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Nutritional Status Influences Functional Outcomes After Robotic-Assisted Unicompartmental Knee Arthroplasty

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Study protocol

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Abstract

Background

Robotic-assisted unicompartmental knee arthroplasty (RA-UKA) improves component alignment; however, improved radiographic precision does not consistently translate into superior clinical outcomes. Nutritional status may influence postoperative recovery and functional adaptation. We investigated whether preoperative nutritional status modifies the relationship between surgical technique and early functional outcomes after UKA.

Methods

Eighty-eight elderly patients (≥ 60 years) undergoing unilateral UKA were retrospectively analyzed. GNRI was calculated preoperatively. Restricted cubic spline modeling identified a GNRI threshold of 105. Patients were stratified into GNRI ≤ 105 and GNRI > 105 groups. Radiographic alignment parameters and postoperative Knee Society Scores (KSS) were compared between robotic-assisted and conventional UKA. Multivariable regression models adjusted for age, sex, BMI, and baseline KSS.

Results

RA-UKA demonstrated reduced alignment variability compared with conventional UKA. In the overall cohort, postoperative KSS did not differ significantly between techniques. Among patients with GNRI ≤ 105, RA-UKA was independently associated with higher postoperative KSS (adjusted $P < 0.05$). In contrast, among patients with GNRI > 105, improved alignment accuracy did not result in superior functional outcomes.

Conclusion

Preoperative nutritional status appears to influence the functional relevance of alignment precision in UKA. Elderly patients with lower GNRI may derive greater early functional benefit from robotic assistance. Nutritional assessment may assist in patient selection for RA-UKA.

Introduction

Unicompartmental knee arthroplasty (UKA) has become an established surgical option for isolated compartment osteoarthritis due to its bone preservation, faster recovery, and more physiological kinematics compared with total knee arthroplasty [1–3]. Nevertheless, a subset of elderly patients reported suboptimal functional recovery after UKA despite technically successful procedures [4,5].

Robotic-assisted UKA (RA-UKA) was introduced to improve the precision of bone resection, implant positioning, and limb alignment [6–8]. Multiple radiographic studies have demonstrated reduced outliers and improved component placement with robotic systems [9]. However, consistent improvement in

patient-reported functional outcomes has not been uniformly observed [10,11]. This discrepancy suggests that radiographic precision alone may not fully determine early functional recovery [12].

UKA is biomechanically sensitive to minor deviations in coronal and sagittal alignment [13,14]. Small changes in tibial slope or femoral positioning may alter load distribution within the preserved compartments [14,15]. At the same time, postoperative function depends not only on mechanical alignment but also on muscle strength, neuromuscular control, and rehabilitation capacity—factors closely related to nutritional status [16,17].

The geriatric nutritional risk index (GNRI), calculated from serum albumin and body weight parameters, reflects systemic nutritional reserve and has been associated with postoperative complications and recovery outcomes in arthroplasty patients [18–20]. We hypothesized that nutritional status may modulate the functional impact of alignment precision in UKA.

Therefore, this study aimed to investigate whether GNRI modifies the relationship between surgical technique (robotic versus conventional UKA) and early postoperative functional outcomes in elderly patients.

Materials and Methods

Study Design and Population

This study was approved by the Ethics Committee of Guangdong Provincial Second People's Hospital (No. 2023-XJS-040-02) and was conducted in accordance with the Declaration of Helsinki. Patients aged 18–85 years who underwent primary unilateral UKA were screened. Inclusion criteria were: (1) Medial compartment osteoarthritis; (2) First-time unilateral UKA; (3) Availability of complete radiographic and laboratory data. Exclusion criteria included: (1) BMI > 35 kg/m²; (2) Active infection; (3) Severe osteoporosis; (4) Neuromuscular disorders; (5) Systemic diseases affecting rehabilitation. For the present analysis, only patients aged ≥ 60 years were included [20].

