these may all be computed with minimal equipment. Composite

Table 1 Spatial, temporal and spatiotemporal parameters of gait

Gait variable	Definition	Units	Type
Step length	Average distance between two consecutive contacts of any foot with the ground	Metres (m)	Spatial
Stride length	Average distance between two consecutive contacts of the same foot with the ground	Metres (m)	Spatial
Step time	Average time between two consecutive contacts of any foot with the ground	Seconds (s)	Temporal
Stride time	Average time between two consecutive contacts of the same foot with the ground	Seconds (s)	Temporal
Walking speed (or gait velocity)	Average distance travelled per second	Metres/second (m/s)	Spatiotemporal
Cadence	Average rate (or frequency) of steps	Steps/minute	Spatiotemporal
Step time variability	Step-to-step variability of step time	Standard deviation (SD) coefficient of variance (cov = SD/mean)	Gait variability
Step length variability	Step-to-step variability of step length	Standard deviation (SD) coefficient of variance (cov = SD/mean)	Gait variability
Walking speed (or gait velocity) variability	Step-to-step variability of walking speed	Coefficient of variance (cov = SD/mean)	Gait variability
Step time asymmetry	Average difference in time taken for successive steps on left and right foot	Seconds (s)	Gait asymmetry
Step length asymmetry	Average difference in length for successive steps on left and right foot	Metres (m)	Gait asymmetry

'spatiotemporal' measures of gait can be derived from these variables: walking speed and cadence. More complex 'derived' metrics include gait variability (step-to-step variation) and asymmetry (average difference between left and right foot). Step (rather than stride) measurements reflect gait variability more reliably (14).

Objectives

A search of the literature was conducted to determine the changes in spatial and temporal gait metrics involved with each type of degenerative lumbar spine disease: LSS, LDH and chronic LBP.

Literature search

A search strategy was created to identify relevant studies (Appendix 1). Medline, Embase and PubMed databases were searched from their date of inception to April 18th, 2021. Relevant articles were screened (Appendix 2) according to:

Eligibility criteria

Inclusion criteria

(I) Original articles investigating spatiotemporal gait metrics;
(II) Articles involving at least one (or more) lumbar spine pathology groups (LSS, LDH, LBP) and/or healthy control groups;
(III) Articles written in English;
(IV) Human studies published between 1980–April 2021.

Exclusion criteria

(I) Studies investigating other variables of gait e.g., range-of-motion, tri-dimensional forces, posture;
(II) Studies without comparative healthy control participants;
(III) Studies investigating normal human gait activities (e.g., running, walking);
(IV) Studies investigating gait metrics associated with interventions (surgical or pharmacological);
(V) Reviews, Conference Abstracts, Books.

Table 2 Overview of typical gait alterations (compared to healthy controls)

	Gait velocity	Cadence	Gait lengths	Gait durations	Swing	Single-limb support	Double-limb support	Step width	Gait asymmetry	Gait variability
Lumbar spinal stenosis	↓	↘	↓	↗	X	X	X	X	↑↑	↑↑
Lumbar disc herniation	↓↓	↓↓	↓	↑	↑	↑↑	↑↑	X	X	↑↑
Low back pain	↓	↘	↘	↗	↗	↗	↑	↑	X	~

Included studies investigating spatiotemporal changes at self-selected and unobstructed walking speeds. ↓↓, markedly decreased (>50%); ↓, decreased (10–50%); ↘, slightly decreased (0–10%); ↗, slightly increased (0–10%); ↑, increased (10–50%); ↑↑, markedly increased (>50%), ~, no significant findings; X, not studied. SDL, Stride Length; SDT, Stride Time.

Data collection

Differences in gait parameters were abstracted from included studies as a percentage difference compared to healthy controls. These variables include: (I) Gait Velocity; (II), Cadence; (III) Gait Lengths (Step or Stride Length); (IV) Gait Durations (Step or Stride Length); (V) Stance; (VI) Swing; (VII) Single-Limb Support; (VIII) Double-Limb Support; (IX) Step Width; (X) Gait Asymmetry; (XI) Gait Variability.

Results

A total of 1,989 relevant studies were identified from a database search of PubMed, Medline and Embase. One thousand two hundred ninety-eight studies remained after removal of duplicates. These were screened (by abstract and title) and assessed (by full-text review) for eligibility independently by 2 reviewers (PN, RDF), with a third reviewer consulted until consensus reached (MM). One hundred two hundred fifty-one studies were excluded by screening, 30 studies removed by full-text review, leaving a final 17 included studies for qualitative synthesis in the present narrative review (Appendix 1).

