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Original Research

A Retrospective Study on the Feasibility of Using Low-burden Patient-reported Pain Scores to Track Recovery and Outcomes After Total Joint Replacement

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A B S T R A C T

Background: Patients undergo total joint arthroplasty to improve function and resolve pain. Patient-reported outcome measures (PROMs) are often sought to determine the success of total joint arthroplasty but are time-consuming and patient response rates are often low. This study sought to determine whether pain numeric rating scores (NRSs) were associated with PROMs and objective mobility outcomes.
Methods: This is a retrospective review of data in patients who utilized a smartphone-based care management application prior to and following total joint arthroplasty. NRS, Hip Disability and Osteoarthritis Outcome Score, Joint Replacement and Knee Injury and Osteoarthritis Outcome Score, Joint Replacement, and objective mobility data (step counts, gait speed, and gait asymmetry) were collected preoperatively and at 30 and 90 days postoperatively. Quantile regression was performed to evaluate the correlations between NRS and PROMs.
Results: Total knee arthroplasty patients reported higher NRS than total hip arthroplasty patients postoperatively. NRS was significantly correlated with gait speed preoperatively and at 30 and 90 days postoperatively on quantile regression. Gait asymmetry was significantly associated with NRS at 30 days postoperatively. Regression results suggested significant correlations between NRS and PROMs scores; Hip Disability and Osteoarthritis Outcome Score, Joint Replacement, −0.46 (95% confidence interval: −0.48 to −0.44, $P < .001$) and Knee Injury and Osteoarthritis Outcome Score, Joint Replacement, -0.38 (95% confidence interval: −0.40 to −0.36, $P < .001$).
Conclusions: NRS is correlated with both objective and subjective measures of function in patients undergoing arthroplasty. Simple pain ratings may be a valid measurement to help predict functional outcomes when collection of traditional PROMs is not feasible.

Introduction

The treatment for end-stage osteoarthritis, total joint arthroplasty (TJA), is pursued after the failure of conservative treatment, where pain and loss of function can no longer be managed without surgical intervention. The success of surgery is most often defined in terms of patient-reported outcome measures (PROMs), which include subjective reports of return to activity and adequate reduction of pain [1]. A number of these PROMs have been created and validated for use in populations who have undergone total hip arthroplasty (THA) or total knee arthroplasty (TKA). Specifically, the Hip Disability and Osteoarthritis Score and Knee Injury and Osteoarthritis Outcome Score (KOOS) are among the most commonly used PROMs for these populations [2,3].

Given the length of the questionnaires and the level of burden completion places on both the patient and clinician, shorter versions have been created and validated. Specifically, the Hip Disability and Osteoarthritis Outcome Score, Joint Replacement (HOOS JR) and Knee Injury and Osteoarthritis Outcome Score, Joint

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Replacement (KOOS JR) have been designed for use in joint replacement populations, encompassing pain and function in daily living domains [4,5]. In fact, collection of these PROMs has been mandated under the CMS Comprehensive Care for Joint Replacement Model [6]. While these versions are less taxing, the patient response rates in many studies remain quite low. Digital collection of these surveys has led to improvements in patient compliance [7], but some shortcomings continue to exist with regard to these PROMs. Specifically, authors have suggested that significant ceiling effects exist, wherein the granularity of information is lost because such a high proportion of patients reach the highest possible score [8].

Recent research has begun to focus on objective measures of function after TJA. Mobility metrics such as step counts and gait speed [9–11] can now be collected passively and accurately using mobile devices, which most Americans now own [12]. Gait speed has been suggested as a good indicator of functional capacity and has been associated with commonly reported arthroplasty outcomes such as range of motion and quadriceps strength, as well as exhibiting correlation with traditional functional tests including the Stair Climbing Test and Timed-Up and Go test [13–16]. In many studies where both PROMs and mobility metrics are obtained, there is often little correlation between the objective and subjective accounts of function after arthroplasty, with correlation coefficients between steps and PROMs between 0.17 and 0.29 [17–19]. The majority of patients report high satisfaction after their procedure, suggesting continued value in collection of PROMs and need for more research to understand how objective mobility relates to other outcome measures. Despite the adaptation of shorter PROMs and their apparent usefulness in clinical practice, it would be advantageous to identify a measure that could predict outcomes while introducing as little inconvenience as possible. The pain numeric rating score (NRS) is a well-known, validated system for collection of patient-reported pain in medicine [20]. This study seeks to investigate the relationship between this score and traditional PROMs. In addition, we evaluated the correlation of objectively collected mobility metrics with NRS in a cohort of patients who have undergone TJA.

