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Smartphone-based real-life activity data for physical performance outcome in comparison to conventional subjective and objective outcome measures after degenerative lumbar spine surgery

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ABSTRACT

Introduction: Outcome assessments after surgery for degenerative lumbar disorders (DLDs) rely on subjective patient-reported outcomes (PROMs). New objective functional capacity tests, like the smartphone-based 6-min walking test (6WT), have been introduced but presumably also do not reflect the patient's real-life functional performance.

Research question: Pilot study to analyze changes in smartphone-based real-life activity data for physical performance outcome in patients undergoing surgery for DLD.

Material and methods: Prospective observational study of DLD patients. Objective functional capacity and subjective outcomes were measured using 6WT and PROMs. Real-life physical performance data were acquired retrospectively using Apple iPhone Health data and compared against objective capacity and subjective outcomes.

Results: Eight patients (mean 46 years, 62% male) provided 286.858 smartphone mile counts. PROMs and physical capacity (6WT) significantly improved postoperatively. 6WT results increased from 352m pre-to 555/567m at 6/12 weeks postoperatively ($p = 0.03$). For physical performance a linear mixed effect models showed an increase in daily distance in the first 4 months after surgery (slope +0.178; $p < 0.001$). However, those increases reversed from 4 until 12 months postoperatively (negative slope estimate of −0.076; $p < 0.001$). Smartphone-derived physical performance measures showed a positive correlation with corresponding physical capacity in the 6WT ($R = 0.57, p = 0.004$) and negative correlations with PROMs (COMI: $R = -0.62 p = 0.001$; ZCQ-Physical-Function: $R = -0.68, p < 0.001$; ZCQ-Symptom-Severity: $R = -0.52, p = 0.009$).

Discussion and conclusion: Smartphone-based real-life activity data allows for longitudinal physical performance assessment. Physical performance correlated with physical capacity and patient's subjective perception of disability. However, physical performance may be more resistant to postoperative longtime change which should consult a more cautious use as objective outcome measure.

1. Introduction

Surgical interventions in patients with degenerative lumbar disorders (DLDs) aim to ameliorate pain and functional impairment. The definition of treatment success is highly dependent on the accurate measurement of these dimensions (Maldaner and Stienen, 2020). Patient-reported outcome measures (PROMs) are the current gold-standard to estimate a patient's change in symptoms and function after surgery. However, PROMs do not represent a direct measurement of function rather than a patient's subjective perception of disability, which may be subject to major inaccuracies (Stienen et al., 2019; Carragee, 2010; Smuck et al., 2018). Recently, the broad availability of smartphones, equipped with accelerometers and global positioning systems, has opened new avenues towards a digital, continuous and objective assessment of functional impairment (Maldaner et al., 2020a). Objective functional test like the 6-min walking test (6WT), a self-performed app-based test, have demonstrated solid psychometric properties all while achieving higher user acceptance and satisfaction compared to PROMs (Sosnova et al., 2021; Maldaner et al., 2021; Zeitlberger et al., 1976).

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Abbreviations

6WD	6-min walking distance
6WT 6	minute walking test
CI	confidence interval
COMI	Core Outcome Measures index
DLDs	degenerative lumbar disorders
LDH	lumbar disc herniation
LSS	lumbar spinal stenosis
PROMs	patient-reported outcome measures
SD	standard deviation
VAS	Visual-Analogue-scale
ZCQ PF	ZCQ-physical-function
ZCQ SS	ZCQ-symptom-severity
ZCQ	Zurich-Claudication-Questionnaire

When assessing function in patient with DLD one has to distinguish between two distinct categories, defined by the WHO International Classification of Functioning: capacity and performance (Smuck et al., 2018; World Health Organization, 2001). Capacity reflects a patient's ability within a given physical task in a controlled environment (e.g. 6WT). Performance, on the other hand, represents a person's real-life physical activity in his/her current environment. While there are several studies examining patients' capacity in different physical test, there is limited data on DLD patients' change in performance, i.e. longitudinal real-life activity (Smuck et al., 2018; Basil et al., 2021). Little is known whether changes in a DLD patient's subjective PROM and objective functional test capacity correlate with longitudinal changes in real-life physical performance. This knowledge is important to appreciate the relevance of a postoperative change in function of the individual patient and to assess the ability of different dimensions of function to serve as objective outcome criteria (Maldaner et al., 2021).

