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 (GSiTM) – Observational study

Pragadesh Natarajan a,b,c,d,*, R. Dineth Fonseka a,b,c,d, Luke Sy a,e, Ralph Jasper Mobbs a,b,c,d, Monish Maharaja a,b,c,d

Abstract

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; Sonesson, 1999). LDH also 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 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; Sonesson, 1999).

1. Introduction

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; Betteridge et al., 2021a). The Gait Symmetry Index (GSiTM), a chest-based inertial wearable sensor, aims 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 objective and quantitative metric for walking asymmetry exploration, the Gait Symmetry Index (GSiT).

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 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 (GSiTM), 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...
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 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 calculated 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.

### Abbreviations

| Abbreviation | Description |
|--------------|-------------|
| 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 |

### Table 1

| Metric | Normative Values (Mean ± SD) | Scoring Range | Score |
|--------|-----------------------------|---------------|-------|
| 1. Gait velocity (m/s) | 1.43 ± 0.18 | 0.1-1.4 | 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

| Gait Velocity (GV) | Step time asymmetry (STA) | Step length asymmetry (SLA) |
|--------------------|--------------------------|-----------------------------|
| GV < 1.35 m/s | $\frac{GV}{14} \times 40$ | STA > 32 ms | $\frac{32}{STA} \times 30$ |
| GV > 1.35 m/s | 40 | STA < 32 ms | 30 |

![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.](image-url)
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 captured data 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 (IMU-GaitPy 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):

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

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

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

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

Table 3

| Demographic and clinical characteristics of participants. | Controls | LDH | LDH Subgroups | P |
|--------------------------------------------------------|---------|-----|--------------|---|
| Demographic                                            |         |     |              |   |
| N                                                      | 33      | 33  | 14           | 19|
| Age (mean ± SD)                                        | 44 ± 13 | 44 ± 13 | 44 ± 9     | 45 ± 16 |
| Female (%)                                             | 17 (52) | 7 (21) | 2 (14)     | 5 (26) |
| Height (m)                                             | 168 (1.50-1.88) | 178 (1.48-1.95) | 1.78 (1.52-1.93) | 1.77 (1.48-1.95) |
| Weight (kg)                                            | 72 (50-110) | 81 (50-121) | 82 (71-120) | 81 (50-121) |
| BMI                                                    | 25 (18-37) | 27 (22-38) | 26 (23-38) | 27 (21-38) |
| Smoking (%)                                            | 1 (3) | 3 (9) | 2 (14) | 1 (5) |
| Diabetes (%)                                           | 2 (6) | 1 (3) | 0 (0) | 1 (5) |
| Clinical                                               |         |     |              |   |
| Daily Step Count                                       | N/A    | 3500 (100-12000) | 3500 (100-12000) | 0.8547 |
| Oswestry Disability Index (mean ± SD)                  | 0      | 42.2 ± 21.6 | 47.7 ± 22.7 | 0.4077 |
| VAS Pain Score (mean ± SD)                             | 0      | 6.1 ± 2.4  | 6.6 ± 2.5  | 0.3729 |
| Diagnosis (Level)                                      |         |     |              | 0.6681 |
| Multi (L5/S1, L4/5)                                    | N/A    | 2    | 2            | 0 |
| 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.

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-Wilk’s 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).

\[
SLA = \frac{\sum_{i=1}^{n} (\text{step length}_i - \text{step length}_{i-1})}{2n}
\]
measures (Table 5) such as the ODI (Fig. 4), with a slope of

Table 4
Gait metrics of participants derived from wearable device.

| Spatial and Temporal Metrics | Healthy (n = 33) | LDH | Surgical (n = 14) | Conservative (n = 19) | F/H | P  |
|-----------------------------|-----------------|-----|------------------|----------------------|-----|-----|
| Gait Velocity (m/s)         |                 |     |                  |                      |     |     |
| (control – difference)      | 1.43 ± 0.182    | 1.14 ± 0.260 | 1.06 ± 0.328 | 1.21 ± 0.180 | 12.4 | <0.0001 |
| Step Length (cm)            |                 |     |                  |                      |     |     |
| (control – difference)      | 72.9 ± 10.2     | 66.0 ± 12.0 | 61.9 ± 13.1 | 69.0 ± 10.6 | 3.75 | 0.0135 |
| Step Time (s)               |                 |     |                  |                      |     |     |
| (control – difference)      | 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 |
| Asymmetry                   |                 |     |                  |                      |     |     |
| Step Time Asymmetry (ms)    |                 |     |                  |                      |     |     |
| (control – difference)      | 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 |
| Step Length Asymmetry (cm)  |                 |     |                  |                      |     |     |
| (control – difference)      | 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 |
| Gait Symmetry Index (GSI)   |                 |     |                  |                      |     |     |
| GSI (score/100)             | 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.

