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Predicting Recovery Following Total Hip and Knee Arthroplasty Using a Clustering Algorithm

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ABSTRACT

Background: Recovery following total joint arthroplasty is patient-specific, yet groups of patients tend to fall into certain similar patterns of recovery. The purpose of this study was to identify and characterize recovery patterns following total hip arthroplasty (THA) and total knee arthroplasty (TKA) using patient-reported outcomes that represent distinct health domains. We hypothesized that recovery patterns could be defined and predicted using preoperative data.

Methods: Adult patients were recruited from a large, urban academic center. To model postoperative responses to THA and TKA across domains such as physical health, mental health, and joint-specific measures, we employed a longitudinal clustering algorithm that incorporates each of these health domains. The clustering algorithm from multiple health domains allows the ability to define distinct recovery trajectories, which could then be predicted from preoperative and perioperative factors using a multinomial regression.

Results: Four hundred forty-one of 1134 patients undergoing THA and 346 of 921 undergoing TKA met eligibility criteria and were used to define distinct patterns of recovery. The clustering algorithm was optimized for 3 distinct patterns of recovery that were observed in THA and TKA patients. Patients recovering from THA were divided into 3 groups: standard responders (50.8%), late mental responders (13.2%), and substandard responders (36.1%). Multivariable, multinomial regression suggested that these 3 groups had defined characteristics. Late mental responders tended to be obese ($P = .05$) and use more opioids ($P = .01$). Substandard responders had a larger number of comorbidities ($P = .02$) and used more opioids ($P = .001$). Patients recovering from TKA were divided among standard responders (55.8%), poor mental responders (24%), and poor physical responders (20.2%). Poor mental responders were more likely to be female ($P = .04$) and American Society of Anesthesiologists class III/IV ($P = .004$). Poor physical responders were more likely to be female ($P = .03$), younger ($P = .04$), American Society of Anesthesiologists III/IV ($P = .04$), use more opioids ($P = .02$), and be discharged to a nursing facility ($P = .001$). The THA and TKA models demonstrated areas under the curve of 0.67 and 0.72.

Conclusions: This multidomain, longitudinal clustering analysis defines 3 distinct patterns in the recovery of THA and TKA patients, with most patients in both cohorts experiencing robust improvement, while others had equally well defined yet less optimal recovery trajectories that were either delayed in recovery or failed to achieve a desired outcome. Patients in the delayed recovery and poor outcome groups were slightly different between THA and TKA. These groups of patients with similar recovery patterns were defined by patient characteristics that include potentially modifiable comorbid factors. This research suggests that there are multiple defined recovery trajectories after THA and TKA, which provides a new perspective on THA and TKA recovery.

Level of Evidence: III.

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Introduction

The chances of achieving a successful outcome and the timing of recovery are critical issues in patient counseling, risk stratification, and resource allocation in surgical care episodes. Yet, predicting the trajectory of recovery remains extremely challenging. Patient response to orthopaedic surgery is highly personal and follows variable trajectories over time, impacted by physical, mental, and joint-specific health domains. For example, recovery may be rapid or delayed and optimal or suboptimal at the chosen endpoint of measurement depending upon the physical, mental, or joint-specific health domain that is being measured. Standardized outcome measures often do not completely characterize the variability in the pathway of recovery also known as the “trajectory” of recovery for groups of patients. Likewise, common outcome measures like implant survival, reoperations, or readmissions may not correlate with patients perceived recovery [1,2]. Due to issues such as subjectivity in patient and physician health assessment, the limits of available outcome measurement tools, and the complexity of integrating the impact of multiple domains of health on surgical recovery, clinicians generally remain unable to provide consistently accurate estimates of the success and timing of recovery.

The outcome after total hip arthroplasty (THA) and total knee arthroplasty (TKA) replacement is variable over time and difficult to define in simple bimodal (“good or bad”) terms. Recovery after surgery involves dynamic interactions between multiple facets of overall health, including pain, mental health, physical function, and joint-specific symptoms (Fig. 1). For example, mental health has been associated with postoperative pain and satisfaction, but the exact impact on recovery remains unclear [3,4]. Several studies have explored recovery in a more granular or individualized fashion by defining discrete patterns of recovery following total joint arthroplasty [5-7]. These studies identify clusters of patients with patterns of recovery derived from repeated measurements of single patient-reported outcomes. Recent advances in statistical methodology have enabled more advanced models to comprehensively capture longitudinal recovery across multiple health domains [8].