The aim of this study was therefore to analyze the usability of retrospectively collected smartphone-based, real-life activity data for physical performance assessment and to compare it with a set of pre-specified, prospectively collected subjective as well as objective outcome measures in a cohort of patients undergoing surgery for DLD.

2. Methods

2.1. Patient selection and study group

Patients with DLD who were scheduled for spine surgery for either 1) lumbar disc herniation (LDH), 2) lumbar spinal stenosis (LSS), or 3) DLDs requiring lumbar fusion, were prospectively enrolled between 2019 and 2020 at the Department of Neurosurgery of the Cantonal Hospital St. Gallen, Switzerland. Out of ten patients who possessed an Apple iPhone and gave consent to provide smartphone activity data, in 8 patients pre- and postoperative datapoints were available after data extraction (see Supplementary Fig. 1). All patients with LDH underwent lumbar microdiscectomy. Patients with LSS underwent uni- or bilateral microsurgical decompression while patients with DLDs requiring fusion underwent open transforaminal or posterior lumbar interbody fusion. *Postoperative accompanied en-bloc mobilization was permitted 6 h after surgery. Further mobilization on the ward was carried out according to physical therapies instructions from the first postoperative day onwards. At discharge patient did not receive walking distance limitations and were free to ambulate according to their symptoms.*

After inclusion all patients were subject to a comprehensive subjective (PROM-based) and objective (6WT) assessment pre-, 6 and12 weeks postoperative. At 1 year follow up, patients were contacted and asked to provide their smartphone activity data as additional objective performance assessment. To ensure comparability, only data retrieved from Apple iOS devices were included in the study. Patient without iPhone or patient who did not agree to transfer their data therefore had to be excluded from further analysis.

2.2. Data collection and subjective PROMs

Demographic and clinical data depicted in Table 1 were collected for each patient. For the pre- and 6/12 weeks postoperative time points, patients were asked to provide the following PROMs:

1. The Visual-Analogue-scale (VAS) measures pain intensity for lower back pain (back) and lower extremity (leg) pain ranging from 0 (none) to 10 (severe pain).
2. The Zurich-Claudication-Questionnaire (ZCQ), with its two main scores (Stucki et al., 1996):
   a. ZCQ-symptom-severity (ZCQ SS), range: 1 (none) to 5 (severe symptoms)
   b. ZCQ-physical-function (ZCQ PF), range: 1 (none) to 4 (severe disability)
3. The Core Outcome Measures index (COMI) Back ranging from 0 (none) to 10 (severe back-related disability) (Mannion et al., 2009).

2.3. Digital objective outcome measures

Patients were asked to self-perform the 6WT twice using the “6WT” app at the following time points as an objective measure of function: Preoperatively, at 6/12 weeks postoperatively. Please find a link to the app in the supplemental methods. As previously described, the 6WT is a physical task assessing a patient functional capacity by measuring the maximum distance a subject can walk within 6 min (main outcome: 6-min walking distance (6WD)) (Tosic et al., 2020). Previous work could show that patient with DLD who suffer from back or leg pain, neurogenic claudication and/or neurological deficits are typically restricted in their walking abilities resulting in a shorter 6WD (Maldaner et al., 2020b).

At a 1-year follow-up, patients were contacted by phone or mail and

Table 1
Patient cohort and operative characteristics.

Patient Characteristic	N = 8
Sex	
male	5 (62%)
female	3 (38%)
Age	45.75 (13.32)
BMI	26.59 (6.09)
Smoking	
Non-Smoker	6 (75%)
Smoker	2 (25%)
Working preoperative	
Full-time	4 (50%)
Part-time	2 (25%)
Disabled	1 (12%)
Retired	1 (12%)
Previous spine surgery	1 (12%)
Working postoperative	
Full-time	5 (62%)
Part-time	3 (38%)
Surgery indication	
Lumbar disc herniation	5 (62%)
Degenerative lumbar stenosis	2 (25%)
Lumbar DDD with or without instability requiring lumbar fusion	1 (12%)
Complication intraoperative	
None	7 (88%)
Dural tear or spinal fluid leak	1 (12%)
Complication follow-up	
None	8 (100%)
Revision follow-up	
None	8 (100%)

Patient and operative characteristics. Statistics presented: Mean (±SD); n (%). BMI body-mass-index.

asked to download the "QS Access" (Quantified Self Labs, San Francisco, California) app via the Apple iOS App Store. With the app, participants were able to export their Apple Health activity data and send it via secure mail. Activity data comprised of walking distances in miles by each hour of a specific day for various timespans representing a patient's performance or real-life physical activity.