Nutritional Assessment

GNRI was calculated as: The GNRI score was calculated using the formula: 1.489 × serum albumin (g/l) + 41.7 (current weight in kilograms/ideal weight). Ideal weight was calculated using the Lorenz formulas: height (cm)-105- [(height (cm) -150)/4] for men and height (cm)-105-[(height (cm)-150) /2.5] for women [21,22]. Restricted cubic spline (RCS) modeling was performed to evaluate nonlinear associations between GNRI and postoperative outcomes. An inflection point was identified at GNRI ≈ 105, which was used for stratified analyses [20].

Radiographic and Clinical Evaluation

Radiographic parameters included: (1) Coronal tibial component angle (CTCA); (2) Coronal femoral component angle (CFCA); (3) Sagittal tibial component angle (STCA); (4) Sagittal femoral component angle (SFCA); (5) Hip–knee–ankle (HKA) angle. Postoperative knee function was assessed using: (1) Knee Society Score (KSS); Visual Analog Scale (VAS).

Statistical Analysis

Continuous variables were assessed for normality using the Shapiro–Wilk test. (1) Normally distributed variables were presented as mean ± standard deviation and compared using independent t-tests; (2) Non-normally distributed variables were presented as median (interquartile range) and compared using the Mann–Whitney U test; (3) Categorical variables were compared using χ^2 or Fisher's exact tests.

Multivariable Analysis

To evaluate independent associations: 1. Linear regression models were constructed to assess the relationship between surgical technique and postoperative KSS. 2.Separate linear regression models were used to assess associations between surgical technique and alignment deviation.

Statistical Software

All analyses were performed using R software and SPSS. A two-sided P value < 0.05 was considered statistically significant.

Results

Baseline Characteristics

After applying inclusion and exclusion criteria, 88 elderly patients (≥ 60 years) were included in the final analysis, comprising 24 patients in the RA-UKA group and 64 patients in the conventional UKA group. Baseline characteristics, including age, sex distribution, BMI, preoperative HKA deviation, baseline KSS, and GNRI score, were comparable between groups (all P > 0.05), indicating no significant preoperative imbalance. (Table 1). A flow diagram was shown in Fig. 1.

Table 1
Baseline characteristics of RA-UKA and Conventional UKA among elderly adults.

Characteristics	Total	RA-UKA	Conventional UKA	P
Man (%)	21.7% (25/115)	29.2% (7/24)	19.8% (18/91)	p = 0.4755
Age (years)	70.65 ± 5.71	71.46 ± 5.28	70.44 ± 5.83	p = 0.4396
BMI	27.14 ± 3.63	26.8 ± 3.22	27.3 ± 3.44	P>0.05
HKA deviation	171.99 ± 4.50°	171.56 ± 4.14°	172.10 ± 4.61°	p = 0.6019
KSS score	41.14 ± 3.63	41.8 ± 3.22	41.3 ± 3.44	P>0.05
GNRI score	107.33 ± 7.76	105.15 ± 7.68	107.91 ± 7.72	p = 0.1215

GNRI, geriatric nutritional risk index; HKA deviation, preoperative hip-knee-ankle angle deviations; KSS score, preoperative Knee Society score.

Alignment Accuracy

Postoperative HKA angle deviation and CTCA, CFCA, SFCA, and STCA deviation were calculated to evaluate the performance of component position and lower limb alignment. There is no significant difference in CTCA or SFCA deviation between the RA-UKA group and the conventional UKA group. The STCA deviation (P = 0.035) in the RA-UKA group was significantly lower than conventional UKA group. Meanwhile, the RA-UKA group seemed to have lower CFCA deviation (P = 0.065) and HKA angle deviations (P = 0.075); however, the differences were not statistically significant. KSS scores were used to evaluate the postoperative knee function and clinical outcomes. The results showed that postoperative KSS scores had no significant difference. VAS scores were measured to assess the pain circumstances and there is no significant difference in VAS scores between the RA-UKA group and the conventional UKA group (Table 2). These results indicate that for the elderly adult population, RA-UKA may have higher accuracy in prosthesis placement and lower limb axis alignment but was not significantly superior than conventional UKA in knee joint function and pain improvement. Logistic regression was performed to further investigate the association between the RA-UKA and HKA angle deviation. Our results showed that the RA-UKA group had a significantly lower HKA angle deviation than the conventional UKA group with a P-value of 0.01 and an OR of 1.41 (95% CI: 1.09–1.83). Then adjusted logistic regression models were established and OR remained stable after adjustment for sex, age (OR = 1.42, 95% CI: 1.09–1.84). In addition, we adjusted the current model with preoperative HKA angle deviation and then obtained an OR of 1.43 (95% CI: 1.09–1.88) (Table 3). These results indicated that RAUKA is more accurate for component positioning and limb alignment among the elderly adult population than conventional UKA.