The purpose of this study was to define and predict recovery patterns following THA and TKA from patient-reported outcomes, representing multiple distinct health domains tracked over time. Specifically, we explore longitudinal, multidomain patterns of recovery for populations undergoing primary THA and TKA. To assess multidomain recovery, we employ an unsupervised longitudinal clustering algorithm that incorporates postoperative changes in patient-perceived mental, physical, and joint-specific health. We hypothesized that clusters of recovery patterns (also called trajectories of recovery) specific to THA and TKA patients would be observed, influenced differentially by various health domains, and predicted using preoperative and perioperative data. Defining the common patterns of recovery and anticipating patient-specific recovery determined by risk factors for suboptimal recovery patterns would support personalized care approaches for improving outcomes and expectations.

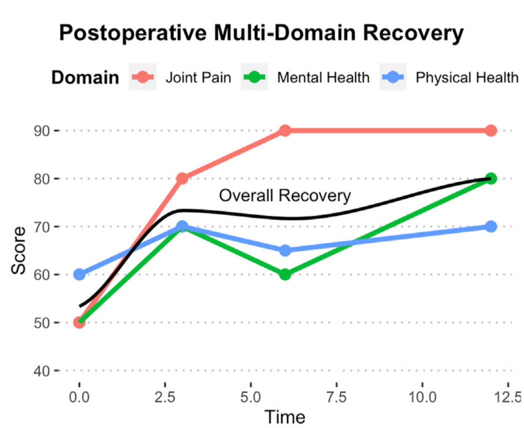

Figure 1. Concept of “multidomain recovery.” Colored lines represent the trajectories of individual health domains during recovery. Black line represents the theoretical overall recovery concept.

Material and methods

Subjects, study design, and outcomes

This observational longitudinal cohort study is approved by our institution’s ethics board (UCSF IRB 23-40714). Adult patients undergoing primary elective unilateral THA or TKA at a large, urban academic center between 2012 and 2022 with at least 1 year of follow-up were eligible for inclusion. Patients were excluded who underwent bilateral surgery, arthroplasty of another lower extremity joint during the study period, or if they failed to complete a minimum of 3 surveys over the 1-year study period. All surgeries were performed by one of 8 fellowship-trained arthroplasty surgeons. Outcomes collected include the Veterans Rand 12 (VR12) Mental and Physical Component Subscores (MCS and PCS) as well as the relevant Hip or Knee Osteoarthritis Outcome Score (HOOS or KOOS) [9,10]. Lower scores for VR12 MCS, VR12 PCS, HOOS, and KOOS (all ranges 0-100) represent more severe symptoms. All scores were centered by subtracting the sample mean and standardized by dividing by the sample standard deviation. Baseline demographic, medical, and surgical factors were recorded, as well as hospital length of stay (LOS), disposition (eg, nursing facility, home, home with home health), perioperative opioid use, readmissions, and emergency department visits. Opioid quantities are expressed as oral morphine equivalents.

Univariable recovery models

To determine optimal model parameters for each tracked patient-reported outcome, unsupervised univariable clustering was first performed. For the purposes of this analysis, a recovery cluster refers to a group of patients who follow a similar recovery trajectory postoperatively. Univariable models were generated separately for both cohorts to characterize recovery in each domain (mental, physical, and joint-specific health). Therefore, 6 models were selected. Latent class mixed models were generated for 2 to 6 recovery clusters using the lcmm package in R [11]. The best-fitting model for each cohort and outcome was independently selected according to Bayesian and Akaike information criteria, entropy, and cluster size. Time was modeled as a continuous variable using the exact dates of survey completion relative to the surgery date, and nonlinear trajectories were modeled using a b-spline basis with 3 degrees of freedom. Patients were assigned to clusters according to the highest posterior probability of membership.