Material and methods

This is a retrospective study of a database of patients who were prescribed the use of a smartphone-based care management platform for standard clinical care (sbCMP, mymobility, Zimmer Biomet, Warsaw, IN), or who were enrolled in a prospective trial investigating the sbCMP (NCT03737149). Results of the RCT phase of the study evaluating this platform have been previously reported [21–23]; this analysis included only patients enrolled in the observational longitudinal phase of the study. The sbCMP is an iOS and Android-supported application with connectivity to the Apple Watch (Apple Inc, Cupertino, CA) for collection of step counts in Apple iPhone users. Apple HealthKit data, including gait speed and gait asymmetry, was available only for iPhone users and was collected by the mymobility application upon download and acceptance of user terms and conditions. The sbCMP provides education to patients that is synchronized with their stage in the episode of care, delivering questionnaires in a similar manner with regard to the clinical timeline, where PROMs (KOOS JR and HOOS JR) are requested to be completed preoperatively as well as at 30 and 90 days postoperatively. The option to deliver the NRS questionnaire and its delivery frequency are chosen on a provider basis; however, patients have the ability to self-report pain up to 3 times daily in addition to prompts. Those enrolled in the clinical study were eligible only if they owned a smartphone compatible with the smartwatch, were not a current abuser of drugs or alcohol, were ambulatory with maximum support of a single cane or crutch, and were not planning staged bilateral procedures <90 days apart. Only patients in the trial were provided with a smartwatch; those in the commercial database were required to be deemed suitable for in-home telerehabilitation and own a smartphone prior to downloading the application. Patients in both the study and the commercial cohorts were treated according to each individual institution's preoperative and perioperative standard of care (surgeon's choice of technique, pain medication, in-person physical therapy, etc.).

Patients undergoing TKA or THA with NRS pain scores reported between April 2021 and June 2022 and treated at 34 unique sites were eligible to be included in the analysis. Analyses of correlations to PROMs and mobility metrics were limited to those with available data during the preoperative period (−30 to −1 days), 30-day postoperative period (25 to 35 days), and 90-day postoperative (85 to 95 days) timeframe. For the analysis of mobility metrics and their correlation with NRS at different points in the episode of care, we only considered patients with data available for step count, gait speed, and gait asymmetry measures in all of the listed time periods. Patients missing pain scores or a single mobility metric at any one of these timeframes were excluded from analysis. Gait asymmetry is presented as a percentage, referring to the percentage of time that asymmetric steps are detected within a qualified walking bout and determined by the smartphone's algorithms, recorded as a daily average [24]. Step count readings of zero were filtered out. Secondary analysis of the commercial dataset was considered exempt by the institutional review board due to the deidentified nature of the data used (IRB# 20222582). All patients in the prospective trial provided written informed consent to participate.

Statistical analysis

Baseline characteristics are reported with descriptive statistics, as frequency with percentages for categorical data and as median with interquartile range for continuous variables. Correlations were evaluated by univariate quantile regression, comparing NRS pain scores with the corresponding timeframe's PROMs or mobility metrics, where both NRS and PROMs are normalized on a 0 to 10 scale. All pain and PROM scores (preoperative, 30-day, and 90-day) were plotted together in a single scatterplot for quantile regression for KOOS JR and HOOS JR scores separately. The relationship between preoperative pain scores and those reported at 30 and 90 days postoperatively was also investigated by quantile regression. The coefficient at the 50% quantile parameter is reported for all regressions presented. Analyses were performed using Python version 3.8.11 (2021 Python Software Foundation, Wilmington, DE). Two-tailed P-value < .05 was considered statistically significant.

Results

In total, 327 patients had pain scores and all 3 mobility metrics available in the preoperative, 30-day postoperative, and 90-day postoperative windows. The median age of the TKA cohort was 67.0 years (interquartile range 60.0, 72.0) and 59.1% were female (Table 1). The THA cohort was 56.1% female with median age of 65.0 years (58.0, 71.0). Scatterplots displaying the results of the normalized KOOS JR and HOOS JR compared to the normalized NRS from the corresponding timepoints are shown in Figure 1. In patients who underwent TKA, the NRS pain score was significantly correlated with KOOS JR, where the relationship suggests that as pain decreases, KOOS JR scores increase by −0.38 (95% confidence interval [CI] −0.40 to −0.36, P < .001). HOOS JR scores were also significantly associated with NRS pain (Fig. 1) with regression coefficient of −0.46 (95% CI −0.49 to −0.44) (Table 2). Preoperatively,

Table 1
Baseline and postoperative patient characteristics, including NRS pain score, mobility metrics and PROMs scores.

