



# Proposed objective scoring algorithm for clinical evaluation of walking asymmetry in lumbar disc herniation, based on relevant gait metrics from wearable devices: The Gait Symmetry Index (GSi<sup>TM</sup>) – Observational study



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## 1. Introduction

With an incidence between 5 and 20 per 100 lumbar disc herniation (LDH) remains one of the most common causes of low back pain (Andersson, 1999). LDH also remains among the most common diagnoses and principal causes of spine surgery in adults (Martin et al., 2008). In severe acute episodes surgical intervention may be required typically in the form of a lumbar decompression and microdiscectomy (Swartz and Trost, 2003; Vialle et al., 2010). Conservative measures may be implemented during the healing process including regular analgesia, steroid injections, physiotherapy and hydrotherapy (Vialle et al., 2010; Wang et al., 2002). Ultimately the goals of these interventions as well as surgery are uniform: to promote return to a baseline level of pain, mobility, and function.

The decision for any intervention is clinical, although a variety of adjuncts may be used to influence treatment decisions. Not limited to LDH, a variety of subjective validated patient questionnaires including the SF-36 and the Oswestry Disability Index (ODI) are often implemented to assess the functional impact of these conditions as well as intervention efficacy (by pre- and post-operative comparison) (Falavigna et al., 2017). In the COVID-19 milieu of prevalent telehealth use, the utility of these questionnaires has also been vital where patients may not always have safe access to direct patient interaction and assessment (Mobbs et al., 2020; Mobbs and Betteridge, 2020a). Although telehealth-based strategies have emerged for a variety of physician-patient interactions this has not yet reached a satisfactory level to substitute examination (Shigekawa et al., 2018).

Walking metrics can be used as useful predictors of spine health and function when assessing and monitoring a patient's recovery (Mobbs et al., 2018; Ghent et al., 2020; Mobbs, 2020; Mobbs and Betteridge, 2020b). These objective and quantitative metrics range from simple gait

parameters as step count and gait velocity to complex algorithms such as the Gait Posture Index or Simplified Mobility Score (Mobbs et al., 2018; Mobbs, 2020; Mobbs and Betteridge, 2020b; Betteridge et al., 2021a).

The use of wearable devices to capture objective walking metrics and evaluate a patient's functional ability is not a novel concept (Mobbs et al., 2018, 2019, 2020; Mobbs and Betteridge, 2020a, 2020b; Ghent et al., 2020; Mobbs, 2020; Betteridge et al., 2021a; Chakravorty et al., 2019; Simpson et al., 2019), although its uptake and use in the clinical environment is sparse (Lu et al., 2020). Consumer volumes of smart devices that measure gait patterns have been increasing in the last 5–10 years, with devices becoming more accurate, sophisticated, and affordable in this process (Henriksen et al., 2018). Despite this there are currently no standard recommendations on how to interpret simple parameters and integrate them into the clinical decision-making process.

Using a chest-based inertial wearable sensor, we aim to examine the quantitative gait pattern (in particular, walking asymmetry) of participants with LDH when compared with 'normative' gait according to a healthy and pain-free age-matched control population. The present study is the first of its kind exploring aspects of walking asymmetry and employing a wearable sensor-based study design. From analysing this data, we propose a novel clinical scoring unit, the *Gait Symmetry Index (GSi<sup>TM</sup>)*, to objectively evaluate walking asymmetry in LDH and other unilateral gait-altering pathologies, such as hip and knee osteoarthritis or stroke.

## 2. Methods

### 2.1. Rationale for Gait Symmetry Index (GSi)

The GSi aims to quantify walking symmetry with a scoring range of 0 (highly asymmetric) to 100 ('normal' gait symmetry). The GSi reflects

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Abbreviations	
GV	Gait Velocity
ST	Step Time
SL	Step Length
STA	Step Time Asymmetry
SLA	Step Length Asymmetry
GSI	Gait Symmetry Index
IMU	Inertial Measurement Unit
MMC	MetaMotionC - Commercial IMU Device
ODI	Oswestry Disability Index
VAS	Visual Analogue Score
LDH	Lumbar Disc Herniation
BMI	Body Mass Index

