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

Two-year continuous data capture using a wearable sensor to remotely monitor the surgical spine patient: a case report

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Abstract: We report the case of a 46-year-old male with long-standing low back pain who presented with a deterioration of symptoms characterised by back and right leg pain corresponding to the L4 and L5 dermatomes. An MRI scan revealed severe central and lateral recess stenosis at L4/5 secondary to a large central disc protrusion. We remotely monitored activity and general health metrics over a time-period exceeding two years. This is the first study to monitor these metrics remotely and continuously in the surgical spine patient. Over this time, he received several interventions including a spinal cord stimulator implant, and an L4/5 microdiscectomy. We tracked his fluctuating health status using the Oura Ring [objectively measuring metrics including step count, sleep patterns, heart rate (HR), heart-rate variability (HRV), and respiratory rate (RR)] and with daily self-reported scores on the Visual Analogue Scale. The Oura Ring is a convenient and lightweight wearable device that is worn on any finger. Taken together, metrics provided a comprehensive picture of deterioration and recovery, paralleling key events in the patient's history. The use of wearable devices is feasible in enabling long-term remote continuous monitoring. This may assist surgeons and rehabilitation providers in identifying early deterioration and monitoring the post-intervention course of recovery.

Keywords: Disc herniation; wearable sensor; digital health; remote monitoring; case report

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Introduction

Spinal pathologies are a common problem in clinical medicine, with a one-year incidence of a first-ever episode of low back pain ranging from 6.3% to 15.4% (1). When conservative therapies fail, spinal pathologies may be managed surgically. The monitoring of pain and functional outcomes is important for patients and healthcare providers, as it facilitates the delivery of patient-centred care whilst maintaining an efficient allocation of resources. Surgical management is associated with substantial costs (hospital admission costs alone for lumbar fusion surgery amounting to over USD $50,000 per admission over 2004–2015 in the United States (2), and thus monitoring the effectiveness of surgical techniques is also important for insurance payers and governments. This has yielded a significant body of research into the most effective ways of assessing patients with spinal pathologies.

The measurement of pre- and post-intervention outcomes in spine surgery is typically performed using patient-reported outcome measures (PROMs) such as the Oswestry Disability Index (ODI) and Visual Analogue Scale (VAS) (3). However, these measures are limited by their subjectivity (therefore restricting comparison between patients as each patient perceives their pain and disability uniquely) and inability to continuously monitor patients (4). This also makes it difficult to determine the optimal timing of intervention, with, for example, a Cochrane review pointing out a lack of agreement surrounding the timing of surgical intervention for lumbar disc prolapse (5). Instead, wearable devices (wearables) offer an objective method of pre- and postoperative patient evaluation and can be used in addition to PROMs to facilitate a more comprehensive evaluation of patients. Wearables are cheap, lightweight, and have the capacity to continuously monitor patients from a remote location, thereby exhibiting enormous potential as a mainstay of future clinical practice (6).

In the field of spine surgery, wearables have been predominantly used to capture metrics pertaining to physical activity [such as daily step count (DSC), distance travelled, and caloric expenditure] (7-9), and spatiotemporal gait metrics (such as gait velocity, step time, and step length) (10,11). However, other metrics of health that can also be measured by wearables and that have seen limited exploration in the field of spine health include heart rate (HR), respiratory rate (RR), heart-rate variability (HRV), and sleep time (12-14). Together, these form a collection of objective outcomes that can be continuously streamed to healthcare providers remotely to identify deterioration and track the postoperative course of recovery.

This case report explores the use of wearables to continuously (over a time-period exceeding two years) and remotely monitor the fluctuations in health status of a spine patient undergoing microdiscectomy surgery for lumbar disc herniation at the level of L4/5. We use a comprehensive collection of metrics including step count and general health metrics. No other study has monitored these metrics remotely and continuously in the surgical spine patient. We present the following case in accordance with the CARE reporting checklist (available at https://jss.amegroups.com/article/view/10.21037/jss-21-89/rc).