Multivariable recovery clustering

Multivariable recovery clusters represent groups of patients who respond similarly to total joint arthroplasty across all measured health domains. A nonparametric, longitudinal multivariable clustering analysis encompassing mental health, physical health, and joint-specific symptoms was generated for patients undergoing THA and TKA. Patient-specific trajectories were generated from the univariable models for VR12 MCS, VR12 PCS, and HOOS or KOOS. These univariable trajectories were sampled at

5 equidistant time points over the first postoperative year and used as input for a multivariable, longitudinal k-means clustering analysis using *klm3d* [12,13]. Clustering for each cohort was selected based on optimal Calinski and Harabasz criteria, Akaike information criteria, Bayesian information criteria, cluster size, and clinical likelihood.

Statistical analyses

Associations between multivariable cluster membership and baseline demographic, medical, and surgical factors were first assessed using univariable analyses, including analysis of variance for continuous variables and chi-squared tests for nominal variables. Age, sex, and any predictors significant at the 0.10 level were included in a multivariable multinomial logistic regression to predict patient cluster. Predictive validity was assessed using the area under the receiver operating characteristic curve. All analyses were conducted in R [14]. Statistical significance was set at 0.05.

Results

Four hundred forty-one of 1134 patients undergoing THA and 346 of 921 undergoing TKA completed 3 surveys during the first year and were eligible for inclusion in the trajectory models. Patient demographics and medical characteristics are summarized in Table 1.

Trajectory models

Univariable recovery models were generated for each outcome in each cohort. Model selection criteria are displayed in Supplementary Table 1. The joint-specific health, mental health, and physical health recovery models were optimized with between 2 and 4 clusters in the unsupervised univariable algorithm. Multivariable, longitudinal clusters were then generated and optimized with 3 clusters for both the THA and TKA cohorts (Fig. 2).

Table 1
Baseline demographic and medical information for patients undergoing total hip and knee arthroplasty.

Variables	TKA	THA
Patients	346	441
Female	208	249
Age		
Mean (y)	66.25	65.52
Over 75	53	73
Under 75	293	368
Ethnicity		
Not Hispanic	313	401
Hispanic	21	23
Race		
White	267	343
Black	14	19
Asian	30	38
Other	29	32
Not recorded	6	9
BMI		
Mean	29.03	27.00
Normal	98	190
Overweight	127	145
Obese	121	105
ASA classification		
1-2	263	354
3-4	82	84
Not recorded	1	3
Preoperative opioid use?	70	108

BMI, body mass index.

Among patients undergoing THA, standard responders (50.8%) were characterized by robust and sustained improvement in all domains. Late mental responders (13.2%) reported an isolated initial decrease in mental health before improving at around 1 year. Finally, substandard responders (36.1%) reported adequate improvement in all domains, although to a lesser extent than standard responders.

Among patients undergoing TKA, standard responders (55.8%) were characterized by robust improvement in physical health, joint-specific symptoms, and reported constantly high mental health. In contrast, poor mental responders (24%) reported improved physical and joint-specific health but with persistently low to decreasing mental health. Finally, poor physical responders (20.2%) exhibited an isolated lack of improvement in physical health.

Association of preoperative and perioperative factors with trajectory membership

Ethnicity, body mass index, Charlson comorbidity index, preoperative opioid utilization, perioperative opioid consumption, discharge disposition, LOS, and procedure duration were associated with post-THA clusters and were included in the multivariable model. Body mass index, American Society of Anesthesiologists (ASA) classification, preoperative opioid utilization, perioperative opioid consumption, discharge disposition, LOS, and procedure duration were associated with the post-TKA cluster included in the multivariable model (Table 2).

In multivariable analysis to predict post-THA cluster, late mental responders were more likely to be obese (odds ratio [OR] 1.99, 95% confidence interval [CI] 1.01-3.95, $P < .05$) and use greater quantities of opioids perioperatively (OR 2.87, 95% CI 1.53-5.35, $P < .001$). Substandard responders were more likely to have higher Charlson comorbidity index scores (OR 1.21, 95% CI 1.04-1.42, $P = .016$) and use greater quantities of opioids perioperatively (OR 2.15, 95% CI 1.20-3.87, $P = .01$).