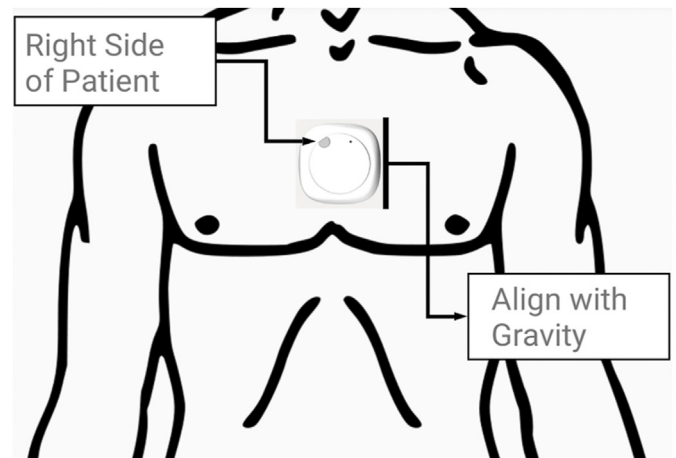


Fig. 1. Frontal view of subject showing position of MetaMotionC wearable device attachment, prior to walking episode. Device was placed on the skin immediately superior to the sternal angle for gait analysis of participants.

deviation from mean normative values for each gait metric. The normative values were acquired from wearable sensor-based objective data capture in a control population of 33 participants in the present study. We propose gait velocity, step time asymmetry and step length asymmetry as relevant metrics to be considered when assessing walking asymmetry (Table 1). Due to the significant correlation of gait velocity with functional disability in various gait-altering pathologies (Mobbs, 2020), a slightly higher weighting was allotted in the scoring algorithm (Table 2).

The GSI aims to objectify clinical gait assessment in unilateral gait disorders (e.g., stroke, sciatica, osteoarthritis). In particular, the GSI seeks to evaluate walking asymmetry in the community or at-home (termed ‘free-living’ gait) with data extraction from a wearable device providing continuous, non-biased, and objective data stream of patient performance. Clinical performance of the proposed GSI was assessed in a prospective, non-randomised single surgeon series of 33 patients with LDH patients, by similar objective data capture using wearable inertial sensors.

## 2.2. Study participants

The participants of this study were a sample of patients presenting to the NeuroSpine Clinic (Sydney, Australia), with radiating buttock and/or leg pain (sciatica) in February–July 2021. During their clinic visit, study parameters and risks were discussed, and consent obtained. Patients presenting with symptoms of radiating buttock and/or leg pain or ‘sciatica’, secondary to LDH were considered for inclusion. Exclusion criteria included infection, cancer, prior lumbar spine surgery at the index level, and presence of other potentially gait-altering pathologies including knee, hip or neurological dysfunction. Participants completed a

Table 1  
Relevant metrics in GSI.

Metric	Normative Values (Mean ± SD)	Scoring Range	Score
1. Gait velocity (m/s)	1.43 ± 0.18	0–1.4	0–40
2. Step time asymmetry (ms)	31.6 ± 16.2	>32	0–30
3. Step length asymmetry (cm)	5.37 ± 2.01	>5.4	0–30
GSI total			100

Table 2  
Scoring of GSI.

Gait Velocity (GV)		Step time asymmetry (STA)		Step length asymmetry (SLA)	
$GV < 1.35 \frac{m}{s}$	$\left\{ \frac{GV}{1.4} \right\} \times 40$	$STA > 32 \text{ ms}$	$\left\{ \frac{32}{STA} \right\} \times 30$	$SLA > 5.4 \text{ cm}$	$\left\{ \frac{54}{SLA} \right\} \times 30$
$GV > 1.35 \frac{m}{s}$	40	$STA < 32 \text{ ms}$	30	$SLA < 5.4 \text{ cm}$	30

participant questionnaire and a subsequent semi-structured interview. After obtaining demographic and clinical information for each participant by this process, eligibility for inclusion was determined. Age-matched healthy participants were recruited from the community as controls in a 1:1 ratio for this study following a similar process. With consent from participants, their electronic medical record was also accessed and cross-checked against exclusion criteria.

## 2.3. Ethics

Approval was obtained from the South Eastern Sydney Local Health District, New South Wales, Australia (HREC 17/184). All participants provided written informed consent.