Case presentation

Case history

We report the case of a 46-year-old male with long-standing low back pain who presented with a deterioration of symptoms during October 2017. His symptoms included 7/10 low back and right leg pain (which, upon physical examination, corresponded to the L4 and L5 dermatomes) with associated muscle spasms occurring when sitting or lying supine. The patient's relevant past medical history includes an anterior lumbar interbody fusion procedure in 2013, after which intermittent discogenic low back pain was managed with a spinal cord stimulator, implanted in July 2016.

After neurosurgical assessment in October 2017 following his exacerbation of symptoms, it was determined that the spinal cord stimulator be removed. Now no longer contraindicated, an MRI scan revealed severe central and lateral recess stenosis at L4/5 secondary to a large central disc protrusion (*Figure 1*). With conservative options exhausted, rhizolysis decompression and L4/5 microdiscectomy were recommended. These procedures were completed in late October 2017, with no perioperative complications. The patient was discharged within 24 h of his final operation and returned to his information technologies occupation and light duties after 2 weeks. A timeline of the patient's medical history relevant to this case report is summarized in *Figure 2*.

Long-term data capture

From June 2016 onwards, the patient wore an Oura Ring (Oura Health Ltd., Oulu, Finland) during waking and sleep hours (except when bathing or swimming), facilitating the capture of a continuous stream of objective metrics such as step count, sleep duration, RR, HR, and HRV. In addition, the patient self-reported subjective VAS scores for most days during this time-period. Ultimately, we obtained day-by-day objective and subjective data from this patient for a time-period exceeding two years. In this way, our case report is unique since most studies investigating remote patient monitoring have timeframes under 6 months (12-15), possibly due to the difficulties in patient compliance that arise for research studies involving the long-term remote monitoring of patients.

The Oura Ring is worn around any finger and contains a pulse waveform and pulse amplitude variation detector with infrared photoplethysmography sensor, and a three-dimensional accelerometer and gyroscope (sampling rate of 250 times per second). It has a battery life lasting seven days on a single charge, with a charging time ranging from 20 to 80 min. It is waterproof, weighs four to six grams, has a width of 7.9 mm and a thickness of 2.55 mm. It is made from titanium (coated with scratch-resistant diamond-like carbon) with medical grade non-allergenic, non-metallic inner moulding (16). Although not the gold-standard, this device has been shown to have moderate-high accuracy for the measurement of heart-rate-related metrics (17), physical activity (17), and sleep-related metrics (17,18).

During the timeframe of data capture, objective measurements (made using the Oura Ring) can be