Of the 17 relevant studies included in the review, 5 studies investigated gait patterns in LSS, 10 studies investigated LBP and 2 studies investigated LDH. Of these, 4 studies employed wearable accelerometry in LSS (2 studies) and LBP (2 studies).

Discussion

A tabulation of statistically significant findings from included studies suggests LSS, LBP and LDH have unique patterns of gait deterioration (*Table 2*). LSS is associated with reduced gait velocity, and gait (step or stride) lengths along with slightly increased gait durations. However, the most marked changes are increases to gait asymmetry and variability. Changes to durations of swing, stance and limb-support phases in LSS have not been studied. Conversely, LDH is characterised by marked reductions to gait velocity, cadence and increases to gait variability, single-limb support and double-limb support. Moderate decreases to gait lengths and moderate increases to swing times, and gait durations are also present. Changes to step width and gait asymmetry have not been studied previously. Gait patterns in LBP involve moderate increases to double-limb support time and step width, with moderate reductions to gait velocity. These changes are accompanied by slightly increased gait durations, swing time, and single-limb support time with slightly decreased gait lengths.

LSS

Gait deterioration in LSS patients (compared to healthy participants) involves markedly decreased gait velocity and step length together with slightly decreased cadence and slightly increased step duration (*Table 3*) (10,15-18). Moreover, as ratios of double-limb support (+23%) and stance (+5%) phases increase, swing phase ratio decreases (–8%). Between-feet gait asymmetry is also increased during all phases including stance (+131%), swing (+170%) and double-limb support (+9%) (15). Further, LSS patients also demonstrate greater stride-to-stride gait variability (17). These altered gait patterns likely arise as compensatory adjustments to radicular pain, muscle weakness, (and therefore) low walking tolerance and instability that are exacerbated on upright walking posture (lumbar extension) (19).

Intermittent claudication is typically considered to

Table 3 Summary of gait analysis studies on lumbar spinal stenosis

	Gait velocity	Cadence	Gait length	Gait duration	Gait asymmetry	Gait variability
Loske *et al.* (2018)	–16%	–	–12% (SL)	+8% (ST)	+131% (ST)	X
Odonkor *et al.* (2020)	–15%	–10%	–14% (SDL)	X	X	X
Papadakis (2009)	X	X	X	X	X	+436%[†]
Perring *et al.* (2020)	–37%	–14%	–24% (SL)	+16% (ST)	X	X
Sun *et al.* (2018)	–12%	–	–14% (SL)	–	X	X
Gait pattern	↓	↘	↓	↗	↑↑	↑↑

Included studies investigating spatiotemporal changes at self-selected and unobstructed walking speeds. [†], signal processing variable; ↓, decreased (10–50%); ↘, slightly decreased (0–10%); ↗, slightly increased (0–10%); ↑↑, markedly increased (>50%); [†], signal processing variable; –, no significant findings; X, not studied. ST, step time; SL, step length.

be characteristic of LSS, implying the importance step length as an objective gait parameter in informing surgical intervention. However, our findings suggest gait asymmetry and gait variability also be relevant (*Table 3*).

However, psychological factors like Hawthorne effect (20) and reverse white-coat syndrome (21) may influence testing in observed and unfamiliar laboratory settings via greater conscious control of the walking cycle (22). These factors especially affect stride rhythm and may account for Sun *et al.* (16) and Loske *et al.*'s (15) lack of significant findings for cadence and step duration.

Although between-group differences in gait parameters are largely consistent amongst these studies, large discrepancies are present in mean group values possibly owing to variations in cohort demographics such as age, ethnicity, gender distribution, comorbidities and disease severity (23). As such, Odonkor *et al.* (18) additionally reported effect size differences as a more generalisable representation of gait deterioration in LSS.

These gait patterns in LSS were explored by a more novel methodology: wearable accelerometry in Sun *et al.* (16) and Loske *et al.* (15) (*Table 2*), albeit with a few discrepancies. Sun *et al.* found LSS patients to have no significant difference in stride duration (P=0.858) and cadence (P=0.629) compared to healthy participants (16). These findings contradict those of Loske *et al.* (15), who found an (8%) increase in stride duration. This discrepancy likely stems from greater statistical power in Loske *et al.*'s (15) larger sample size (29 LSS and 27 healthy, versus 20 LSS and 12 healthy participants) compared to Sun *et al.*'s (16) validation study which primarily sought to demonstrate accuracy and reliability. Moreover, both studies were limited in their analysis of gait metrics to basic spatiotemporal measurements, and future wearable accelerometry studies should endeavour to investigate other gait parameters such as durations and ratios of gait phases.