## 2.4. Sample size calculations

Due to no prior studies of this design, it was not possible to estimate an expected effect size, and thus power analysis was not performed to calculate required sample size. However, based on the few existing (laboratory-based) studies of gait in lumbar disc herniation by Bonab et al. (2020) (Bonab et al., 2020) and Huang et al. (2011) (Huang et al., 2011), an idea of minimum required sample size (for LDH participants) was obtained to guide participant recruitment (n = 25 and n = 12, respectively).

## 2.5. Procedure

Prior to the walk, participants were fitted at the sternal angle (Fig. 1) with the inertial measurement unit: MetaMotion© (MMC) manufactured by Mbientlab Inc. (California, USA). Following a short initial pause to orient the MMC device, participants walked a self-selected distance (15–120 m) along an unobstructed pathway on level ground. Trials were discarded if the patient did (or could) not pause to orient the device, walk a minimum of 15 m or required a walking aid during the bout.

### 2.6. Wearable device

The MMC is a wearable sensor which contains a 16bit 100 Hz triaxial accelerometer for the detection of linear acceleration (anteroposterior, mediolateral, and vertical), a 16bit 100 Hz triaxial gyroscope for the detection of angular acceleration (pitch, roll and yaw), and a 0.3 μT 25 Hz triaxial magnetometer to assess orientation relative to the Earth's magnetic field (North-South). Following signal processing with a Kalman filter, captured data is stored as a matrix of the values corresponding to each time point (100 captures per second) for up to 20 min of walking.

### 2.7. Data processing

The data collection and processing protocols used in the present study are reported in detail by Betteridge et al. (2021) (Betteridge et al., 2021b). For the purposes of this study, the MMC device recorded the entire walking bout, and the data captured was transmitted via Bluetooth™ to an Android™ smartphone running the IMUGait Recorder application developed specifically for this study. The IMUGait Recorder application then uploaded the raw data to a centralised database where a modified version of Czech et al.'s open-source python program (IMUGaitPy program) was used to process the gait metrics for that walking bout (Czech and Patel, 2019). The IMUGaitPy program was then used for gait detection and extraction of gait features across three domains (spatiotemporal, asymmetry and variability) to calculate relevant gait metrics including, gait velocity, step time, step length, step time asymmetry and step length asymmetry. Relevant gait metrics for healthy controls and lumbar disc herniation patients was calculated according to the equations below (ST = step time, SL = step length, GV = gait velocity, STA = step time asymmetry, SLA = step length asymmetry, n = steps taken over a given bout, i = specific step number):

$$GV = \frac{\text{Total distance}}{\text{Total time}} = \frac{\text{average SL}}{\text{average ST}} = \frac{\sum_{i=1}^n GV \text{ of step}_i}{2n}$$

$$ST = \frac{\sum_{i=1}^n \text{step time}_i}{2n}$$

$$SL = \frac{\sum_{i=1}^n \text{step length}_i}{2n}$$

$$STA = \frac{\sum_{i=2}^n (\text{step time}_i - \text{step time}_{i-1})}{2n}$$

**Table 3**  
Demographic and clinical characteristics of participants.

	Controls	LDH	LDH Subgroups		P
			Surgical	Conservative	
<b>Demographic</b>					
N	33	33	14	19	
Age (mean ± SD)	44 ± 13	44 ± 13	44 ± 9	45 ± 16	0.9965
Female (%)	17 (52)	7 (21)	2 (14)	5 (26)	<b>0.0191</b>
Height (m)	168 (1.50–1.88)	1.78 (1.48–1.95)	1.78 (1.52–1.93)	1.77 (1.48–1.95)	<b>0.0028</b>
Weight (kg)	72 (50–110)	81 (50–121)	82 (71–120)	81 (50–121)	<b>0.0094</b>
BMI	25 (18–37)	27 (22–38)	26 (23–38)	27 (21–38)	0.2909
Smoking (%)	1 (3)	3 (9)	2 (14)	1 (5)	0.5656
Diabetes (%)	2 (6)	1 (3)	0 (0)	1 (5)	0.7816
<b>Clinical</b>					
Daily Step Count	N/A	3500 (100–12000)	2000 (100–12000)	3700 (1000–10000)	0.8547
Oswestry Disability Index (mean ± SD)	0	42.2 + 21.6	47.7 + 22.7	37.8 + 20.2	0.4677
VAS Pain Score (mean ± SD)	0	6.1 + 2.4	6.6 + 2.5	5.7 + 2.4	0.3729
<b>Diagnosis (Level)</b>					
Multi (L5/S1, L4/5)	N/A	2	2	0	0.6681
L5/S1	N/A	11	4	7	
L4/5	N/A	8	3	5	
L3/4	N/A	2	0	2	
L2/3	N/A	2	0	2	