Table 2
Postoperative characteristics of RA-UKA and Conventional UKA among elderly adults.

Characteristics	Total	RA-UKA	Conventional UKA	P
CTCA	84.64 ± 3.65	86.20 ± 2.66	84.23 ± 3.77	p = 0.0179*
CFCA	2.94 ± 1.77	3.27 ± 2.23	2.85 ± 1.62	p = 0.3124
SFCA	8.54 ± 3.28	6.32 ± 3.60	9.12 ± 2.94	p = 0.0001***
STCA	31.50 ± 7.92	32.00 ± 6.59	31.36 ± 8.26	p = 0.7292
HKA deviation	176.41 ± 2.53	177.28 ± 1.46	176.18 ± 2.70	p = 0.0585
KSS score	63.14 ± 3.63	64.14 ± 3.63	62.14 ± 3.63	P>0.05
VAS score	2.88 ± 1.18	2.74 ± 1.00	2.92 ± 1.23	p = 0.191

CFCA, coronal femoral component angle; CTCA, coronal tibial component angle; HKA deviation, postoperative hip-knee-ankle angle deviations; KSS score, postoperative Knee Society score; SFCA, sagittal femoral component angle; STCA, sagittal tibial component angle; VAS score, visual analog scale score.

Table 3
Adjusted odds ratios and 95% CI of the association of RA-UKA with postoperative HKA deviations.

Gourps	OR(95%)	P
Unadjusted	1.404	0.012
Model 1	1.415	0.006
Model 2	1.412	< 0.001

Model 1 = sex, age. Model 2 = Model 1 + preoperative HKA deviations.

RCS and GNRI Stratification

RCS were used to flexibly model and visualize the relationships between GNRI scores, KSS scores, and HKA deviation (**Figure. 2**). We found that KSS scores and HKA deviation tended to slightly rise with the GNRI score increasing. Participants in the RA-UKA group can remain stably high level of KSS score and stably low level of HKA deviation with the GNRI score increasing. In the conventional UKA group, the KSS score keep stably low until the GNRI reached 105 and then increased. Besides, their HKA deviation continuously increased until GNRI reached 105. Therefore, all participants were categorized into two groups with GNRI ≤ 105 and GNRI > 105 for further GNRI stratified analyses.

Subgroup Analysis : GNRI ≤ 105

Twenty-three participants were scored as low GNRI elderly adults (GNRI ≤ 105) and the baseline characteristics were shown in Table 4. Age, sex, preoperative HKA angle deviation, KSS score, and GNRI

score have no significant differences between RA-UKA and conventional UKA groups while RA-UKA groups seemed to have a lower BMI (P = 0.031).

Table 4
Baseline characteristics of RA-UKA and Conventional UKA among elderly adults with GNRI ≤ 105.

Characteristics	Total	RA-UKA	Conventional UKA	P
Male (%)	32	10	28	P>0.05
Age (years)	68.41 ± 6.95	71.95 ± 5.51	68.01 ± 6.21	P<0.05
BMI	27.14 ± 3.63	26.8 ± 3.22	27.3 ± 3.44	P>0.05
HKA deviation	172.35 ± 4.36	171.55 ± 4.07	172.49 ± 4.41	P<0.05
KSS score	41.14 ± 3.63	41.8 ± 3.22	41.3 ± 3.44	P>0.05
GNRI score	97.81 ± 8.01	97.13 ± 8.33	98.50 ± 8.39	P>0.05
Surgery time (minute)	96.81 ± 10.01	100.13 ± 11.33	90.50 ± 8.39	P<0.05

HKA deviation, preoperative hip-knee-ankle angle deviations; KSS score, preoperative Knee Society score; GNRI, geriatric nutritional risk index.