LBP

LBP most notably involves reduced gait velocity (11,24-31) and increased stride width (11,24,25). Many of the other spatiotemporal parameters of gait undergo much more subtle changes involving slightly increased gait durations whilst cadence and gait lengths undergo slight reductions (*Table 4*). These gait differences (compared to healthy participants) seem to be greatest in moderate (rather than severe) LBP participants according to findings by Demirel *et al.* (30).

These gait adaptations likely arise to minimise (anterior-posterior shear) joint forces on the low back and thus relieve pain (32,33). Supporting this 'guarding' hypothesis are the correlation analyses by Bonab *et al.* (29) whereby reductions in gait velocity and cadence explained nearly 70% and 74% of variance in pain as measure by Visual Analogue Scale (VAS). However, contradicting these findings is Gombatto *et al.*'s (34) report of no significant differences in spatiotemporal variables of gait. A likely explanation is a much younger population sample (mean age =27.85), suggesting gait deterioration in LBP is not consistent across all age groups.

Only slight alterations to swing, stance, single-limb support and double-limb support durations of gait have been reported by some authors (24,28,29). These differences falling shy of statistical significance for other authors like Henchoz *et al.* (11) and Demirel *et al.* (30) suggest these gait changes are less prominent in LBP. Similar inconsistent findings have been reported for gait variability in LBP by Lamoth *et al.* (25) and Hamacher *et al.* (31). However, this discrepancy may be due to differences in disease-severity with (VAS) pain scores (VAS; 0= no pain, 10= severe pain)

Table 4 Summary of gait analysis studies on LBP

	Gait velocity	Cadence	Gait length	Gait duration	Step width	Swing	Stance	Single-limb support	Double-limb support	Gait variability
Barzilay *et al.* (2016)	–12%	–3%	–9% (SL)	X	X	X	+2%	+3%	X	X
Bonab *et al.* (2020)	–26%	–19%	–9% (SL), –10% (SDL)	+9% (ST), +8% (SDT)	X	+9%	X	X	+16%	X
Demirel *et al.* (2020)*	–13%	–	–13% (ST), –9% (SDL)	–	X	–	–	–	–	X
Demirel *et al.* (2020)**	–5%	X	–7% (ST), –3% (SDL)	X	X	–	–	–	–	X
Hamacher *et al.* (2016)	–10%	X	X	X	X	X	X	X	X	+75% (SDL), +33% (SDT)
Henchoz *et al.* (2015)	–12%	–25%	–15% (SDL)	X	+25%	X	X	–	–	X
Hicks *et al.* (2017)	–13%	X	–9% (SDL)	+6% (ST)	+50%	X	X	X	+14%	X
Gombatto *et al.* (2015)	–	X	–	–	X	X	X	X	X	X
Lamoth *et al.* (2008)	–14%	X	–14% (SDL)	X	–	X	X	X	X	–48% (SDL)
Lee *et al.* (2007)	–19%	X	X	X	X	X	X	X	X	X
Taylor *et al.* (2003)	–	–	–6% (SDL)	X	X	X	X	X	X	X
Gait pattern	↓	↘	↘	↗	↑	↗	↗	↗	↑	–

Included studies investigating spatiotemporal changes at self-selected and unobstructed walking speeds. *, Moderate LBP; **, severe LBP; ↓, decreased (10–50%); ↘, slightly decreased (0–10%); ↗, slightly increased (0–10%); ↑, increased (10–50%); –, no significant findings; X, not studied. SDL, stride length; SDT, stride time.

ranging from 2.5–4.8 in Lamoth *et al.* (25) compared to 4 or higher in Hamacher *et al.* (31).

Gait patterns in LBP may also be influenced by fear avoidance beliefs or kinesiophobia (30) as significant correlations exist with catastrophising and anticipating pain (35,36). As such, when Lamoth *et al.* (25) controlled for gait speed many of these differences in spatiotemporal gait parameters (except stride width) are diminished. Nonetheless, the presence of these gait patterns at self-selected (free-living) gait speeds has implications to mobility and quality of life, and also clinical relevance in identifying disease-specific gait patterns.

Wearable accelerometers were used to analyse and profile the gait patterns of LBP participants by Henchoz *et al.* (11) and Hamachar *et al.* (31), with similar results to prior laboratory-based finding (*Table 4*). However, at fixed walking speeds these differences ceased to exist aligning with the prior laboratory-based findings of Hicks *et al.* (24). Detrembleur *et al.* (37) hypothesises that musculoskeletal diseases (such as LBP) induce lower-level gait changes compared to neurological pathologies (such as LDH and LSS). Hence, it is plausible that the motor control changes in LBP are too minimal for detection by currently used methodologies–wearable accelerometry-based and laboratory-based techniques alike.