P value in the table represents difference between groups derived from Kruskal Wallis tests or ANOVA. Findings significant at the level p < 0.05 are bolded. BMI = Body Mass Index.

$$SLA = \frac{\sum_{i=2}^n (\text{step length}_i - \text{step length}_{i-1})}{2n}$$

### 2.8. Statistical analysis

Data analyses were performed using Prism 9 (GraphPad Software). Normality was assessed using Shapiro-Wilk tests and inspection of histograms where necessary and statistical significance was considered for p-value < 0.05. Descriptive statistics were calculated for demographic variables including; age, gender, presence of diabetes and smoking. Spatiotemporal parameters of gait were calculated, and step measurements chosen for calculations of gait asymmetry due to greater reliability being reported in literature, compared stride measurements (Galna et al., 2013). Differences in the aforementioned gait metrics and GSi scores between LDH participants (surgical management and conservative management and pooled groups) and control participants were calculated using Kruskal-Wallis H test or one-way analysis of variance (ANOVA) tests following analysis of histogram and Shapiro-Wilks testing for normality. Correlation of GSi scores with ODI and VAS Pain scores was assessed by simple linear regression.

## 3. Results

### 3.1. Participant demographics

A total of 66 participants met the inclusion for this observational study of gait over the study period comprising of 24 females and 42 males. 33 LDH participants were sub grouped into 14 surgical management and 19 conservative management with 33 age-matched controls recruited. Included participants were of similar demographic characteristics (age, BMI, smoking and diabetic status) as seen in Table 3, with the average age (mean ± age) for the study cohort being 44 ± 13 years (surgical: 44 ± 9, conservative: 45 ± 16).

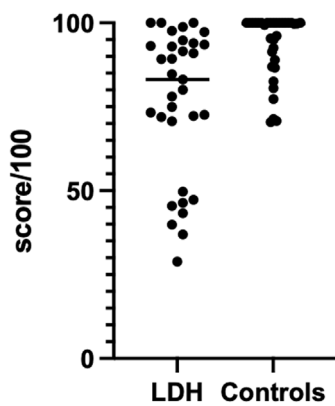
The average daily step count of LDH participants was 3500 (range, 100–12000) with ODI of 42.2 ± 21.6 (mean ± SD) and VAS pain score of 6.1 ± 2.4. Single-level disc herniation diagnoses comprised a range of index levels including L5/S1 (11), L4/5 (8), L3/4 (2) and L2/3 (2). 2 LDH participants had multi-level disc herniations (L4/5 and L5/S1). Although these preoperative characteristics were on average worse in the operative management subgroup compared to the conservative management subgroup, these differences were not statistically significant (Table 3).