In multivariable analysis to predict the post-TKA cluster, poor mental responders were more likely to be female (OR 1.88, 95% CI 1.02-3.47, $P = .044$) and ASA class III/IV (OR 2.76, 95% CI 1.38-5.49, $P = .004$). Poor physical responders were more likely to be female (OR 2.17, 95% CI 1.09-4.3, $P = .03$), younger than 75 (OR 0.31, 95% CI 0.1-0.96, $P = .04$), ASA class III/IV (OR 2.19, 95% CI 1.04-4.63, $P = .04$), use greater quantities of opioids perioperatively (OR 2.64, 95% CI 1.21-5.76, $P = .02$), and be discharged to a skilled nursing facility (SNF) (OR 8.35, 95% CI 2.37-29.41, $P = .001$, Table 3).

Using only objective preoperative and perioperative data, models demonstrated area under the receiver operating characteristic curves of 0.67 and 0.72 for predicting the standard response to THA and TKA, respectively (Fig. 3).

Discussion

This analysis identified 3 distinct recovery patterns in patients undergoing elective THA and TKA associated with preoperative and perioperative characteristics. After THA, distinct recovery clusters were characterized as standard responders, late mental responders, and substandard responders. After TKA, clusters were characterized as standard responders, poor mental responders, and poor physical responders. Between clusters, differences were observed in both modifiable and nonmodifiable factors, including sex, age, comorbidities, disposition, and opioid consumption. Patient-specific multidomain recovery was predicted using objective preoperative and perioperative data.

There are several interesting differences in the identified recovery patterns between THA and TKA patients. While both THA

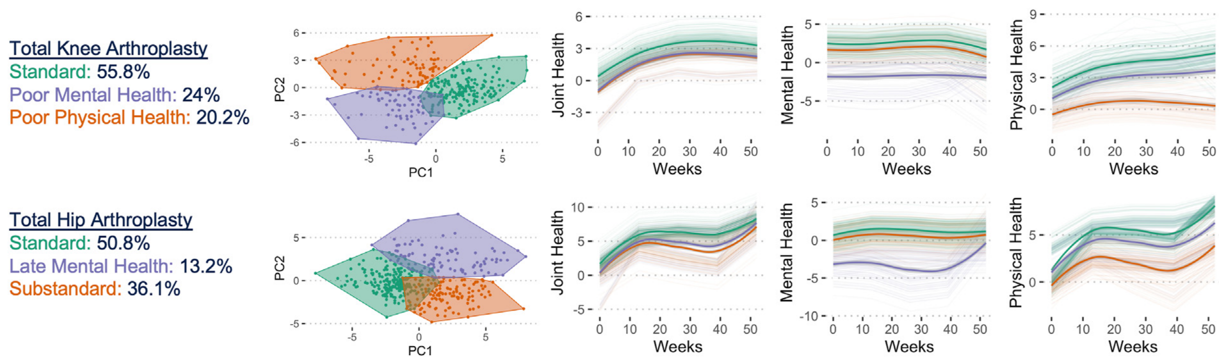

Figure 2. Results of multidomain clustering analysis from multidomain longitudinal clusters. Percentages refer to cluster size relative to the entire cohort. On the left, borders and colors represent individual multidomain clusters. Each point represents an individual patient. Axes represent the first 2 principal components of a longitudinal principal components analysis. On the right, lines represent postoperative trajectories in each health domain. Bold lines represent the mean trajectory. Thin lines represent each individual's trajectory. PC, principal component.

and TKA are effective treatments for end-stage osteoarthritis, nearly 10% and 20% of patients may remain unsatisfied, respectively [1,15]. This clustering analysis supports the notion that most patients experience symptomatic improvement following both THA and TKA. However, there is notable variability in the rates and patterns of overall recovery. Although similar numbers of standard responders were identified after TKA and THA, a larger proportion of patients reported improvement following THA. In contrast to poor mental responders after TKA, late mental responders after THA trended toward improved mental health at the 1-year time point. Additionally, the output variables are standardized for each population separately, so substandard responders after THA are only "substandard" relative to other patients undergoing THA. The absolute degree of multidomain improvement may still be greater for patients undergoing THA than patients undergoing TKA, but it cannot be compared directly in this analysis.

Table 2
Demographic, baseline, and medical information for each cohort by cluster.