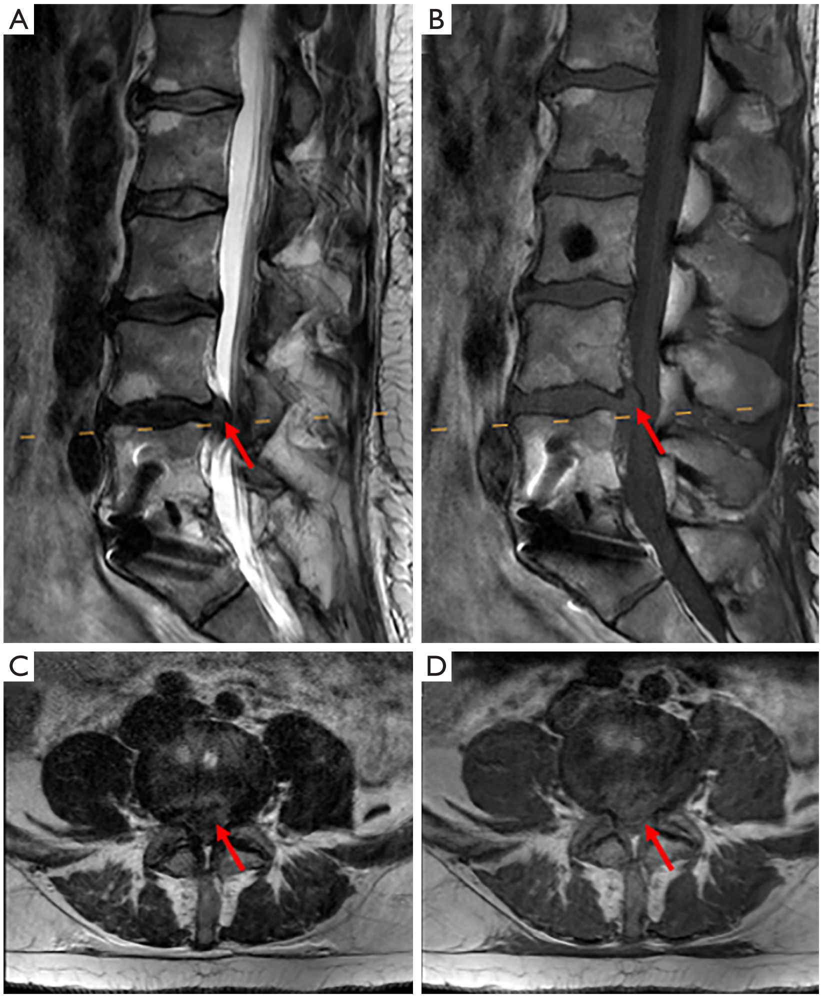

Figure 1 Our patient's lumbar disc herniation as visualized on magnetic resonance imaging. (A,B) T2-weighted image and (C,D) T1-weighted image. In each panel, the red arrow marks the disc herniation.

compared with the patient's own subjective experience (VAS scores) to provide a detailed picture of patient deterioration and recovery (holistically represented in *Figure 2*). After implantation of the spinal cord stimulator in July 2016, the patient's VAS scores demonstrate an improvement in rolling average by two points to 5/10 during September 2016 (*Figure 3*). This correlates with the beginning of an upward trend in step count (signifying post-intervention improvement), with its rolling average rising from 3,500 steps per day during September 2016 to 7,500 steps per day during January 2017 (*Figure 4*). However, the patient's VAS scores rise to a peak in rolling average of 6.8 points during July 2017, possibly reflecting overexertion with rising step counts (*Figures 3,4*). This is also near when the patient's disc herniation was speculated to have occurred, preceding the patient's rhizolysis decompression and microdiscectomy in October 2017 (*Figure 2*). This matches plateaus in the patient's sleep duration time (from rolling averages of 8 and 4 h per night of total sleep time and rapid eye movement (REM) sleep time during September 2017, to 6 and 3 h per night during October 2017, respectively) (*Figure 5*) and HRV (rolling average of 26 ms during September 2017, to 22 ms during December 2017) (*Figure 6*). Following the patient's decompression and microdiscectomy, VAS scores show a downward trend (rolling average down to 5.5 during January 2018). This parallels a steady improvement in step count rolling average (eventually exceeding 10,000 steps per day by September 2018) (representing postoperative recovery). Average HR (*Figure 7*) and RR (*Figure 8*) remained fairly stable for the timeframe of data capture.