2.4. Statistical analysis

Patient characteristics are reported as mean ± standard deviation (SD) for continuous and count (percentage) for categorical data.

At each timepoint (pre-, 6-/12-weeks postoperative) the average 6WD of both 6WT trials was calculated and is reported as raw walking distance (mean 6WD (m) ± SD and 95% confidence interval (CI))

Raw smartphone hourly mile counts of all patients were extracted and used to computationally derive summed daily distances. We defined the month before surgery as reference and used paired Wilcoxon signed rank tests to compare the mean daily distances of the reference month with the postoperative months. Since individual patients differed strongly in their overall activity levels, we normalized each patient's daily distances by his/her mean daily distance over the entire observation period. To then examine trends in physical performance, regions of interest in the pre- and postoperative course were defined and used for further analysis. Linear mixed effect models were fitted with the normalized daily mile counts to account for random effects originating by different patients. Pearson correlation coefficients (R) were calculated to quantify the direction and strength of the relationship between pre- and postoperative 6WT results and normalized daily distances for each patient.

2.5. Ethical considerations

The collection and publication of data was permitted by the local ethics committee ("Kantonale-Ethikkommission": 2019–01209). This study was registered with the ClinicalTrials.gov database (NCT03977961). All patients provided written informed consent prior to the initiation of data collection.

3. Results

3.1. Study group

Of 10 patients who agreed to provide their activity logs, 2 had to be excluded because of incomplete preoperative mobile distance count data (see inclusion flowchart as Supplementary Fig. 1). This resulted in the final study cohort of 8 patients.

Mean age was 45.8 years, 62% were male. See Table 1 for further characteristics. *Six patients (75%) underwent lumbar microdiscectomy, whereas one patient with lumbar degenerative disc disease received decompression with fusion.* One patient experienced a dural tear intraoperatively. There were no surgical complications or revision.

3.2. Pre- and postoperative subjective and objective outcome measures

At the 6 and 12-weeks follow-up significantly improvements were observed in all PROMs. Functional capacity, measured with the 6WT, improved significantly from a mean 6WD of 352 m preoperative to 555 m and to 567 m ($p = 0.03$, Friedman test for paired samples) at 6 and 12 weeks, respectively. Detailed pre- and postoperative results are summarized in Table 2.

3.3. Patient smartphone-derived performance measures

A total of 286.858 smartphone mile counts were extracted from the raw smartphone data. Postoperative month 1 ($p = 0.008$), month 3 ($p = 0.008$), month 4 ($p = 0.02$) and month 5 ($p = 0.016$) showed significantly higher mean distances per month compared to the reference month preceding the operation (see Fig. 1).

Table 2
Pre- and postoperative subjective and objective outcome measures.

Measure	Timepoint			p-value
	Preoperative	6 weeks postoperative	12 weeks postoperative	
ZCQ – Physical Function	2.25 (0.46)	1.10 (0.21)	1.20 (0.21)	<0.001
ZCQ – Symptom Severity	3.88 (0.64)	2.16 (1.01)	2.09 (0.74)	0.018
COMI Back	7.55 (0.72)	2.19 (2.44)	2.41 (1.89)	0.002
6WD	351.56 (133.20)	555.25 (59.31)	567.38 (70.61)	0.03

Results are expressed as mean (SD). Friedman tests for paired samples were used to calculate significance levels. 6WD, 6-min walking distance; COMI, Core Outcome Measures Index; VAS, visual analogue scale; ZCQ, Zurich Claudication Questionnaire.

To illustrate the different activity levels between patients, cumulated distances per day relative to the date of surgery are shown for each patient in Supplementary Fig. 2. Individual patients had a strong effect on overall activity and daily distances (see summarized distances per day for each patient in Fig. 2 and Supplementary Fig. 2). Therefore, the cumulated distance counts for all patients were plotted in Fig. 3 after normalizing by the mean daily distance for each patient over the entire observation period. Normalized distances of all patients showed a slight decrease in recorded distances preoperatively (months -6-0, see blue area in Fig. 3). This changed to a slight increase in the first postoperative months (months 0–4, see red area in Fig. 3) which seemed to reverse in the further postoperative course (months 4–12, see black area in Fig. 3).