Class	THA			P	TKA			P
	Standard responders (A)	Late mental responders (B)	Substandard responders (C)		Standard responders (A)	Poor mental responders (B)	Poor physical responders (C)	
Patients	**229**	**122**	**90**		**193**	**83**	**70**	
Sex				.42				<.01
Female	125 (54.59%)	75 (61.48%)	49 (54.44%)		101 (52.33%)	58 (69.88%)	49 (70%)	
Age				<.001				.51
Over 75	32 (13.97%)	33 (27.05%)	8 (8.89%)		33 (17.1%)	12 (14.46%)	8 (11.43%)	
Under 75	197 (86.03%)	89 (72.95%)	82 (91.11%)		160 (82.9%)	71 (85.54%)	62 (88.57%)	
Ethnicity				.052				.57
Non-Hispanic	207 (90.39%)	115 (94.26%)	79 (87.78%)		178 (92.23%)	73 (87.95%)	62 (88.57%)	
Hispanic	9 (3.93%)	5 (4.1%)	9 (10%)		8 (4.15%)	7 (8.43%)	6 (8.57%)	
Race				.48				.67
White	178 (77.73%)	98 (80.33%)	67 (74.44%)		154 (79.79%)	61 (73.49%)	52 (74.29%)	
Black	7 (3.06%)	8 (6.56%)	4 (4.44%)		8 (4.15%)	3 (3.61%)	3 (4.29%)	
Asian	21 (9.17%)	8 (6.56%)	9 (10%)		17 (8.81%)	7 (8.43%)	6 (8.57%)	
Other	16 (6.99%)	8 (6.56%)	8 (8.89%)		13 (6.74%)	9 (10.84%)	7 (10%)	
Not recorded	7 (3.06%)	0 (0%)	2 (2.22%)		1 (0.52%)	3 (3.61%)	2 (2.86%)	
BMI				.065				<.01
Normal	112 (48.91%)	47 (38.52%)	31 (34.44%)		60 (31.09%)	27 (32.53%)	11 (15.71%)	
Overweight	72 (31.44%)	42 (34.43%)	31 (34.44%)		81 (41.97%)	23 (27.71%)	23 (32.86%)	
Obese	44 (19.21%)	33 (27.05%)	28 (31.11%)		52 (26.94%)	33 (39.76%)	36 (51.43%)	
ASA class				.18				.001
ASA 1-2	194 (84.72%)	91 (74.59%)	69 (76.67%)		162 (83.94%)	56 (67.47%)	45 (64.29%)	
ASA 3-4	34 (14.85%)	30 (24.59%)	20 (22.22%)		31 (16.06%)	27 (32.53%)	24 (34.29%)	
Not recorded	1 (0.44%)	1 (0.82%)	1 (1.11%)		0 (0%)	0 (0%)	1 (1.43%)	
Charlson comorbidity index	2.52 (1.55)	3.27 (2.07)	2.63 (1.63)	<.001	2.97 (1.5)	2.73 (1.86)	3.13 (1.94)	.34
Opioid utilization								
Used preoperatively?	36 (15.72%)	40 (32.79%)	32 (35.56%)	<.001	26 (13.47%)	18 (21.69%)	26 (37.14%)	<.01
In-hospital use (OME)	99.52 (80.9)	150.82 (184.6)	150.63 (145.2)	<.001	138.49 (175.1)	213.93 (312.8)	228.66 (233.4)	<.01
Discharge disposition				<.01				<.001
Home health	111 (48.47%)	64 (52.46%)	49 (54.44%)		111 (57.51%)	41 (49.4%)	38 (54.29%)	
Placement	6 (2.62%)	15 (12.3%)	7 (7.78%)		9 (4.66%)	12 (14.46%)	18 (25.71%)	
Home	112 (48.91%)	43 (35.25%)	34 (37.78%)		73 (37.82%)	30 (36.14%)	14 (20%)	
Length of stay (h)	36.04 (16.9)	48.16 (42.2)	45.53 (27.8)	<.001	42.05 (23.5)	47.17 (22.0)	56.36 (29.3)	<.001
Procedure duration (min)	93.89 (22.78)	103.24 (29.65)	111.06 (42.6)	<.001	102.32 (22.7)	103.81 (31.69)	118.97 (53.9)	<.01

BMI, body mass index; OME, oral morphine equivalents.