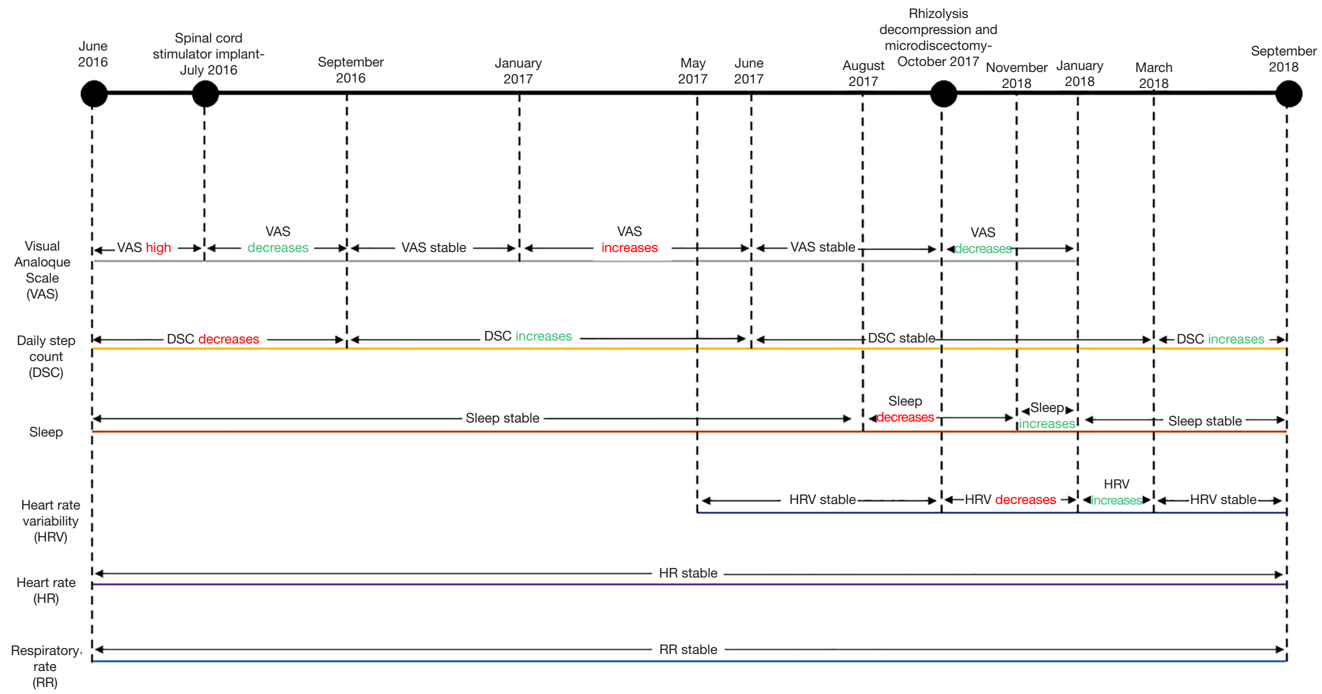

Figure 2 Timeline of significant events and long-term trends of data. The black line represents the timeline of significant events in the patient's medical history. The grey line represents long-term fluctuations in the patient's VAS score. The yellow line represents long-term fluctuations in the patient's DSC. The dark orange represents long-term fluctuations in the patient's sleep times (both total sleep time and REM sleep time follow this trend). The purple line represents long-term fluctuations in the patient's HR. The dark blue line represents long-term fluctuations in the patient's RR. VAS score data only provided until January 2018, and HRV data only available from May 2017 onwards. VAS, Visual Analogue Scale; DSC, daily step count; HRV, heart-rate variability; HR, heart rate; RR, respiratory rate; REM, rapid eye movement.