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

Fig. 3. 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 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) findings from a WIN-TRACK platform suggesting wearable devices may be of reasonable consistency with gold-standard gait analysis methods to warrant clinical use.
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.

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 \( \text{GSi}^{TM} \). 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

---

**Table 5**

|                  | Slope  | 95% CI          | \( R^2 \) | \( P \text{ value} \) |
|------------------|--------|-----------------|----------|-----------------------|
| ODI (\( n = 29 \)) | -0.7345 | -1.066 to -0.4627 | 0.5325   | <0.0001               |
| VAS Pain Score (\( n = 33 \)) | -4.021 | -6.923 to -1.119  | 0.2049   | 0.0082                |

\( \text{GSi}^{TM} \) = Gait Symmetry index; ODI = Oswestry Disability Index, VAS = Visual Analogue Scale.

---

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. 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.

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.
Symmetry Index, LDH

Screening and stratification to determine the presence of (any) clinically pertinent cut-offs. The vanant components (Fig. 3b) scores in the pathological LDH population (Figs. 2 and 3a) and its relevance demonstrates GSi’s utility at detecting gait abnormalities however ongoing 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.

Funding

The authors declare that they have no funding.

Declaration of competing interest

The authors declare that they have no competing interests.
Acknowledgements

The authors would like to thank the staff including Devon McCarthy, Collette and Catherine Ragy from NeuroSpine clinic for assisting with conduct of the project and provision of study materials.

References

Anderson, G.B., 1999. Epidemiological features of chronic low-back pain. Lancet 354, 581–585.

Betteridge, C., Mobbs, R.J., Ho, D., 2021. Proposed objective scoring algorithm for walking performance, based on relevant gait metrics: the Simplified Mobility Score (SMs™)-observational study. J. Orthop. Surg. Res. 16, 419. https://doi.org/10.1186/s13018-021-02546-4.

Betteridge, C., Mobbs, R., Fonseka, R., Natarajan, P., Ho, D., Choy, W., Sy, L., Pell, N., 2021. Objectifying clinical gait assessment: using a single-point wearable sensor to quantify the spatiotemporal gait metrics of people with lumbar spinal stenosis. J. Spine Surg. 7.

Bonab, M.A.R., Colak, T.K., Toktas, Z.O., Konya, D., 2020. Assessment of spatiotemporal walking performance, based on relevant gait metrics: the SimpliMobility Score. Turk. Neurosurg. 30, 277–284.

Chakravorty, A., Mobbs, R.J., Anderson, D.B., Rooke, K., Phan, K., Yoong, N., Maharaj, M., Choy, W.J., 2019. The role of wearable devices and objective gait analysis for the assessment and monitoring of patients with lumbar spinal stenosis: systematic review. BMC Musculoskelet. Disord. 20, 288. https://doi.org/10.1186/s12891-019-2663-4.

Czech, M.D., Patel, S., 2019. GaitPy: an open-source python package for gait analysis using an accelerometer on the lower back. J. Open Sour. Softw. 4, 1778.

Falavigna, A., Dozza, D.C., Teles, A.R., Wong, C.C., Barbagallo, G., Brodke, D., Al-Mutair, A., Ghogawala, Z., Riew, K.D., 2017. Current status of worldwide use of patient-reported outcome measures (PROMs) in spine care. World Neurosurg. 108, 328–335.

Galina, B., Lord, S., Rochester, L., 2013. Is gait variability reliable in older adults and Parkinson’s disease? Towards an optimal testing protocol. Gait Posture 37, 580–585.

Ghent, F., Mobbs, R.J., Mobbs, R.R., Sy, L., Betteridge, C., Choy, W.J., 2020. Assessment and post-intervention recovery after surgery for lumbar disk herniation based on relevant gait metrics from wearable devices using the gait posture index. World Neurosurg. 142, e111–e116.