The corresponding linear mixed effect model showed a slope estimate of −0.094 ($p < 0.001$; 95% CI: −0.136 to −0.053), indicating a decrease in daily distance 6 month preceding the operation (see blue area in Fig. 3). In contrast, in the first postoperative phase (until month 4 postoperative, see red area in Fig. 3), slope estimate was +0.178 ($p < 0.001$; 95% CI: −0.087 to −0.269) indicating an increase in daily distance. In the late postoperative phase (after 4 months until 12 months postoperatively, see black rectangle in Fig. 3), the model fit showed again a negative slope estimate of −0.076 ($p < 0.001$; 95% CI: −0.1 to −0.005).

Correlation of smartphone-derived physical performance with physical capacity and PROMs

Mean normalized daily distances for the first month preoperative as well as first and third postoperative months showed a moderate correlation to their corresponding mean 6WD measures (Pearson correlation coefficient $R = 0.57$, $p = 0.004$, see Fig. 4), as well as PROMs (COMI scores: $R = -0.62$, $p = 0.001$; ZCQ PF: $R = -0.68$, $p < 0.001$; ZCQ SS $R = -0.52$, $p = 0.009$).

4. Discussion

To the best of our knowledge this is the first study to compare smartphone-based longitudinal real-life physical activity data as performance outcome with prospectively assessed subjective as well as objective outcome measures in patients undergoing surgery for DLD. Some interesting findings emerged. First, using longitudinal smartphone data encompassing 286.858 data points we found that individual real-life physical performance varied considerably between different subjects. Second, after normalization physical performance showed clear trends related to the operation with a decrease in daily distance 6 month preceding the operation and an increase in the first postoperative months following a slow decline over the further postoperative course. Lastly, physical performance showed a moderate positive correlation to physical capacity captured with the 6WT at different timepoints.

We found that patients improved significantly between preoperative

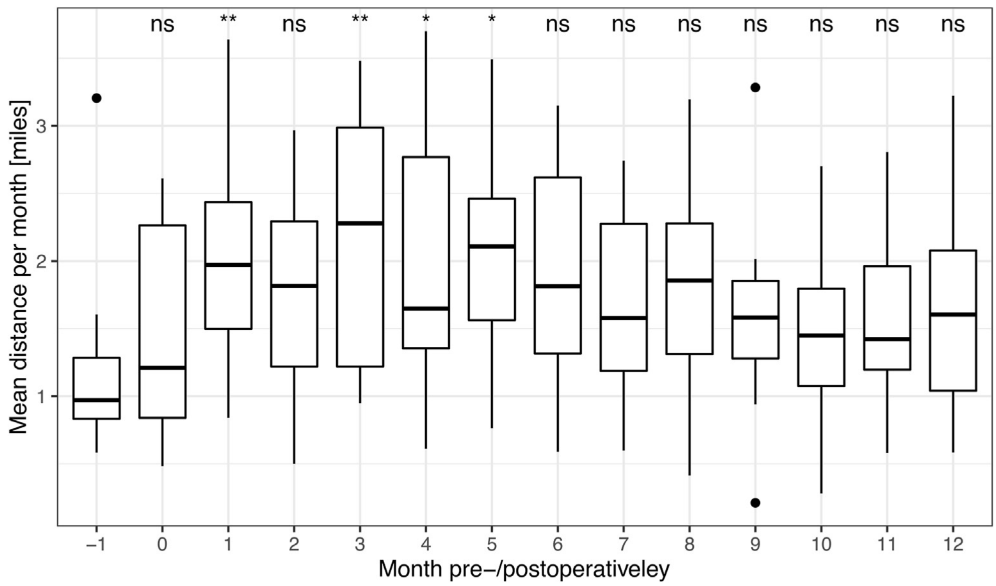

Fig. 1. Postoperative mean daily distances relative to preoperatively.