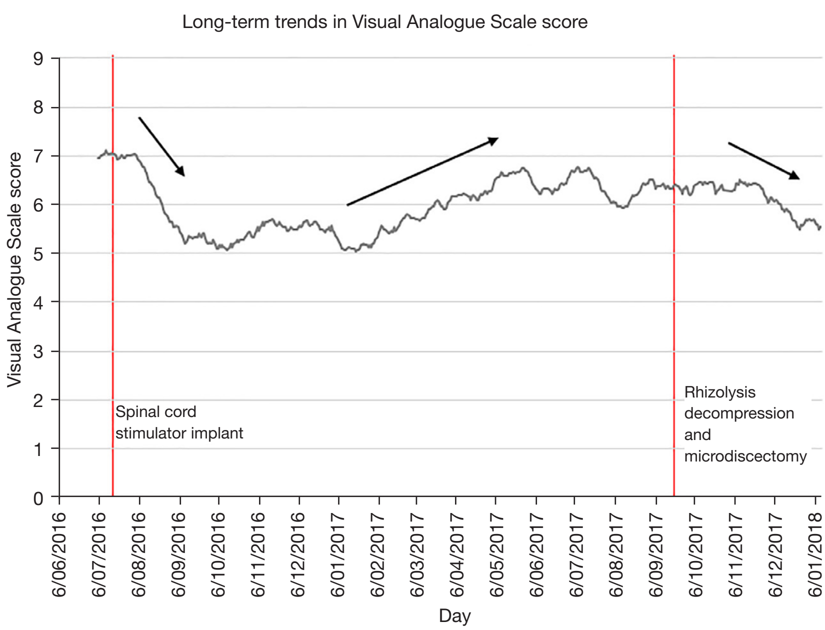

Figure 3 Long-term trends in VAS score. Thirty-day moving average is depicted. Black arrows show large-scale trends. VAS, Visual Analogue Scale.

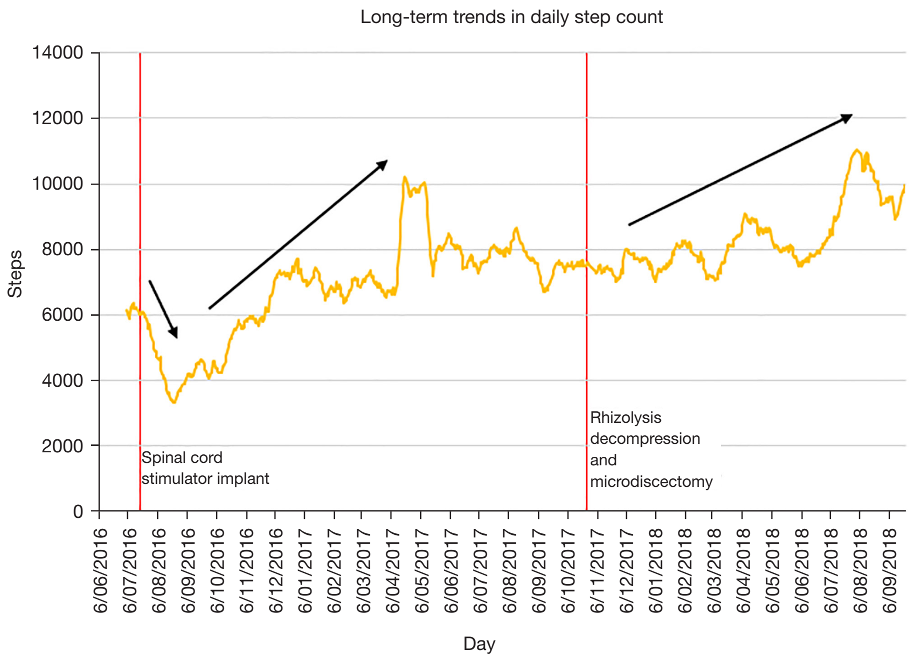

Figure 4 Long-term trends in DSC. Thirty-day moving average is depicted. Black arrows show large-scale trends. DSC, daily step count.