Variable	Preoperative	30 days postoperative	90 days postoperative
Total knee arthroplasty			
Gender (female)	59.1%		
Age (median)	67.0 (60.0, 72.0)		
NRS	6.0 (4.0, 7.33)	3.0 (2.0, 4.5)	1.0 (0.33, 3.0)
KOOS JR	50.0 (42.3, 59.4)	63.8 (57.1, 68.3)	68.3 (61.6, 76.3)
Step count	3943.0 (1948.75, 5892.25)	2898.0 (1379.25, 4558.0)	4018.5 (2206.0, 6453.25)
Gait speed	0.99 (0.93, 1.07)	0.82 (0.73, 0.91)	0.97 (0.89, 1.05)
Gait asymmetry	5% (1%, 10%)	31% (10%, 61%)	5% (2%, 14%)
Total hip arthroplasty			
Gender (female)	56.1%		
Age (median)	65.0 (58.0, 71.0)		
NRS	6.33 (5.0, 7.67)	1.75 (1.0, 3.0)	1.0 (0, 1.3)
HOOS JR	53.0 (46.7, 61.8)	70.4 (64.7, 80.6)	80.6 (70.4, 92.3)
Step count	3523.5 (2216.25, 6296.0)	4091.0 (2363.0,6110.0)	5038.0 (2704.5, 7823.5)
Gait speed	1.02 (0.94, 1.11)	0.93 (0.81, 1.02)	1.03 (0.95, 1.11)
Gait asymmetry	3% (2%, 7%)	9% (3%, 29%)	3% (1%, 7%)

All continuous variables are presented as median with interquartile range (25th, 75th percentile values).

NRS was similar between the TKA and THA cohorts, though median scores were lower in those who underwent THA at 30 days postoperatively (Fig. 2).

Univariable quantile regression models were fit to investigate the association between NRS and each of the mobility metrics collected during the corresponding time windows (Table 3). The preoperative NRS showed association with gait speed (−0.10, 95% CI −0.19 to −0.02, $P = .02$), but not with step count or gait asymmetry. Pain score was also significantly associated with gait speed at both 30 days and 90 days postoperatively. The negative coefficients suggest higher pain reports were associated with slower walking speeds. The regression analyses of gait asymmetry suggest that patient-reported NRS was only significantly associated with gait symmetry at 30 days postoperatively, where higher pain levels were correlated with higher percentages of gait asymmetry. There was no association between NRS and asymmetry at 90 days postoperatively (Table 3).

Finally, quantile regression was utilized to evaluate the relationship between 90-day NRS pain scores with preoperative and 30-day pain scores. Preoperative pain scores were not associated with patient-reported pain at 90 days (0, 95% CI −0.05 to 0.05, $P = 1.0$); however, 30-day pain scores were highly associated with 90-day pain scores (0.47, 95% CI 0.43-0.51, $P < .001$) (Fig. 3).

Discussion

In this study, we demonstrate that patient-reported pain scores, as collected using the well-established 0 to 10 point NRS were significantly correlated with validated PROMs for patients undergoing both TKA and THA. In addition, correlations of NRS pain with mobility metrics were also investigated, suggesting that patient-reported pain may be correlated with gait quality. These results support the potential value of regular collection of NRS pain scores to assist clinicians in identifying patients whose gait recovery may not progress as desired.

Several of our findings are consistent with previous reports in the literature. Our observation of preoperative gait speed was similar to those reported by other authors, which typically ranges between 0.85 and 1.13 m/s in arthroplasty populations [25,26]. Preoperative step counts are also aligned with existing literature, where average daily steps range between 2078 and 5237 in THA cohorts and 1861 and 4777 in TKA patients [9,17,18]. Few studies have reported asymmetry as recorded by smartphone algorithms as included herein; the majority describe asymmetric steps in terms of single limb support, step length, or force- and weight-bearing [27,28]. Those reports have also observed increases in asymmetric patterns in the early postoperative period, which may recover more slowly than step counts. We also observed that pain reduction occurred more quickly in patients undergoing THA compared with those who underwent TKA. Previous authors have reported greater reductions in pain after surgical intervention in THA patients utilizing both NRS pain scores and pain domains contained within a variety of PROM tools [29]. The average pain scores that we observed preoperatively and postoperatively were also comparable to previously reported figures [30]. Comparisons of pain reports highlight the need to standardize not only the instrument used for