**Table 4**  
Gait metrics of participants derived from wearable device.

	Healthy (n = 33)	LDH			F/H	P
		Pooled (n = 33)	Surgical (n = 14)	Conservative (n = 19)		
<b>Spatial and Temporal Metrics</b>						
<b>Gait Velocity (m/s)</b>	1.43 ± 0.182	1.14 ± 0.260	1.06 ± 0.328	1.21 ± 0.180	12.4	<0.0001
(control – difference)		–20.3%	–25.9%	–15.4%		
<b>Step Length (cm)</b>	72.9 ± 10.2	66.0 ± 12.0	61.9 ± 13.1	69.0 ± 10.6	3.75	0.0135
(control – difference)		–9.47%	–15.1%	–5.35%		
<b>Step Time (s)</b>	0.519 (0.415–0.590)	0.574 (0.497–0.889)	0.581 (0.501–0.889)	0.574 (0.497–0.661)	30.2	<0.0001
(control – difference)		+10.6%	+12.0%	+10.6%		
<b>Asymmetry</b>						
<b>Step Time Asymmetry (ms)</b>	29.0 (11.9–70.2)	35.7 (12.6–425)	73.0 (22.1–425)	34.2 (12.6–155)	9.56	0.0227
(control – difference)		+23.1%	+51.7%	+17.9%		
<b>Step Length Asymmetry (cm)</b>	4.86 (2.54–9.71)	6.76 (3.25–33.6)	9.94 (3.44–15.0)	5.37 (3.25–33.6)	12.1	0.0071
(control – difference)		+39.1%	+105%	+10.5%		
<b>Gait Symmetry Index (GSi)</b>						
<b>GSi (score/100)</b>	99.8 (70.5–100.0)	83.1 (28.9–100.0)	61.2 (28.9–100.0)	89.2 (36.9–100.0)	21.3	<0.0001
(control – difference)		–16.7%	–38.7%	–10.6%		

Normally distributed data analysed using one-way ANOVA is displayed as (mean ± standard deviation) while non-parametric analysis is displayed as (median (minimum–maximum)). P value in the table represents difference between groups derived from Kruskal Wallis tests or ANOVA. m = metre, s = second. ms = millisecond.

**Gait Symmetry Index (GSi)**



**Fig. 2.** Distribution of Gait Symmetry Index for lumbar disc herniation participants (n = 33), as compared to control participants (n = 33). GSi = Gait Symmetry Index, LDH = lumbar disc herniation, n = number of participants.

3.2. Gait metrics

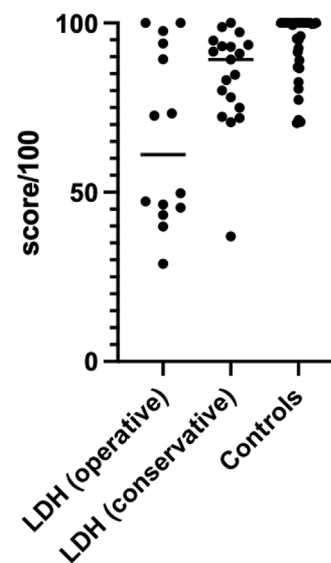
Spatiotemporal parameters including gait velocity (p < 0.0001), step length (p = 0.0135) and step time (p < 0.0001) along with asymmetry parameters for step time (p = 0.0227) and step length (p = 0.0071) were significantly different between LDH and controls (Table 4). LDH participants have a typical gait pattern of lower gait velocity (–20.3%) lower step length (–9.47%) whilst step time (+10.6%), step time asymmetry (+23.1%) and step length asymmetry (+39.1%) are increased. These deteriorations in gait parameters were greater in the surgical management subgroup, compared to the conservative management subgroup.

3.3. Correlation with pain and function

Walking asymmetry according to GSi was significantly different across control and LDH participants (p < 0.0001). GSi scores (median, range) were lower in LDH participants (83.1, 28.9–100.0) compared to controls (99.8, 70.5–100) as seen in Fig. 2. Differences in GSi scores between the surgical management (61.2 (28.9–100.0) and conservative management (89.2 (36.9–100.0) subgroups demonstrate a large range to identify, assess and monitor walking asymmetry of LDH participants (Fig. 3a–d).

Moreover, GSi scores also correlated with patient-reported outcome measures (Table 5) such as the ODI (Fig. 4), with a slope of –0.7345 (r squared = 0.5325, p < <0.0001). This correlation was also present with

**Gait Symmetry Index (GSi)**



**Fig. 3a.** Distribution of Gait Symmetry Index for lumbar disc herniation based on operative (n = 14) and conservative management (n = 19) subgroups, as compared to control participants (n = 33). GSi = Gait Symmetry Index, LDH = lumbar disc herniation, n = number of participants.

VAS Pain Scores (albeit weaker), with a slope of –4.021 (r squared = 0.2049, p = 0.0082), as seen in Fig. 5.