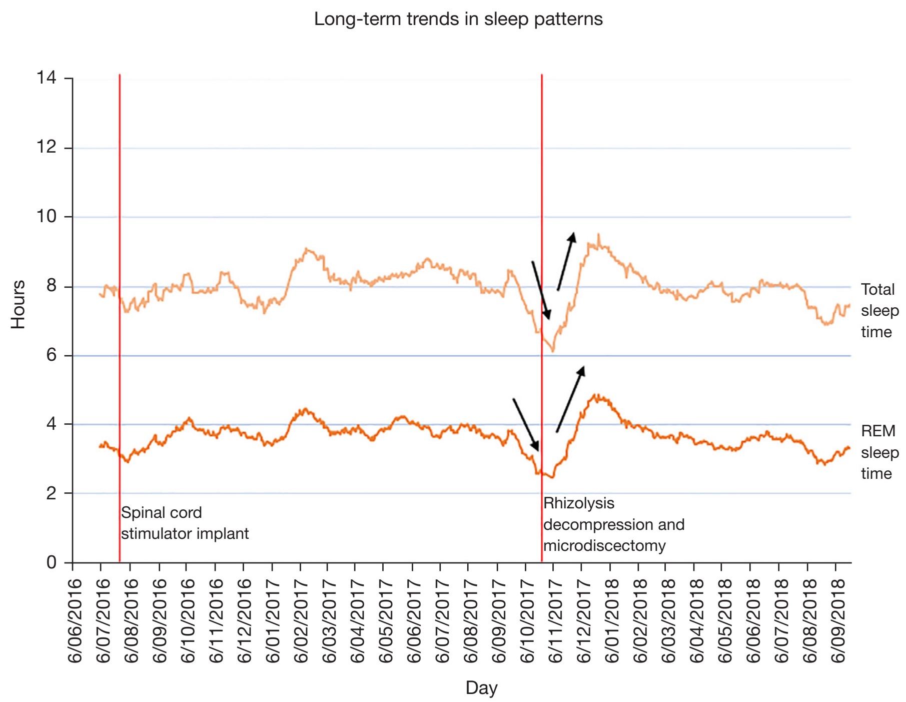

Figure 5 Long-term trends in sleep patterns. Thirty-day moving average is depicted. Black arrows show large-scale trends. Light pink trendline represents daily total sleep time, and dark orange trendline represents total REM sleep time. REM, rapid eye movement.

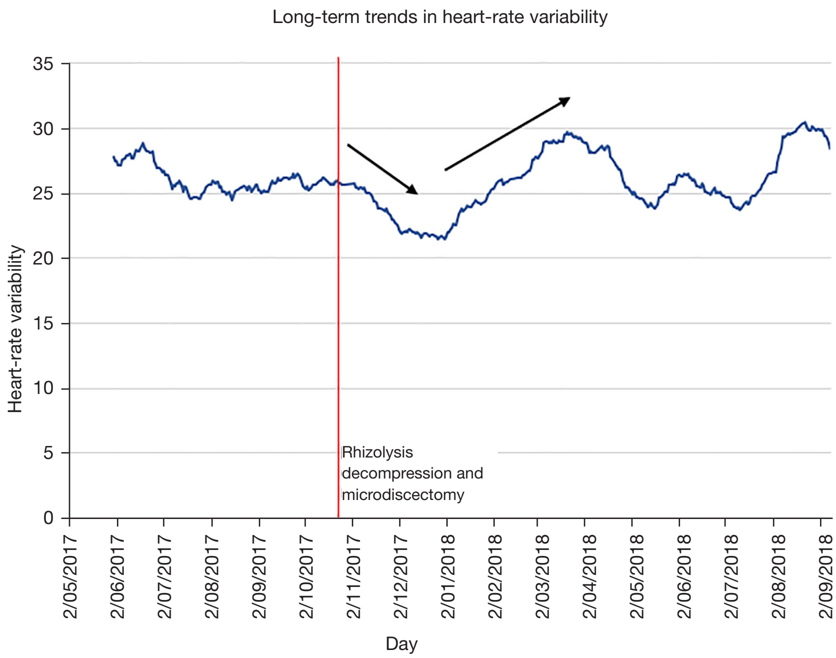

Figure 6 Long-term trends in HRV. Thirty-day moving average is depicted. Black arrows show large-scale trends. HRV, heart-rate variability.

Figure 7 Long-term trends in HR. Thirty-day moving average is depicted. HR, heart rate.