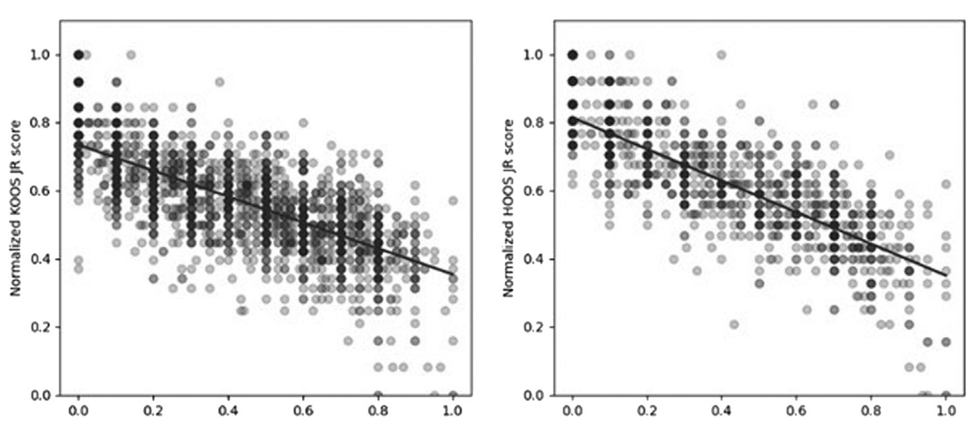

Figure 1. Scatterplot of normalized NRS and PROMs scores utilized in regression model.

Table 2
Quantile regression estimating the correlation between KOOS and HOOS JR total scores with corresponding NRS pain scores.

Variable	Regression coefficient (95% CI)	*P*-value
KOOS Jr total score	−0.38 (−0.40 to −0.36)	<.001
HOOS Jr total score	−0.46 (−0.49 to −0.44)	<.001

collection but also the timeframes for recording this outcome, as the data presented in the literature varies from days to weeks, and even years, postoperatively. It is important to note as well that patients' definition and reporting of pain may be multifactorial, perhaps not limited only to the pain of the operative joint but also to neuromuscular pain caused by the use of muscles that have atrophied postoperatively.

Several authors have observed similar trends in PROMs, with greater improvements in functional outcomes and higher levels of patient satisfaction after surgery for those undergoing THA compared to TKA [31]. Because the raw scores of these validated PROMs do not always correlate with patient perceived improvement, research has begun to focus on patient acceptable symptom state thresholds, where focus is placed on a patient-defined satisfactory outcome rather than the minimal clinically important difference. Kunze and colleagues showed that patient acceptable symptom state thresholds were higher for those undergoing THA (76.7 points) compared to those undergoing TKA (63.7 points), which was expected given the fact that HOOS score changes are greater after hip arthroplasty procedures. Similarly, we observed greater functional improvements in THA patients as captured by HOOS JR. Given the concomitant larger reductions in pain scores for THA patients, the quantile regression results suggesting a stronger relationship between NRS and HOOS JR compared to KOOS JR scores in TKA patients might be expected.

It has been suggested by many authors that the bulk of improvement in both pain and function after TJA is observed within the first 2 months after surgery [9,18]. Investigators have begun to assess the relationships between pain and functional recovery utilizing more objective measures of function, specifically those related to physical activity such as step counts and gait speed [32]. These studies have also reported similar findings, where most progress with regard to recovery of physical activity is attained within the first 6 to 10 weeks postoperatively following TJA. Negligible changes are noted between 6 and 12 months after surgery and beyond [30,33]. However, patient satisfaction and function as measured by PROMs have demonstrated only modest correlations with activity measures. This could be related to the ceiling effects demonstrated with some PROM tools, where the ability to discriminate such trends may become difficult when large proportions of patients reach the highest possible score. Lack of discriminatory power could also be related to the difficulty in collecting PROMs frequently; few researchers or clinicians collect

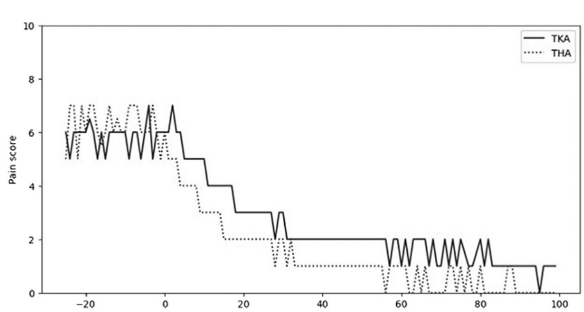

Figure 2. Median pain scores relative to surgery date by procedure type.

Table 3
Quantile regression results evaluating mobility metrics and NRS according to clinical timeframes of interest, where mobility metrics are medians calculated within each time period.