4. Discussion

Our pilot work in the spine surgery setting of lumbar disc herniation revealed significant objective differences in gait metrics when compared to healthy age-matched subjects. Examination of gait metrics has been effective in detecting the expected significant gait deficits in walking asymmetry within the LDH population. This translates to a lower gait velocity (median: 22.6%), step length (median: 12.3%) and cadence (median: 12.2%) and a corresponding increased step time (+10.8%). These results align with Bonab et al.'s (2020) (Bonab et al., 2020) findings from a WIN-TRACK platform suggesting wearable devices may be of reasonable consistency with gold-standard gait analysis methods to warrant clinical use. The accuracy of the chest-based wearable device employed in the present study has been previously validated by Betteridge et al. (2021) (Betteridge et al., 2021b) for gait metrics (videography

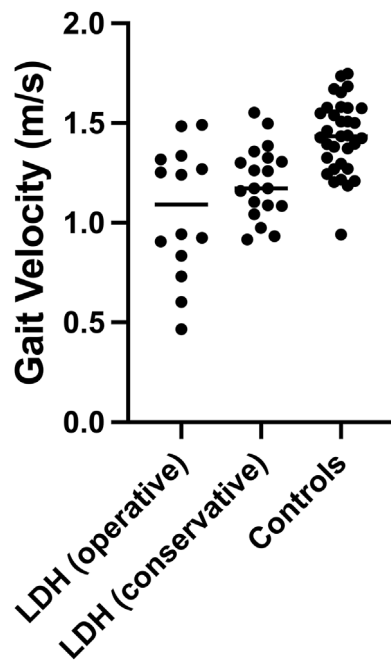


Fig. 3b. Distribution of Gait Velocity (m/s) for lumbar disc herniation based on operative (n = 14) and conservative management (n = 19) subgroups, as compared to control participants (n = 33). GSi = Gait Symmetry Index, LDH = lumbar disc herniation, n = number of participants.

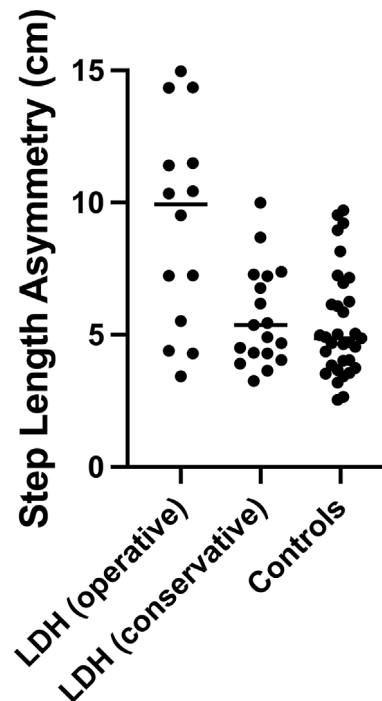


Fig. 3d. Distribution of Step Length Asymmetry (cm) for lumbar disc herniation based on operative (n = 14) and conservative management (n = 19) subgroups, as compared to control participants (n = 33). GSi = Gait Symmetry Index, LDH = lumbar disc herniation, n = number of participants.

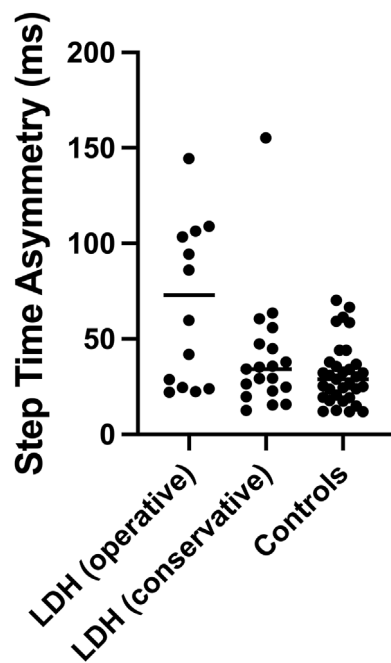


Fig. 3c. Distribution of Step Time Asymmetry (ms) for lumbar disc herniation based on operative (n = 14) and conservative management (n = 19) subgroups, as compared to control participants (n = 33). GSi = Gait Symmetry Index, LDH = lumbar disc herniation, n = number of participants.

versus sensor, intraclass correlation coefficient) including step count (1.00,  $p < 0.001$ ), gait velocity (0.875,  $p < 0.001$ ), step time (0.982,  $p < 0.001$ ) and step length (0.862,  $p < 0.001$ ) in healthy participants (n = 33). Similar accuracy was also reported for participants with neurological pathologies such as lumbar spinal stenosis (n = 21) (Betteridge et al., 2021b). However, the absence of an accuracy arm in this present study is a limitation, and future studies may endeavour to ensure accuracy is consistent across various spinal pathologies.