Participants obtained significantly higher postoperative KSS score in the RA-UKA group than in the conventional UKA group (P = 0.025). However, there is no significant difference in alignment characters like HKA angle deviation and CTCA, CFCA, STCA, and SFCA deviations between the RA-UKA group and the conventional UKA group. Meanwhile, the postoperative VAS score had no significant difference (Table 5). These results showed that for elderly adults with GNRI ≤ 105, RA-UKA and conventional UKA both can achieve effective pain management and accurate component position, meanwhile RA-UKA seemed to lead to better postoperative clinical outcomes.

Table 5
Postoperative characteristics of RA-UKA and Conventional UKA among elderly adults with GNRI ≤ 105.

Characteristics	Total	RA-UKA	Conventional UKA	P
CTCA	84.52 ± 3.65	86.31 ± 2.66	84.77 ± 3.77	p = 0.0122*
CFCA	2.96 ± 1.73	3.24 ± 2.13	2.81 ± 1.67	p = 0.3134
SFCA	8.57 ± 3.33	6.31 ± 3.80	9.41 ± 2.98	p = 0.0001***
STCA	31.53 ± 7.88	32.12 ± 6.62	31.38 ± 8.42	p = 0.6531
HKA deviation	177.22 ± 2.44	177.11 ± 1.49	176.75 ± 2.74	p = 0.0501
KSS score	64.14 ± 3.63	68.14 ± 3.63	62.14 ± 3.63	P<0.05
VAS score	2.88 ± 1.18	2.74 ± 1.00	2.92 ± 1.23	p = 0.191

CTCA, coronal tibial component angle; CFCA, coronal femoral component angle; STCA, sagittal tibial component angle; SFCA, sagittal femoral component angle; KSS score, postoperative Knee Society score; VAS score, visual analog scale score.

Logistic regression analysis also showed that the RA-UKA group had a significantly higher postoperative KSS score with a P-value of 0.043 and an OR of 0.941 (95% CI: 0.888–0.998).

Adjusted for sex and age, our model indicated a P-value of 0.030 and an OR of 0.891 (95% CI: 0.803–0.989). After further adjustment for the preoperative KSS score, the logistic regression model showed a P-value of 0.045 and an OR of 0.757 (95% CI: 0.577–0.994). Finally, we additionally adjusted the current model with BMI and then obtained a P-value of 0.066 and an OR

of 0.766 (95% CI: 0.577–1.018) (Table 6). Hence, it is supposed that elderly adults with GNRI ≤ 105 can expect more knee function benefits after RA-UKA than conventional UKA.

Table 6
Adjusted odds ratios and 95% CIs of the association of RA-UKA with postoperative KSS score among elderly adults with GNRI ≤ 105.

Gourps	OR(95%)	P
Unadjusted	0.941 (0.888–0.998)	0.043
Model 1	0.891 (0.803–0.989)	0.03
Model 2	0.757 (0.577–0.994)	0.045
Model 3	0.766 (0.577–1.018)	0.066

Model 1 = sex, age. Model 2 = Model 1 + preoperative KSS score. Model 3 = Model 2 + BMI.

Subgroup Analysis :GNRI > 105

The baseline characteristics of 65 participants with a GNRI score > 105 were shown in Table 7. There is no significant difference in age, sex, BMI, preoperative HKA angle deviation, KSS score, and GNRI score between RA-UKA and conventional UKA groups. Participants in the RA-UKA group had significantly lower HKA angle deviations (P = 0.039), CFCA (P = 0.040), STCA (P = 0.013) (Table 8). However, there is no significant difference in KSS score and the VAS score between the RA-UKA group and the conventional UKA group. Logistic regression analysis showed that HKA angle deviations are significantly lower in the RA-UKA group with a P-value of 0.012 and an OR of 1.476 (95% CI: 1.089–2.000). In model 1, we adjusted for sex and age, RA-UKA was significantly associated with lower HKA angle deviations with a P-value of 0.013 and OR of 1.483 (95% CI: 1.088–2.020) (Table 9). In addition, these significant associations remained after further adjustment for preoperative HKA angle deviations in model 2.

Table 7
Postoperative characteristics of RA-UKA and Conventional UKA among elderly adults with GNRI>105.