Variable	Regression coefficient (95% CI)	*P*-value
Preoperative NRS		
Step count	−0.11 (−0.23 to 0.04)	.16
Gait speed (m/s)	−0.10 (−0.19 to −0.02)	.02
Gait asymmetry (%)	0.02 (−0.0 to 0.05)	.35
30-day postoperative NRS		
Step count	−0.11 (−0.24 to 0.02)	.09
Gait speed (m/s)	−0.19 (−0.32 to −0.06)	.004
Gait asymmetry (%)	0.37 (0.18 to 0.55)	<.001
90-day postoperative NRS		
Step count	−0.04 (−0.15 to 0.06)	.44
Gait speed (m/s)	−0.15 (−0.27 to −0.03)	.02
Gait asymmetry (%)	0.03 (−0.02 to 0.07)	.19

PROM scores more than once during the period where most recovery occurs within (6 to 10 weeks). Alternately, the NRS pain scores can be easily collected frequently and may be particularly helpful to monitor during this initial recovery period, when it may not be feasible or helpful to collect PROMs on a daily or weekly basis.

Relatively little research has focused on the relationship between pain and physical activity following TJA. It remains unclear whether the improvements appreciated in terms of function and pain translate into increased physical activity, as some authors have found that postoperative activity levels remain roughly 20% lower in patients after arthroplasty compared to similar patients without osteoarthritis [10]. Twiggs et al reported that pain was associated with preoperative step counts as well as steps taken on days 2 to 4 postoperatively [34]. The authors suggest that patients who take more steps immediately following surgery recover their preoperative activity sooner and have higher step counts at 6 weeks postoperatively [34]. Despite this, some investigators suggest that changes in pain are not directly related to changes in physical activity. Patterson et al report that decreased activity after TJA was associated with less pain; those who returned to their preoperative levels of activity earlier did not demonstrate earlier pain reductions or clinically relevant changes in mobility [35]. Alternately, studies clustering patients by pain scores have suggested significant differences in PROMs and physical capacity when comparing those who report better pain recovery trajectories to those whose pain recovers more slowly [36]. This supports the need to collect information about pain after surgery more frequently than is currently done using validated PROMs alone.

In recent years, the use of a patient reported numeric pain rating has fallen out of favor, particularly in the United States. Numeric pain scores were heavily relied upon during the "pain as the fifth vital sign" campaign by the American Pain Society, where adequate pain control was considered an indicator of quality of care and a possible proxy for patient satisfaction [37]. The overtreatment of pain with opioid medications and the ensuing epidemic have left clinicians hesitant to collect simple pain scores from patients. Current guidelines suggest that pain should be collected in terms of its effect on function and with special importance in understanding how pain is affecting progress toward treatment goals [38]. While it may not be reasonable to return to a practice in medicine where pain and its treatment are given utmost precedence, it is reasonable to advocate for collection of simple pain ratings when these may be predictive of, or assist clinicians in managing, patient recovery. This is particularly true for patients recovering from TJA. Previous trials have shown that validated PROMs are not as sensitive to changes in pain as simple ratings, are subject to significant ceiling effects, and exhibit possible shortcomings with regard to the rigid wording

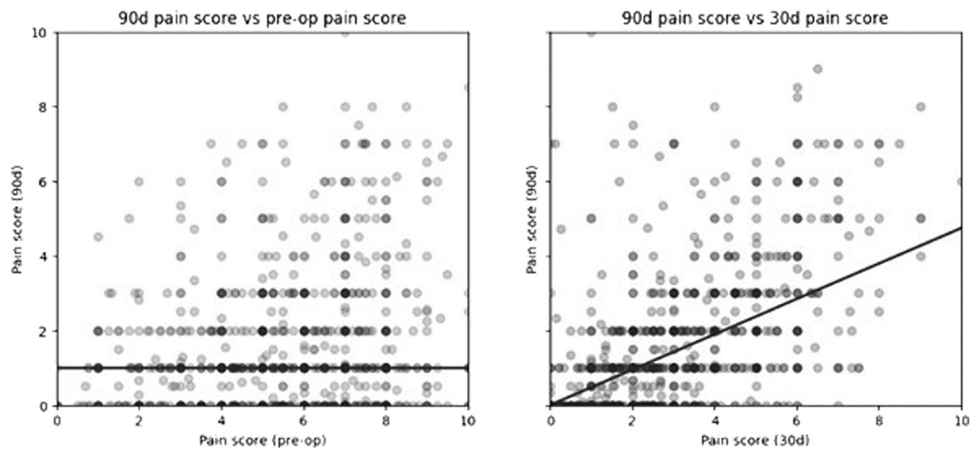

Figure 3. Correlation of 90-day pain scores with preoperative and 30-day NRS.

where changes may not be detected in patients in whom some questions may not be relevant [8,39]. While it is important to measure functionally relevant pain, it is just as important to identify a measure that is both reliable and easy to collect. Our results suggest that NRS may be an early indicator of mobility after TJA and may serve as a supplemental measure alongside PROMs to monitor early recovery, as NRS can be collected and reviewed frequently and easily during the postoperative period and demonstrates significant correlation with PROMs scores. Quite notably, preoperative NRS was not correlated with 90-day pain reports, while 30-day NRS was strongly correlated with pain later in recovery. This suggests pain reports may not be dependent on patients' pain perception as previously proposed [40] and supports the value of repeated measurement postoperatively to predict and monitor for poor outcomes.