Henriksen, A., Haugen Mikalsen, M., Woldaregay, A.Z., Muzzey, M., Hartvigsen, G., Hopstock, L.A., Grimsgaard, S., 2018. Using fitness trackers and smartwatches to measure physical activity in research: analysis of consumer wrist-worn wearables. J. Med. Internet Res. 20, e110. https://doi.org/10.2196/jmir.9157.

Huang, Y.P., Brujin, S.M., Lin, J.H., Meijer, O.G., Wu, W.H., Abbasi-Bafghi, H., Lin, X.C., van Dierendonck, J., 2011. Gait adaptations in low back pain patients with lumbar disc herniation: trunk coordination and arm swing. Eur. Spine J. 20, 491–499.

Lu, Z., Zhang, J., Xie, Y., Gao, F., Xu, S., Wu, X., Ye, Z., 2020. Wearable health devices in healthcare: narrative systematic review. J. Mhealth Uhealth 8, e18907. https://doi.org/10.2196/18907.

Martin, R.I., Deyo, R.A., Minna, S.K., Turner, J.A., Comstock, B.A., Hollingsworth, W., Sullivan, S.D., 2008. Expenditures and health status among adults with back and neck problems. JAMA 299, 656–664.

Mobbs, R.J., 2020. Gait velocity (walking speed) is an indicator of spine health, and objective measure of pre and post intervention recovery for spine care providers. J. Spine Surg. 6, 353.

Mobbs, R.J., Betteridge, C., 2020. WearTel: a potential solution to lack of objective patient assessment tools in remote care during the COVID-19 pandemic. J. Spine Surg. 6, 637.

Mobbs, R.J., Betteridge, C., 2020. Daily step count and walking speed as general measures of patient wellbeing. J. Spine Surg. 6, 635.

Mobbs, R.J., Katzinias, C.J., Choy, W.J., Rooke, K., Maharaj, M., 2018. Objective monitoring of activity and Gait Velocity using wearable accelerometer following lumbar microdiscectomy to detect recurrent disc herniation. J. Spine Surg. 4, 792.

Mobbs, R.J., Mobbs, R.R., Choy, W.J., 2019. Proposed objective scoring algorithm for assessment and intervention recovery following surgery for lumbar spinal stenosis based on relevant gait metrics from wearable devices: the Gait Posture index (GPI). J. Spine Surg. 5, 300–309. https://doi.org/10.21037/jss.2019.09.06.

Mobbs, R.J., Ho, D., Choy, W.J., Betteridge, C., Lin, H., 2020. COVID-19 is shifting the adoption of wearable monitoring and telemedicine (WearTel) in the delivery of healthcare: opinion piece. Ann. Transl. Med. 8.

Shigekawa, E., Fix, M., Corbett, G., Roby, D.H., Coffman, J., 2018. The current state of telehealth evidence: a rapid review. Health Aff. 37, 1975–1982. https://doi.org/10.1377/hlthaff.2018.05132.

Simpson, L., Maharaj, M.M., Mobbs, R.J., 2019. The role of wearables in spinal posture analysis: a systematic review. BMC Musculoskel. Disord. 20, 55. https://doi.org/10.1186/s12891-019-2430-6.

Stienen, M.N., Ho, A.L., Staartjes, V.E., Maldaner, N., Veeravagu, A., Desai, A., Gautschi, O.P., Bellut, D., Regli, L., Ratliff, J.K., 2019. Objective measures of functional impairment for degenerative diseases of the lumbar spine: a systematic review of the literature. Spine J. 19, 1276–1293.

Swartz, K.R., Trost, G.R., 2003. Adherence to home-based patient assessment tools in remote care during the COVID-19 pandemic. J. Spine Surg. 6, 353.

Vialle, L.R., Vialle, E.N., Henao, J.E.S., Giraldo, G., 2010. Lumbar disc herniation. In: Revista Brasileira de Ortopedia (English Edition), 45, pp. 17–22.

Wang, J.C., Lin, E., Brodke, D.S., Youssef, J.A., 2002. Epidural injections for the treatment of symptomatic lumbar herniated discs. Clinic. Spine Surg. 15, 269–272.