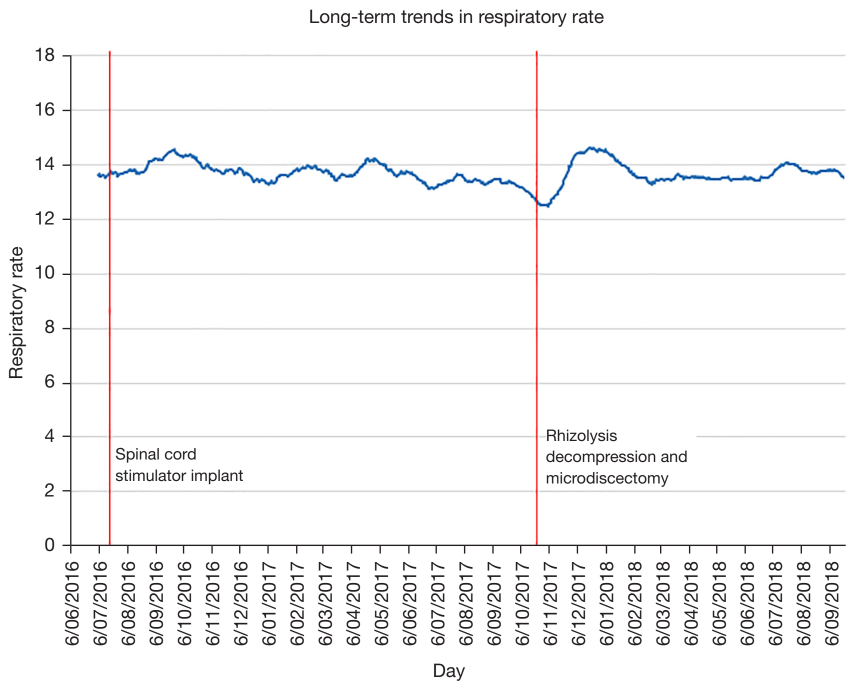

Figure 8 Long-term trends in RR. Thirty-day moving average is depicted. RR, respiratory rate.

All procedures performed in this study were in accordance with the ethical standards of the institutional and/or national research committee(s) and with the Helsinki Declaration (as revised in 2013). Written informed consent was obtained from the patient for publication of this case report and accompanying images. A copy of the written consent is available for review by the editorial office of this journal.

Discussion

Being small, lightweight, and unobtrusive, wearable sensors can be worn in everyday living conditions to allow clinicians to monitor patients remotely (7,19). In this case, a single-point wearable sensor—the Oura Ring—was used to monitor a spine patient continuously and remotely across a time-period exceeding two years. Objective measurements (step count, sleep duration, RR, HR, and HRV) matched trends in subjective measurements (VAS scores), and paralleled key events in the patient's medical history (*Figure 1*). In this way, continuous objective measurements made remotely using wearable sensors could be used as a screening tool to detect patient deterioration, or as an alternative to in-person follow-up visits when measuring postoperative recovery.

Objective metrics relating to walking and gait have been shown to be relevant in the assessment of lumbar spine patients. Step count has been investigated in the hospital setting, leading to the finding that an increase in step count from 4,500 to 8,800 steps per day results in one fewer day hospitalized per three years of life (20). This supports the association of step count with musculoskeletal conditions. It also demonstrates the benefit of step count improvements in the postoperative course of recovery as observed in our patient. Several studies have shown that spatiotemporal gait metrics such as gait velocity and step length are significantly reduced in lumbar spine pathologies (11,21-23). In particular, Bonab *et al.* (22) showed that spatiotemporal gait parameters were more severely compromised in LDH than in other lumbar pathologies, with significant differences in mean gait velocity (599 mm/s slower), mean step length (14 cm shorter), and mean step time (0.1 s longer) compared to healthy controls. Although not measured in our case, similar changes in spatiotemporal gait metrics may have been present in our patient at the time of his disc herniation. Future studies investigating the remote monitoring of spine patients could investigate the use of spatiotemporal gait metrics to track disease progression.