This study is subject to a number of limitations, specifically those related to a retrospective review of data of this type. We were not able to control for any comorbid conditions or the presence of osteoarthritis in other locations. In addition, due to the anonymous nature of the commercial data, we could not control for clinical variables that could impact outcome or postoperative pain, including surgical approach or use of robotic assistance. Moreover, patients were treated by multiple surgeons at different facilities, all of which utilized their own standard of care approach to pain management and postoperative physical therapy; differences in the standard use of physical therapy could impact the activity measures that were included. We could not account for differences in compliance with regard to patient utilization of mobile devices and wearables, as is often a limitation for any study that includes this type of passive continuous activity data. Finally, the eligibility requirement of owning a smartphone may have introduced selection bias, wherein our results may not be generalizable to the arthroplasty population that does not utilize these technologies. However, reports suggest increasing use year-over-year in all age groups, with approximately 85% of the US population currently owning a smartphone, with only 61% over the age of 65 reporting ownership in 2021 [12].

Conclusions

Numeric pain scores are limited in the scope of information that can be provided to a healthcare professional and should not be the sole indicator of recovery or quality of care. However, given the limitations of validated instruments to measure function and pain for patients who have undergone TJA, measures that are easy to administer and interpret and can be collected multiple times early in the postoperative period, when the majority of recovery occurs, are needed. Numeric pain scores may be a good indicator of PROMs and can be administered using mobile devices for remote monitoring of patient recovery, potentially allowing earlier intervention where necessary.

Conflicts of interest

K. Surmacz, A. Ribeiro-Castro, M.B. Anderson, D. Van Andel, and R. Redfern were all employed by Zimmer Biomet with stock or stock options at the time the work took place. M.B. Anderson receives stock options from OrthoGrid Systems, Inc. P. Duwelius is a paid consultant, paid/presenter, and received research support from Zimmer Biomet; the other author declares no potential conflicts of interest.

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References

[1] Goodman SM, Mehta B, Mirza SZ, Singh JA. Patients' perspectives of outcomes after total knee and total hip arthroplasty: a nominal group study. BMC Rheumatol 2020;4:3. https://doi.org/10.1186/s41927-019-0101-8.
[2] Roos EM, Roos HP, Lohmander LS, Ekdahl C, Beynnon BD. Knee injury and osteoarthritis outcome score (KOOS)–development of a self-administered outcome measure. J Orthop Sports Phys Ther 1998;28:88–96. https://doi.org/10.2519/jospt.1998.28.2.88.
[3] Nilsdotter AK, Lohmander LS, Klassbo M, Roos EM. Hip disability and osteoarthritis outcome score (HOOS)–validity and responsiveness in total hip replacement. BMC Musculoskelet Disord 2003;4:10. https://doi.org/10.1186/1471-2474-4-10.
[4] Lyman S, Lee YY, Franklin PD, Li W, Cross MB, Padgett DE. Validation of the KOOS, JR: a short-form knee arthroplasty outcomes survey. Clin Orthop Relat Res 2016;474:1461–71. https://doi.org/10.1007/s11999-016-4719-1.
[5] Lyman S, Lee YY, Franklin PD, Li W, Mayman DJ, Padgett DE. Validation of the HOOS, JR: a short-form hip replacement survey. Clin Orthop Relat Res 2016;474:1472–82. https://doi.org/10.1007/s11999-016-4718-2.
[6] Neginhal V, Kurtz W, Schroeder L. Patient satisfaction, functional outcomes, and survivorship in patients with a customized posterior-stabilized total knee replacement. JBJS Rev 2020;8:e1900104. https://doi.org/10.2106/JBJS.RVW.19.00104.
[7] Pronk Y, Pilot P, Brinkman JM, van Heerwaarden RJ, van der Weegen W. Response rate and costs for automated patient-reported outcomes collection alone compared to combined automated and manual collection. J Patient Rep Outcomes 2019;3:31. https://doi.org/10.1186/s41687-019-0121-6.
[8] Eckhard L, Munir S, Wood D, Talbot S, Brighton R, Walter B, et al. The ceiling effects of patient reported outcome measures for total knee arthroplasty. Orthop Traumatol Surg Res 2021;107:102758. https://doi.org/10.1016/j.otsr.2020.102758.
[9] Lebleu J, Poilvache H, Mahaudens P, De Ridder R, Detrembleur C. Predicting physical activity recovery after hip and knee arthroplasty? A longitudinal

cohort study. Braz J Phys Ther 2021;25:30–9. https://doi.org/10.1016/j.bjpt.2019.12.002.