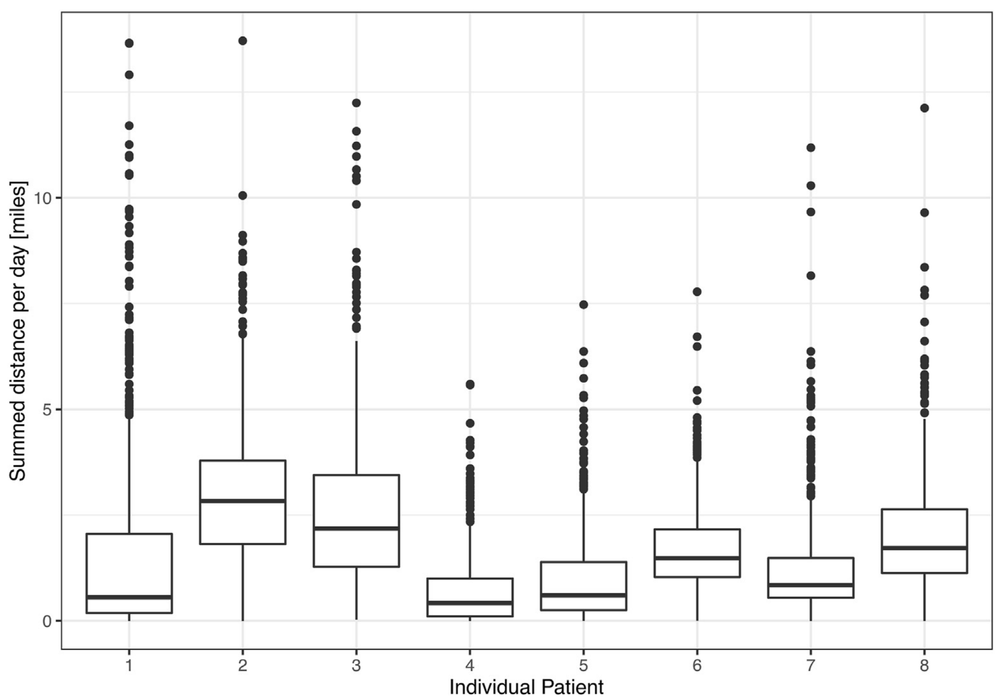

Fig. 2. Summarized distances per patient for entire observation period.

and 6 as well as 12 weeks postoperative in both subjective PROMs as well as objectively measured physical capacity in the 6WT. The improvement in self-reported function over the first three months following surgery are similar to those reported in published literature thus substantiating the generalizability of our results (Gautschi et al., 2016). Using the 6WT as a smartphone app-based functional test we show that the improvement in PROMs is accompanied by an increase in physical capacity indicating the gradual decrease in objective functional impairment three month after surgery. This is in line with previous studies showing improvement in subjective and objective outcome measures including the 6WT (Stienen et al., 2019; Maldaner et al., 2021). When it comes to physical performance, however, evidence is scarce.

Only a few studies have used continuous activity monitoring in patients undergoing surgery for DLD. A 2017 landmark study by Smuck et al., which uses pre- and postoperative accelerometer data over 7 consecutive days in patient with LSS, shows stagnant physical performance despite improvement in physical capacity 6 month after surgery (Smuck et al., 2018). This finding is in contrast to a 2020 study by Basil et al. which demonstrate significantly increased real-life physical performance as measured with an Apple iPhone in 23 patients 7 and 12 month following lumbar fusion surgery (Basil et al., 2021). A study by Stienen et al. (n = 30 patients) published in 2020 indicates that physical performance dropped by 70% early after surgery, with recovery until 4–6 weeks postoperative. However, even though patients indicated doing better on PROM-based assessments, there was no increase in the step count until 1 year postoperative, compared to preoperative (Stienen et al., 2020). Our data supports both Smuck & Stienen et al.'s initial finding that patients may show somewhat stagnant physical performance