The continuous monitoring of objective metrics unrelated to mobility can also be useful in the assessment of spine patients. In our case, a rapid deterioration in sleep duration (both total sleep time and REM sleep time) was detected in the weeks prior to the patient's rhizolysis decompression and discectomy. Although unconfirmed due to MRI being contraindicated (presence of spinal cord stimulator), this may have been an early objective marker of the onset of the patient's disc herniation. This is supported by Sariyildiz *et al.* and Kose *et al.* (24,25) who show that sleep can be compromised in patients with disc herniations, with mean Pittsburgh Sleep Quality Index scores of 8.60 and 6.69, respectively, indicating poor sleep quality, likely due to night-time pain. In addition, HRV can be used as an objective marker of psychological health and stress. In a recent meta-analysis, all but one out of 21 studies investigating the effect of psychological stressors in healthy human participants found that HRV decreased in response to stress (26). Future studies could attempt to measure psychological stress using HRV during hospital stay using an inpatient monitoring system and assess HRV in the perioperative period. Fortunately, our patient's HRV rolling average remained relatively constant besides a slight reduction during the time of his rhizolysis decompression and microdiscectomy, but a significant drop in HRV in instances of more severe preoperative anxiety may be a sign of significant psychological stress that requires intervention.

The assessment of patients with disorders of the lumbar spine is typically performed using PROMs alone. Unfortunately, we are not able to report ODI scores (gold-standard PROM for the assessment of functional status in people with low back pain) for our patient and future studies investigating long-term trends in health status in lumbar spine patients should do so. Although useful in communicating the patient's perception of their disability, PROMs have disadvantages (3). For instance, PROMs are intended to be obtained at discrete time points (3). In contrast, objective measurements using wearable sensors can be continuously streamed to health care providers. As in our case, taken over a period exceeding two years, continuous data allow long-term trends to be mapped. Moreover, the literature has also demonstrated that PROMs have a restricted comparability between patients. A large (n=375) and recent study performed by Stienen *et al.* (4) investigated levels of mental distress and ODI scores of patients with discogenic MLBP and controls. Subjects with higher levels of mental distress, both discogenic MLBP patients and controls alike, scored significantly higher on the ODI (mean scores of 56.19 and 11.56, respectively) than their respective counterparts (mean scores of 43.44 and 1.36, respectively) with lower levels of mental distress ($P<0.001$). This suggests that the association between mental distress and PROM scores is independent of the underlying lumbar disease, as an effect was seen in both healthy and diseased individuals. Overall, objective outcome measures provide a new dimension to assessing the spine patient and can be used alongside PROMs for more holistic care (27,28).

Although the vision for remote monitoring of objective health metrics in daily living is in its infancy, there is a rising number of studies demonstrating their usefulness, particularly in the field of cardiology. Bashi *et al.* (29) found that, in 10 systematic reviews, the remote monitoring of metrics such as blood pressure, HR, weight, and ECG reduced mortality and rehospitalization in patients with CHF. In the field of surgery, there are some papers on remote monitoring in patients undergoing total knee arthroplasty, with Ianculescu *et al.* (14) comparing a 12-week in-person postoperative physiotherapy program with one that was performed remotely by patients using a mobile-phone application and knee-based wearable sensors. Patients in the intervention group had an average of only 2 in-person visits, whilst still scoring 1.3 points higher on average on the Oxford Knee Score. This demonstrates how remote monitoring can reduce in-person visits without compromising the standard of care, thereby allowing clinicians to accommodate a larger number of patients. Interestingly, one report on the remote monitoring of a patient following a lumbar microdiscectomy showed how a rapid deterioration in gait velocity, step count, and distance travelled allowed for the early detection of a recurrent disc herniation (30). This shows how remote monitoring can be used for the detection of postoperative complications.

Conclusions

The use of a continuous objective measurement tool is useful in the long-term assessment of spine patients. Even after the timeframe of this case report, the patient continued to wear the Oura Ring with no deterioration of health metrics. Self-reported PROMs were not used for long-term follow-up. Although their use and benefits should be validated in larger prospective trials, this case report demonstrates that objective measurement tools show significant promise in the long-term tracking of patient progress.

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Footnote

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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. All procedures performed in this study were in accordance with the ethical standards of the institutional and/or national research committee(s) and with the Helsinki Declaration (as revised in 2013). Written informed consent was obtained from the patient for publication of this case report and accompanying images. A copy of the written consent is available for review by the editorial office of this journal.

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