[10] Paxton RJ, Forster JE, Miller MJ, Gerron KL, Stevens-Lapsley JE, Christiansen CL. A feasibility study for improved physical activity after total knee arthroplasty. J Aging Phys Act 2018;26:7–13. https://doi.org/10.1123/japa.2016-0268.

[11] Appelboom G, Yang AH, Christophe BR, Bruce EM, Slomian J, Bruyère O, et al. The promise of wearable activity sensors to define patient recovery. J Clin Neurosci 2014;21:1089–93. https://doi.org/10.1016/j.jocn.2013.12.003.

[12] Demographics of mobile device ownership and adoption in the United States. Pew Research. https://www.pewresearch.org/internet/fact-sheet/mobile/. [Accessed 7 March 2022].

[13] Middleton A, Fritz SL, Lusardi M. Walking speed: the functional vital sign. J Aging Phys Act 2015;23:314–22. https://doi.org/10.1123/japa.2013-0236.

[14] Shibuya M, Nanri Y, Kamiya K, Fukushima K, Uchiyama K, Takahira N, et al. The maximal gait speed is a simple and useful prognostic indicator for functional recovery after total hip arthroplasty. BMC Muscoskel Disord 2020;21:84. https://doi.org/10.1186/s12891-020-3093-z.

[15] Pua YH, Seah FJ, Clark RA, Lian-Li Poon C, Tan JW, Chong HC. Factors associated with gait speed recovery after total knee arthroplasty: a longitudinal study. Semin Arthritis Rheum 2017;46:544–51. https://doi.org/10.1016/j.semarthrit.2016.10.012.

[16] Suh MJ, Kim BR, Kim SR, Han EY, Nam KW, Lee SY, et al. Bilateral quadriceps muscle strength and pain correlate with gait speed and gait endurance early after unilateral total knee arthroplasty: a cross-sectional study. Am J Phys Med Rehabil 2019;98:897–905. https://doi.org/10.1097/PHM.0000000000001222.

[17] Crizer MP, Kazarian GS, Fleischman AN, Lonner JH, Maltenfort MG, Chen AF. Stepping toward objective outcomes: a prospective analysis of step count after total joint arthroplasty. J Arthroplasty 2017;32:S162–5. https://doi.org/10.1016/j.arth.2017.02.058.

[18] Lyman S, Hidaka C, Fields K, Islam W, Mayman D. Monitoring patient recovery after THA or TKA using mobile technology. HSS J 2020;16(Suppl 2):358–65. https://doi.org/10.1007/s11420-019-09746-3.

[19] Kuhn M, Harris-Hayes M, Steger-May K, Pashos G, Clohisy JC. Total hip arthroplasty in patients 50 years or less: do we improve activity profiles? J Arthroplasty 2013;28:872–6. https://doi.org/10.1016/j.arth.2012.10.009.

[20] Alghadir AH, Anwer S, Iqbal A, Iqbal ZA. Test-retest reliability, validity, and minimum detectable change of visual analog, numerical rating, and verbal rating scales for measurement of osteoarthritic knee pain. J Pain Res 2018;11:851–6. https://doi.org/10.2147/JPR.S158847.

[21] Crawford DA, Duwelius PJ, Sneller MA, Morris MJ, Hurst JM, Berend KR, et al. 2021 Mark Coventry Award: use of a smartphone-based care platform after primary partial and total knee arthroplasty: a prospective randomized controlled trial. Bone Joint Lett J 2021;103-B(6 Supple A):3–12. https://doi.org/10.1302/0301-620X.103B6.BJJ-2020-2352.R1.

[22] Crawford DA, Lombardi Jr AV, Berend KR, Huddleston 3rd JI, Peters CL, DeHaan A, et al. Early outcomes of primary total hip arthroplasty with use of a smartphone-based care platform: a prospective randomized controlled trial. Bone Joint Lett J 2021;103-B(7 Supple B):91–7. https://doi.org/10.1302/0301-620X.103B7.BJJ-2020-2402.R1.

[23] Tripuraneni KR, Foran JRH, Munson NR, Racca NE, Carothers JT. A smartwatch paired with A mobile application provides postoperative self-directed rehabilitation without compromising total knee arthroplasty outcomes: a randomized controlled trial. J Arthroplasty 2021;36:3888–93. https://doi.org/10.1016/j.arth.2021.08.007.

[24] Measuring walking quality through iPhone mobility metrics. Cupertino, CA: Apple, Inc.; 2021. https://www.apple.com/de/healthcare/docs/site/Measuring_Walking_Quality_Through_iPhone_Mobility_Metrics.pdf. [Accessed 12 April 2022].