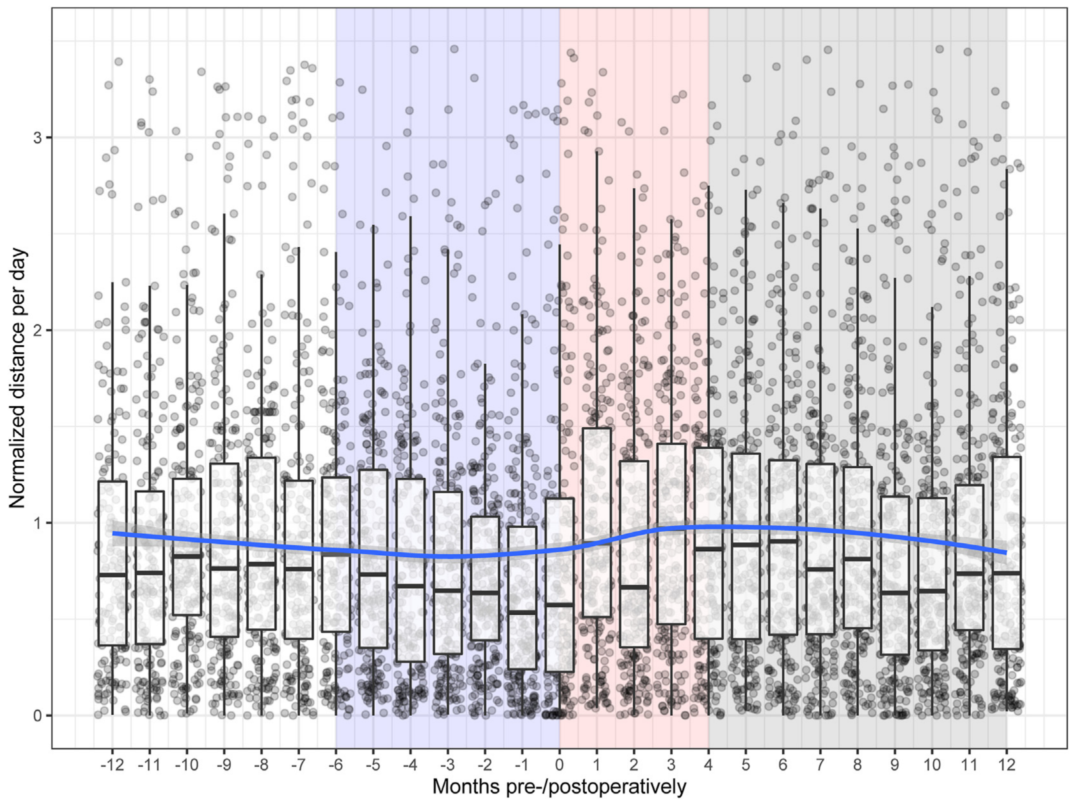

Fig. 3. Normalized distances per month over time for all patients.

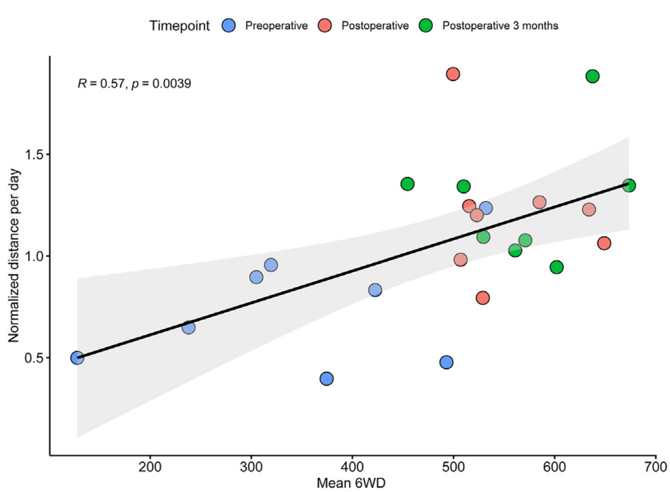

Fig. 4. Correlation plot: normalized daily distance vs. mean 6WD.

despite significant improvement in self-reported function and objective capacity when examined ≥6 month after surgery. However, while Smuck et al. suggest that this might indicate a lack of improvement in physical performance, our longitudinal data suggests otherwise. Patients in our study group demonstrated an increase in physical performance over the first four month after surgery, which was unrelated to the individual patient performance differences. Interestingly, starting five months after surgery patient's physical performance again declined with a negative slope estimate in the linear mixed effect model, loosing daily distance gained in the first months. This turning point can only be appreciated by the continuous longitudinal performance measurement in our study. Smuck et al., on the other hand, assessed patients at only two time points, potentially missing the window of postoperative improvement in physical performance (Smuck et al., 2018).