Table 3
Multivariable analysis to predict recovery clusters from preoperative and perioperative factors.

	THA				TKA			
	Late mental responders	*P*	Substandard responders	*P*	Poor mental responders	*P*	Poor physical responders	*P*
Sex								
Male	reference				reference			
Female	1.24 (0.74-2.07)	.408	0.98 (0.56-1.72)	.95	1.88 (1.02-3.47)	.044	2.17 (1.09-4.3)	.03
Age								
Under 75	reference				reference			
Over 75	1.51 (0.77-2.97)	.229	0.49 (0.19-1.28)	.15	0.49 (0.2-1.25)	.135	0.31 (0.1-0.96)	.04
Ethnicity								
Non-Hispanic	reference				reference			
Hispanic	1.02 (0.29-3.62)	.973	2.4 (0.83-6.92)	.11				
BMI								
Normal	reference				reference			
Overweight	1.53 (0.86-2.72)	.152	1.69 (0.89-3.24)	.11	0.59 (0.29-1.2)	.144	1.32 (0.56-3.14)	.53
Obese	1.78 (0.95-3.35)	.074	1.99 (1.01-3.95)	**.05**	1.07 (0.52-2.2)	.863	2.02 (0.84-4.85)	.11
ASA class								
ASA 1-2					reference			
ASA 3-4					2.76 (1.38-5.49)	.004	2.19 (1.04-4.63)	.04
Charlson comorbidity index	1.21 (1.04-1.42)	.016	1.05 (0.88-1.25)	.61				
Opioid utilization								
Used preoperatively?	1 (1-1.01)	.105	1 (1-1)	.45	1 (1-1)	.149	1 (1-1)	.83
In-hospital use (OME)	2.15 (1.2-3.87)	.011	2.87 (1.53-5.35)	**.001**	1.29 (0.6-2.8)	.514	2.64 (1.21-5.76)	.02
Discharge disposition								
Home health	0.97 (0.57-1.65)	.903	1.07 (0.6-1.91)	.81	0.86 (0.47-1.58)	.622	1.46 (0.7-3.07)	.32
SNF	1.78 (0.54-5.88)	.347	2.12 (0.51-8.89)	.3	3.32 (0.98-11.27)	.055	8.35 (2.37-29.41)	.001
Home	reference				reference			
Length of stay (h)	1.01 (1-1.02)	.236	1.01 (1-1.03)	.1	1 (0.98-1.01)	.618	1.01 (1-1.03)	.16
Procedure duration (above median)	1.45 (0.89-2.37)	.138	1.57 (0.91-2.7)	.1	0.56 (0.31-1.01)	.052	1.57 (0.82-3.01)	.18

BMI, body mass index; OME, oral morphine equivalent.
Odds ratios are presented as odds of membership in a particular cluster relative to "standard responders."

A key contribution of this analysis is the incorporation of multivariable longitudinal clustering, which simultaneously considers patient health across multiple domains that are important in a patient's perception of their surgical outcome. Stated differently, a patient's recovery pattern is a function of time and context that incorporates multiple health factors. Prior analyses centered on one particular health domain or singular composite score may fail to capture important interactions between distinct health domains during surgical recovery [4-6]. For example, Hesseling's previously identified "late dippers," "slow starters," and "fast starters" following THA using a growth mixture model with the Oxford Hip Score. The Oxford Hip Score is a composite score that includes items related to pain and function but does not explicitly query mental health [16]. Our identification of late mental health responders, who were characterized by a late, rapid improvement in mental health, could potentially suggest an etiology for Hesseling's "slow starters."

There were several notable differences between univariable and multivariable trajectories. For example, 4 THA physical health recovery trajectories were identified in univariable analysis, with only 3 trajectories in multivariable clustering. Weaker signals from particular domains in univariable clustering may be silenced relative to stronger signals in other domains during multivariable clustering. There may be additional clusters underrepresented in this sample.