[25] Abbasi-Bafghi H, Fallah-Yakhdani HR, Meijer OG, de Vet HCW, Bruijn SM, Yang LY, et al. The effects of knee arthroplasty on walking speed: a meta-analysis. BMC Musculoskelet Disord 2012;13:66. https://doi.org/10.1186/1471-2474-13-66.

[26] Fransen BL, Pijnappels M, Butter IK, Burger BJ, van Dieen JH, Hoozemans MJM. Patients' perceived walking abilities, daily-life gait behavior and gait quality before and 3 months after total knee arthroplasty. Arch Orthop Trauma Surg 2022;142:1189–96. https://doi.org/10.1007/s00402-021-03915-y.

[27] Lugade V, Wu A, Jewett B, Collis D, Chou LS. Gait asymmetry following an anterior and anterolateral approach to total hip arthroplasty. Clin Biomech 2010;25:675–80. https://doi.org/10.1016/j.clinbiomech.2010.05.003.

[28] Van Onsem S, Verstraete M, Zwaenepoel B, Dhont S, Van der Straeten C, Victor J. An evaluation of the influence of force- and weight bearing (a)symmetry on patient reported outcomes after total knee arthroplasty. Acta Orthop Belg 2020;86:294–302.

[29] Bourne RB, Chesworth B, Davis A, Mahomed N, Charron K. Comparing patient outcomes after THA and TKA: is there a difference? Clin Orthop Relat Res 2010;468:542–6. https://doi.org/10.1007/s11999-009-1046-9.

[30] Sayah SM, Karunaratne S, Beckenkamp PR, Horsley M, Hancock MJ, Hunter DJ, et al. Clinical course of pain and function following total knee arthroplasty: a systematic review and meta-regression. J Arthroplasty 2021;36:3993–4002.e37. https://doi.org/10.1016/j.arth.2021.06.019.

[31] Kunze KN, Fontana MA, MacLean CH, Lyman S, McLawhorn AS. Defining the patient acceptable symptom state for the HOOS JR and KOOS JR after primary total joint arthroplasty. J Bone Joint Surg Am 2022;104:345–52. https://doi.org/10.2106/JBJS.21.00550.

[32] Leroux A, Rzasa-Lynn R, Crainiceanu C, Sharma T. Wearable devices: current status and opportunities in pain assessment and management. Digit Biomark 2021;5:89–102. https://doi.org/10.1159/000515576.

[33] Seetharam A, Deckard ER, Ziemba-Davis M, Meneghini RM. The AAHKS clinical research award: are minimum two-year patient-reported outcome measures necessary for accurate assessment of patient outcomes after primary total knee arthroplasty? J Arthroplasty 2022;37:S716–20. https://doi.org/10.1016/j.arth.2022.02.016.

[34] Twiggs J, Salmon L, Kolos E, Bogue E, Miles B, Roe J. Measurement of physical activity in the pre- and early post-operative period after total knee arthroplasty for osteoarthritis using a Fitbit Flex device. Med Eng Phys 2018;51:31–40. https://doi.org/10.1016/j.medengphy.2017.10.007.

[35] Patterson JT, Wu HH, Chung CC, Bendich I, Barry JJ, Bini SA. Wearable activity sensors and early pain after total joint arthroplasty. Arthroplast Today 2020;6:68–70. https://doi.org/10.1016/j.artd.2019.12.006.

[36] Singh JA, Lemay CA, Nobel L, Yang W, Weissman N, Saag KG, et al. Association of early postoperative pain trajectories with longer-term pain outcome after primary total knee arthroplasty. JAMA Netw Open 2019;2:e1915105. https://doi.org/10.1001/jamanetworkopen.2019.15105.

[37] Levy N, Sturgess J, Mills P. "Pain as the fifth vital sign" and dependence on the "numerical pain scale" is being abandoned in the US: why? Br J Anaesth 2018;120:435–8. https://doi.org/10.1016/j.bja.2017.11.098.

[38] R3 Report Issue 11. Pain assessment and management standards for hospitals. https://www.jointcommission.org/standards/r3-report/r3-report-issue-11-pain-assessment-and-management-standards-for-hospitals/. [Accessed 12 April 2022].

[39] Parkes MJ, Callaghan MJ, O'Neill TW, Forsythe LM, Lunt M, Felson DT. Sensitivity to change of patient-preference measures for pain in patients with knee osteoarthritis: data from two trials. Arthritis Care Res 2016;68:1224–31. https://doi.org/10.1002/acr.22823.

[40] Werner MU, Mjobo PR, Nielsen PR, Rudin A. Prediction of postoperative pain: a systematic review of predictive experimental pain studies. Anesthesiology 2010;112:1494–502.