Table 5

Correlations for GSi and patient-reported outcome measures.

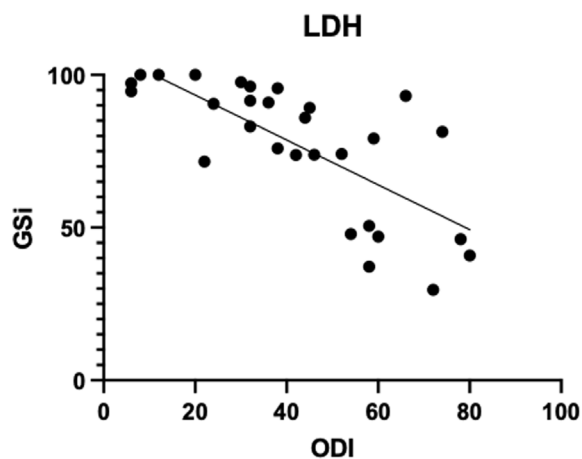
	Slope	95% CI	R <sup>2</sup>	P value
ODI (n = 29)	-0.7345	-1.006 to -0.4627	0.5325	<0.0001
VAS Pain Score (n = 33)	-4.021	-6.923 to -1.119	0.2049	0.0082

GSi = Gait Symmetry index; ODI = Oswestry Disability Index, VAS = Visual Analogue Scale.

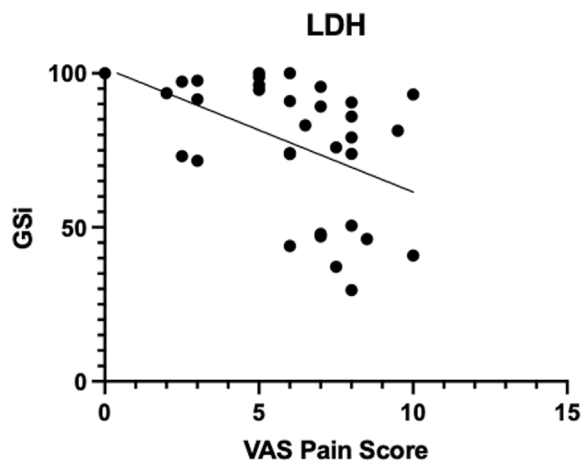
We propose that objective gait data retrieved from more prolonged wearable based assessment tracking multiple gait cycles and significant distance (~100 m) is a more holistic assessment of functional ability compared to patient questionnaires which provide a “snapshot” of health status and are subjective by their very nature. Previous work by Stienen et al. (2019) suggests consistent discordance ( $r < 0.50$ ) between patient-reported questionnaires and objective tools when it comes to assessing functional impairment in degenerative lumbar disease (Stienen et al., 2019). As such, the GSi scores of LDH participants in the present study were not entirely correlated with their self-reported ODI and VAS questionnaire scores. Although the GSi could potentially be used as a remote proxy for the objective assessment of functional impairment, we acknowledge that these objective metrics alone do not necessarily consider the psychosocial aspects associated with the burden of disease.

Most notably, the present study suggests LDH participants experience greater gait asymmetry both in terms of step time (+70.0%) and step length (+51.6%), warranting our interest in the development of the new and novel score of gait symmetry, the GSi<sup>TM</sup>. This is not an unexpected finding as patients experience worse symptoms unilaterally, and try to over-correct gait on the corresponding side to limit time spent loading the symptomatic side and exacerbating pain. Similar findings may also be expected with other unilateral pathologies including arthritic joints, cerebrovascular accident, or myopathy.

The GSi represents a novel index with easy interpretation, specifically designed for the clinical setting as a clinical decision-making adjunct. Although not specific for the LDH setting, at a cursory glance it represents a sensitive measure to detect individuals that may require further



**Fig. 4.** Correlation between Oswestry Disability Index and Gait Symmetry Index for lumbar disc herniation participants ( $n = 29$ ). GSi = Gait Symmetry Index, LDH = lumbar disc herniation, ODI = Oswestry Disability Index,  $n$  = number of participants.