LDH

LDH results in consistent increases in temporal parameters (gait cycle durations, double-limb support and swing duration) and consistent decreases in spatial parameters (gait cycle lengths, gait velocity, and cadence) of gait when compared to healthy controls (*Table 5*) (29,38). According to findings by Keklicek *et al.* (38), LDH also involves increased stride-to-stride variability in step lengths. These gait adaptions likely arise as a protective response to sciatic pain seeking to limit hip and spine movement (12,39). Similar pain-avoidance behaviours to LBP patients likely emerge in LDH due to overlapping symptoms (but of greater intensity) and pain-related fears.

However, contradicting these findings is Huang *et al.*'s (12) report of increased pelvic rotations enabling

Table 5 Summary of gait analysis studies on lumbar disc herniation

	Gait velocity	Cadence	Gait length	Gait duration	Swing	Double-limb support	Gait variability
Bonab *et al.* (2020)	−76%	−67%	−25% (SL), −26% (SDL)	+23% (ST), +28% (SDT)	+23%	+51%	X
Keklicek *et al.* (2018)	X	X	−46% (SL)	X	X	X	+86% (SL)
Gait pattern	↓↓	↓↓	↓	↑	↑	↑↑	↑↑

Included studies investigating spatiotemporal changes at self-selected and unobstructed walking speeds. ↓↓, markedly decreased (>50%); ↓, decreased (10–50%); ↑, increased (10–50%); ↑↑, markedly increased (>50%); X, not studied. SDL, stride length; SDT, stride time.

normal stride lengths to thereby conserve the energy losses that occur with smaller steps (40). However, this discrepancy may be attributable to Huang *et al.*'s experimental protocol of controlled walking speed and stride length.

Limitations

Most included studies employed laboratory-based methodologies such as electronic walkways or 3D motion capture systems which are considered the gold standard for precise quantitative gait analysis (41). However, these tracking methods require specialised equipment, trained personnel and travel to an appropriate facility thus being far too expensive, time-consuming and cumbersome for clinical use. Further, these methods may also not accurately reflect real-life and routine walking behaviours (42,43). According to Brodie *et al.* (43), laboratory assessments overestimate cadence (8.91%, P<0.001) and underestimate gait variability (81.55%, P<0.001) when compared to 'free-living' gait in home and community environments. These discrepancies limit clinical use. Additionally, variations in normative gait from individual to individual, may need to be controlled for with age and sex-matched controls.

However, some studies utilised single-point accelerometers (11,15,16,31), formally termed inertial measurement units (IMUs) which have more recently have become a portable and inexpensive means of gait analysis. Through continuous and long-term monitoring these wearable devices more accurately reflect free-living gait (43). They also demonstrate good agreement with traditional gait analysis systems (44). Despite these benefits, IMUs suffer from issues with patient compliance and are prone to drift errors and noise due to interference from amplified mechanical motions and the magnetic fields of other devices (45). These factors can limit data collection rates to 70–90% for typical health monitoring according to findings by Merilahti *et al.* (46).

Future research

To best of the authors' knowledge, no studies have investigated gait deterioration in LDH with wearable accelerometry. Huang *et al.* and Bonab *et al.* have revealed uniquely different gait patterns in LDH patients but these have been instrumented gait analyses (12,29). Future studies should seek to investigate the 'free-living' gait of this population subset using wearable accelerometry in conjunction with other comparable measures.

Further, a comparison of gait patterns to differentiate between degenerative diseases of the lumbar spine has only been conducted by Bonab *et al.* (29), who examined the gait patterns of LDH, LBP patients and healthy participants. Despite included studies demonstrating significantly altered gait patterns in LDH, LSS and LBP, other gait parameters beyond spatiotemporal metrics such as gait phases, asymmetry and variability have been largely omitted (*Table 2*). Moreover sensitivity/specificity analyses to discriminate between healthy, LDH and LBP participants was not performed. Moreover, results derived from Bonab *et al.*'s "WIN-TRACK" instrumented walkway for gait analysis likely reflects the individual's 'best' performance rather than 'free-living' gait (29). This may arise due to participants focussing more on walking in standardised laboratory settings when electronic walkways, passive marker systems or motion-capture systems are used, when compared to the results of unobserved monitoring using a discrete wearable device.