The question is why do patients loose physical performance again that was gained in their first month after successful surgery? Contrary to physical capacity tests in which patients are actively asked to perform a certain task, physical performance measurements are a passive assessment of a patient's daily activity. It is likely that habitual behaviors play a crucial role in determining a patient's physical performance which might be inherently more resistant to longtime change (Smuck et al., 2018; Tomkins-Lane et al., 2019; Mancuso et al., 2017). It is possible that patients increase their physical performance in the first month postoperative due to a "honeymoon" period of significant improvement in symptoms and functional impairment which then show a gradual decline to baseline over time (Mancuso et al., 2017). While our findings must be replicated in studies with larger patient population it has potentially important implications both clinically as well as in research. Our findings should consult a more cautious use of physical performance as objective outcome measure that might be highly dependent on the length of follow-up and period of data analysis.

Interestingly, physical performance measured by daily distance showed a moderate positive correlation with physical capacity assessed in the 6WT, as well as negative correlations with COMI and ZCQ PROMs. This result seems plausible since patients with shorter 6WD would typically be expected to also show declined physical activity. However, the degree of improvement in physical capacity does not necessarily translate into the same improvement in physical activity. The continuous smartphone-based measurement may provide a more in-depth assessment of function over time compared to assessment at fixed time points (Maldaner et al., 2020a).

4.1. Limitations and outlook

This pilot study is valuable for physicians and researchers that use activity monitors as objective outcome measures in patients with DLD. Although the results of this study are promising, some limitations need to be addressed. First, our sample size was small due to the high number of patients that could not or did not want to share their smartphone data. However, the calculated pre- and postoperative trends are based on repeated measures (daily mile counts) and are therefore not affected by the small cohort size. Second, ideally you would like to standardize results by comparison to healthy population values. Normal population reference data allow for the calculation of standardized z-scores that are the current gold standard to assess a patient's standard deviation in function from normal both pre- and postoperative. Z-scores can then be stratified into comprehensive severity categories of objective functional impairment, as has been shown for the 6WT (Maldaner et al., 2020b). While normal population physical activity data is currently not available, we are confident that future studies will be able to further standardize assessment and adjust for factors that naturally influence activity results as the use of smartphone technology in spine outcome research becomes increasingly popular.

5. Conclusions

Using 286.858 smartphone-derived data points, our pilot study illustrates the capability of longitudinal real-life activity data to assess physical performance outcome in patients after DLD surgery. It revealed both, a preoperative deterioration, and a postoperative improvement of patients' daily physical performance. Although, smartphone-based performance assessment correlated with functional 6WD scores, daily activity levels decreased again in the further postoperative period exhibiting a discrepancy between patients' postoperative physical performance and physical capacity. Therefore, our finding should consult a more cautious use of physical performance as objective outcome measure in conjunction with existing physical capacity assessments. The insights gained from this study are valuable for physicians and research that plan to implement activity monitoring as objective outcome measures in patients with DLD.

Authors' contributions

SV, MC, AMZ, MS and NM curated patient data and prepared the manuscript draft. SV and NM did the statistical analysis. SV and NM designed the study. SV and NM wrote the manuscript. MZ, AMZ, MS, OB, LR, DB, AW and MNS critically revised the manuscript. NM supervised the study. All authors approved the final manuscript version.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bas.2022.100881.

Comparison of mean postoperative distances per month with mean distance at 1 months preoperatively for each patient. Paired Wilcoxon signed rank tests were used to calculate significance levels (indicated with asterisks: *: $p \leq 0.05$; **: $p \leq 0.01$). Months pre-/postoperatively relative to the operation (= month 0). ns = not significant

Box plots of summed distances per day in miles for each patient for the entire observation period (12 month pre-until 12 months postoperativeley) show the varying activity levels between patients.

Accumulated pre-/postoperative distances per month over time for all patients. Months relative to the operation (= month 0). Normalized by mean daily distance for each patient over the entire observation period. Overlayed smoothed blue lines in boxplot figures were calculated using LOESS (locally weighted scatterplot smoothing) method.

Colored rectangles indicated areas of interest for further analysis. Jittered dots indicate individual measurements (normalized distances per patient).

Scatter plot indicating correlation between normalized distance per day and corresponding mean 6WD scores for each patient. Dots represent distinct data points, colored filling indicates the respective timepoints. A regression line was fitted to the available data points. 6WD 6-min walking distance.

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