**Fig. 5.** Correlation between Visual Analogue Scale (VAS) Pain Scores and Gait Symmetry Index for lumbar disc herniation participants ( $n = 33$ ). GSi = Gait Symmetry Index, LDH = lumbar disc herniation, VAS = Visual Analogue Scale,  $n$  = number of participants.

investigation or intervention to restore a closer to ‘normal’ (and symmetric) gait pattern. There have been other gait algorithms proposed in the clinical setting (Betteridge et al., 2021a; Mobbs et al., 2019) although uptake has not yet been integrated as measures of walking health.

Our findings suggest that the GSi is sensitive at detecting LDH-associated abnormalities in gait symmetry not only amongst surgical patients with severe symptoms, but also among non-operative patients with more tolerable symptoms (Fig. 5). Given a lower distribution of GSi scores in the pathological LDH population (Figs. 2 and 3a) and its relevant components (Fig. 3b–d), the GSi warrants future large volume examination to determine the presence of (any) clinically pertinent cut-offs. Screening and stratification of patients as such, may objectify investigation lower back pain (for presence of LDH), surgical intervention (rather than conservative management) or implementation of falls preventative measures (such as walking aids). At present this work demonstrates GSi’s utility at detecting gait abnormalities however ongoing research is required to assess its diagnostic utility and feasibility of clinical use, especially in other unilateral gait-altering pathologies. As a repeated measure there is potential for its use in the setting of reassessing gait deficits during rehabilitation and post-surgical follow-up.

However, there are some limitations in this study which must be acknowledged. Firstly, the recruitment of LDH subjects was from a pool

of subjects referred for neurosurgical opinion. This implies that in the spectrum of LDH severity, patients were more likely to be symptomatic and on the severe side of the spectrum possibly exaggerating the effects seen in the LDH pool. Moreover, other factors affecting gait in LDH participants such as duration of symptoms, pre-existing physical activity levels and presence of associated neurological deficits are not accounted for in our analyses. Additionally, although controls are age-matched with LDH participants significant differences are present in gender, body mass index, height and weight which may influence gait performance (in particular, gait velocity). However, given that by design the GSi is not to diagnose, rather detect subjects with the most significant gait deficits (that require assistance or intervention) the magnitude of these discrepancies is debatable.

Additionally, this pilot cohort where the mean age was slightly younger than the typical LDH subject, may confer some difference to the gait parameters of cohorts in other studies. Another limitation is the significant standard deviation in our data for both pathological and normative data, likely attributable to the small-moderate sample size of our analysis (LDH = 33 versus Control = 33). Thus, future studies may require large-volume cohorts to clarify normative values and the magnitude of the effect sizes identified in the present study. Despite the given limitations, the finding of significantly lower distribution of GSi scores in the pathological LDH population demonstrates possible utility of the GSi scoring algorithm for the screening, identification and stratification of patients with (severe) walking asymmetry. However, further testing and validation in a real-world setting with large-volume cohorts is warranted to determine safety and feasibility of clinical use.

## 5. Conclusion

Wearable sensors are capable of detecting gait abnormalities in lumbar disc herniation. Wearable sensor-derived gait metrics allow the development of objective “gait scoring tools” such as the GSi, which may offer objective insight into patient function. GSi scores demonstrated significantly lower distribution among both symptomatic LDH patients requiring intervention (both conservative and surgical) from a control population. More voluminous cohort studies across multiple gait pathologies are needed to determine external validity.

## Ethics

Ethics for this study was obtained from the South Eastern Sydney Local Health District, with reference code 17/184.

## Author statement

**Pragadesh Natarajan:** Conception, Methodology, Software, Writing— Original Draft; **R. Dineth Fonseka:** Methodology, Data curation, Investigation. **Luke Sy:** Software, Methodology, **Ralph Mobbs:** Conception, Methodology, Supervision, Writing – Review & Editing, Project Administration, Resources; **Monish Maharaj:** Supervision, Methodology, Writing— Original Draft.

## Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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## Declaration of competing interest

The authors declare that they have no competing interests.

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