Most existing studies of the lumbar spine did not analyse discriminative performance of gait metrics in distinguishing pathological gait patterns from normative gait. This is with the (only) exception of Bidabadi *et al.* who developed and assessed machine learning algorithms with measured gait parameters in participants with L5 radiculopathy associated dorsiflexion weakness or 'foot-drop' achieving a

classification accuracy of 93.18% (AUC =0.97) (47). These studies have frequently been conducted in other spinal disease patient populations such as spondylarthritis (48), spinal cord injury (49) and other disease populations including dementia (50), Parkinson's disease (51,52), stroke (53,54) and musculoskeletal conditions (55,56). Thus, future studies should investigate the diagnostic utility of gait metrics that differ significantly between healthy participants and participants with lumbar spine diseases. Such studies may pave the way for wearable sensor-based gait analysis and objective gait metrics to be implemented in spine care.

Conclusions

Previous studies have highlighted differing patterns of gait deterioration in degenerative diseases of the lumbar spine, albeit with gaps in knowledge (*Table 2*). While asymmetry and variability are the most distinguishing gait variables in LSS, reduced gait velocity and cadence are present in LDH. Slight spatial and temporal changes are present in LBP. Most of these studies have used laboratory-based methods likely reflecting the individual's 'best' performance, with few studies using discrete wearable devices to capture 'free-living' gait. Whilst emerging in other patient populations, diagnostic performance of wearable accelerometry-derived gait metrics is not commonly assessed in participants with degenerative diseases of the lumbar spine.

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Supplementary

Appendix 1: Search of literature

Medline: 1946 to February 28th, 2021

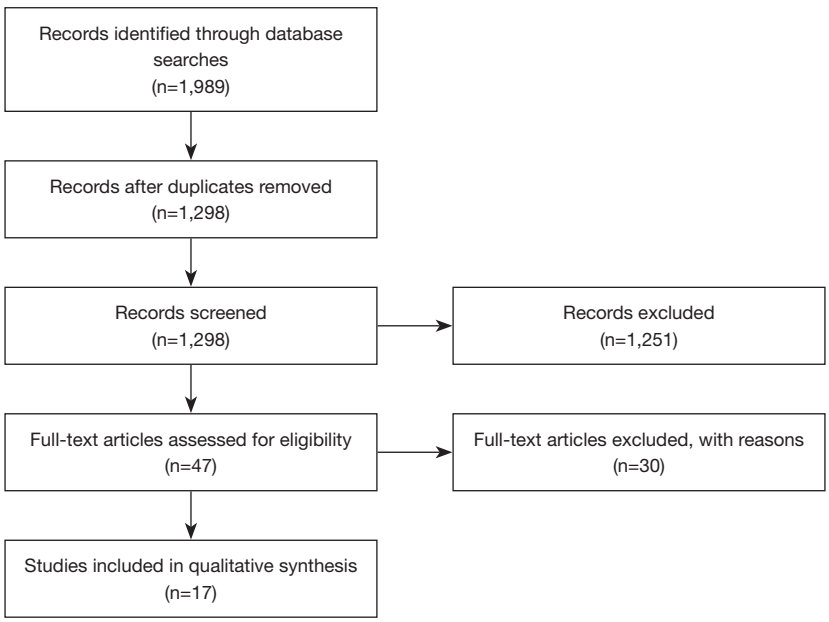
Degenerative Lumbar Spine Disease	*Analysis of Gait and Walking Metrics*
Anatomy:	10. Exp gait/
1. Exp lumbar vertebrae/	11. Exp gait analysis/
2. Exp zygapophyseal joint/	12. (gait OR gait metric*).ti,ab,kw.
3. Exp intervertebral disc/	13. 1-9 OR/
Pathology:	14. 10-12 OR/
6. Exp spinal stenosis/	15. 13 AND 14
7. Exp intervertebral disc degeneration/	16. Limit 15 to (English language and Humans)
8. Exp low back pain/	
9. (lumbar adj3 stenosis OR dis? Adj3 herniat* OR degenerative dis? Disease).ti,ab,kw.	

This search strategy was also translated for Embase and PubMed.
Embase: 1974 to February 28th, 2021
Pubmed: 1966 to February 28th, 2021

Search Source (Database)	*Record Hits*
PubMed	756
Medline	573
Embase	660
Records identified	1989
Duplicate records identified and removed	691
Unique records identified	1298
Included Studies (after title, abstract screening)	47
Included Studies (after full text review)	17
Included Studies (Lumbar Spinal Stenosis)	5
Included Studies (Lumbar Disc Herniation)	2
Included Studies (Low Back Pain)	10

https://dx.doi.org/10.21037/jss-21-91

Appendix 2 Flow-diagram of included articles



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