After THA, late mental responders were more likely to be obese and use greater quantities of opioids, while substandard responders were more likely to have more comorbidities and use greater quantities of opioids. Increased perioperative opioid use was associated with both clusters with worse outcomes following THA. Studies suggest protocols limiting postoperative opioid consumption with an emphasis on multimodal analgesia may improve satisfaction following THA [17,18]. Interestingly, opioid use prior to admission was not related to cluster membership. Obesity and comorbidities have previously been associated with poor responses to THA [5,18]

After TKA, poor mental responders were more likely to be female and ASA class III/IV while poor physical responders were more

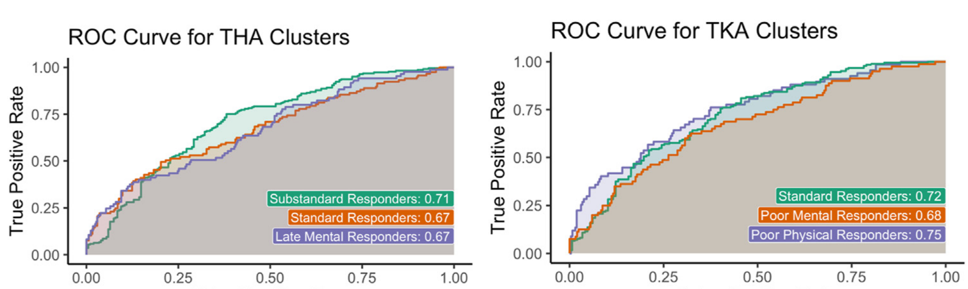

Figure 3. Receiver operating characteristic curve for models to predict recovery cluster from preoperative and perioperative data. Lines and shades represent individual clusters. Numbers represent area under the receiver operating characteristic curve for a decision rule to predict one cluster vs the other 2.

likely to be female, younger, ASA class III/IV, use greater quantities of opioids, and be discharged to a SNF. Females have been shown to report lower mental and physical health compared to male peers following TKA [7,19]. Younger females are also associated with greater opioid consumption following TKA [20]. Worse ASA classification was also associated with poor mental and physical responses. One explanation for the association between younger age and poor physical response is that younger patients may be reporting physical function relative to a more active reference point compared to older patients. SNF discharge was also shown to be a poor predictor of physical response. This is not an unexpected result, given that discharge recommendations at our institution are made by physical therapists after evaluating patient physical function. In contrast to prior literature, race was not found to be associated with outcomes [21,22].

While the patient data used to create this trajectory model was sufficient to test the model, one limitation of this study is the low multiple survey completion rate. Multiple survey time points were required for this analysis to perform the longitudinal characterization of recovery. A total of 1292 and 1071 patients underwent THA and TKA at our institution and were recorded in our database. Of these, 1134 patients undergoing THA and 921 patients undergoing TKA completed at least one survey postoperatively, 1047 and 738 completed 2, and 441 (34.1%) and 346 (32.3%) completed the minimum of 3. Survey compliance with longitudinal studies is challenging, and the completion rates in this analysis are significantly higher than prior similar analyses, which are as low as 8.1% [5]. While we are unable to comment on recovery trends due to missing data, patients completing fewer surveys reported slightly lower HOOS (46.7 vs 49.3, $P < .05$) and KOOS (47.0 vs 50.0, $P < .05$) at baseline, although these are well below the minimal clinically important differences of 18.0 and 15.1 [23]. Other factors previously shown to affect satisfaction and could impact recovery trajectories include pain in another joint [24], surgeon optimism [2], or preoperative patient expectations [25]. Also important to consider are the trajectories of nonoperative treatment and factors that may predispose patients to elect for surgery [26]. These algorithms do not allow us to determine the causality of specific factors in determining postoperative recovery, and understanding these pathways would require further research.

Conclusions

This multidomain, longitudinal clustering analysis provides a fresh perspective on how to integrate multiple health factors that define recovery after THA and TKA, suggesting discrete patterns of recovery over time that may differ between procedures. This type of research that integrates large and diverse sets of data demonstrates the power of advanced analytics to dissect and more completely define complex systems such as surgical recovery. Moreover, the patterns of recovery following TKA and THA identified in this study are associated with preoperative and perioperative factors. Some identified prognostic factors are modifiable (eg, comorbidities, obesity, disposition, in-hospital opioid utilization) and may represent targets for intervention. Identifying and modifying factors that may predispose a patient to a better or worse recovery pattern are key targets for future research directed at delivering patient-specific care following arthroplasty.

Conflicts of interest

T. Vail receives royalties for certain hip and knee products from DePuy, is a paid consultant for DePuy, has stocks in Hyalex Orthopaedics, Cytex, and Tesa Medical, and is on the board of trustees of JBJS. All other authors declare no potential conflicts of interest.

For full disclosure statements refer to https://doi.org/10.1016/j.artd.2024.101395.

CRediT authorship contribution statement

Ryan T. Halvorson: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Abel Torres-Espin:** Supervision, Formal analysis. **Matthew Cherches:** Writing – review & editing, Conceptualization. **Matt Callahan:** Data curation. **Thomas P. Vail:** Writing – review & editing, Supervision, Conceptualization. **Jeannie F. Bailey:** Writing – review & editing, Supervision, Conceptualization.

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Supplementary Table 1
Summary of model selection criteria for univariable models.

	G	Log likelihood	Conv?	npm	AIC	BIC	Entropy	1	2	3	4	5	6
THA HOOS	2	−1127	1	20	2294	2376	0.79	21.8	78.2	0	0	0	0
	3	−1115	1	25	2281	2383	0.82	18.6	78	3.4	0	0	0
	4	−1089	1	30	2239	2361	0.86	5.4	26.3	66	2.3	0	0
	5	−1078	1	35	2226	2369	0.88	0.2	5.7	30.4	61.7	2	0
	6	−1068	1	40	2216	2379	0.89	0.2	5.4	30.2	61	2	1.1
THA mental health	2	−1539	1	20	3117	3199	0.85	86.8	13.2	0	0	0	0
	3	−1539	1	25	3127	3229	0.72	0	86.8	13.2	0	0	0
	4	−1504	2	30	3068	3190	0.85	9.3	79.8	3.4	7.5	0	0
	5	−1504	2	35	3078	3221	0.77	9.3	79.8	0	3.4	7.5	0
	6	−1522	2	40	3124	3288	0.49	0	81.6	0	0	4.5	13.8
THA physical health	2	−1347	1	20	2735	2816	0.77	25.6	74.4	0	0	0	0
	3	−1340	1	25	2730	2832	0.59	25.9	23.4	50.8	0	0	0
	4	−1318	1	30	2697	2820	0.64	6.1	30.2	24.3	39.5	0	0
	5	−1318	2	35	2705	2849	0.59	5.7	26.8	9.3	48.8	9.5	0
	6	−1308	2	40	2696	2860	0.65	2.7	2.9	27	10	41.7	15.6
TKA KOOS	2	−1041	1	20	2122	2199	0.73	92.8	7.2	0	0	0	0
	3	−1035	1	25	2120	2216	0.77	2.9	91.3	5.8	0	0	0
	4	−1060	1	30	2181	2296	0.76	0.6	75.4	13.8	10.3	0	0
	5	−1049	1	35	2168	2302	0.79	42.4	0.6	47.6	8.3	1.1	0
	6	−1051	1	40	2183	2337	0.74	29.8	5.4	37.5	9.2	16.6	1.4
TKA mental health	2	−1192	1	20	2424	2501	0.81	85.7	14.3	0	0	0	0
	3	−1158	1	25	2366	2462	0.81	9.8	82.4	7.8	0	0	0
	4	−1173	1	30	2406	2522	0.46	13.8	25.8	53.3	7.2	0	0
	5	−1157	1	35	2383	2518	0.73	8.6	56.4	26.9	3.4	4.6	0
	6	−1134	1	40	2349	2503	0.8	8.9	2.6	62.2	20.3	5.7	0.3
TKA physical health	2	−1149	1	20	2338	2416	0.49	17.5	82.5	0	0	0	0
	3	−1115	1	25	2279	2375	0.73	23.7	74	2.3	0	0	0
	4	−1111	1	30	2283	2398	0.63	0.9	42.8	23.7	32.7	0	0
	5	−1116	1	35	2301	2436	0.63	1.7	24.4	15.2	39.5	19.2	0
	6	−1110	1	40	2300	2454	0.7	0.9	20.1	19.2	7.4	36.7	15.8

AIC, Akaike information criteria; BIC, Bayesian information criteria.