Characteristics	Total	RA-UKA	Conventional UKA	P
Male (%)	78	9	69	P>0.05
Age (years)	73.52 ± 5.86	71.62 ± 5.80	74.12 ± 5.87	0.3022
BMI	27.14 ± 3.63	26.8 ± 3.22	27.3 ± 3.44	P>0.05
HKA deviation	170.77 ± 4.91	170.77 ± 5.56	170.76 ± 4.81	0.9965
KSS score	41.14 ± 3.63	41.5 ± 3.22	41.6 ± 3.44	P>0.05
GNRI score	97.88 ± 5.43	97.44 ± 6.06	98.03 ± 5.34	0.7951
Surgery time (minute)	94.81 ± 10.01	101.13 ± 11.33	89.50 ± 8.39	P<0.05

HKA deviation, preoperative hip-knee-ankle angle deviations; KSS score, preoperative Knee Society score; GNRI, geriatric nutritional risk index.

Table 8
Postoperative characteristics of RA-UKA and Conventional UKA among elderly adults with GNRI>105.

Characteristics	Total	RA-UKA	Conventional UKA	P
CTCA	84.88 ± 3.62	86.76 ± 2.63	84.77 ± 3.75	p = 0.0131*
CFCA	2.91 ± 1.71	3.23 ± 2.12	2.85 ± 1.63	p = 0.3211
SFCA	8.52 ± 3.36	6.35 ± 3.82	9.31 ± 2.93	p = 0.0001***
STCA	31.55 ± 7.99	32.13 ± 6.66	31.31 ± 8.46	p = 0.6555
HKA deviation	177.12 ± 2.51	177.55 ± 1.88	176.70 ± 2.79	p = 0.0541
KSS score	65.14 ± 3.63	66.14 ± 3.63	64.14 ± 3.63	P>0.05
VAS score	2.89 ± 1.21	2.75 ± 1.11	2.93 ± 1.25	p = 0.111

Table 9
Adjusted odds ratios and 95% CIs of the association of RA-UKA with postoperative KSS score among elderly adults with GNRI>105.

Gourps	OR(95%)	P
Unadjusted	1.476 (1.08–2.000)	0.012
Model 1	1.483 (1.088–2.020)	0.013
Model 2	1.543 (1.109–2.145)	0.01
Model 3	1.682 (1.112–2.544)	0.014

Discussion

Principal Findings

The most important finding of this study is that preoperative nutritional status modifies the functional impact of robotic alignment precision in unicompartmental knee arthroplasty. While robotic-assisted UKA significantly reduced alignment variability across the cohort, this mechanical advantage translated into meaningful functional improvement only among patients with lower GNRI (≤ 105). In contrast, patients with adequate nutritional reserve (GNRI > 105) demonstrated improved radiographic precision without measurable functional superiority. These findings suggest that the clinical relevance of mechanical accuracy in UKA is conditional rather than universal.

Mechanical Precision Versus Functional Recovery

Robotic-assisted UKA was developed to enhance intraoperative planning accuracy, reduce component malposition, and minimize alignment outliers [23,24]. Multiple studies have demonstrated that robotic systems improve reproducibility of tibial slope, femoral positioning, and coronal alignment [25,26]. However, consistent improvement in early patient-reported outcomes has not been universally observed [10,11]. Our findings align with this paradox. In the overall cohort, although alignment variability was reduced, postoperative KSS did not significantly differ between techniques. This indicates that radiographic precision alone does not guarantee superior early knee function. The explanation likely lies in the multifactorial nature of postoperative recovery.

Biomechanical Sensitivity of UKA

Unlike total knee arthroplasty, UKA preserves native compartments and cruciate ligaments [27]. Load transfer therefore remains compartment-specific and biomechanically sensitive to subtle deviations [14,28]. Small alterations in: (1) Coronal alignment; (2) Tibial slope; (3) Femoral component rotation. It may alter contact stress distribution in the preserved cartilage and subchondral bone. However, the clinical expression of such deviations depends on the patient's ability to compensate biomechanically.

Nutritional Status as a Marker of Physiological Reserve

GNRI reflects systemic nutritional reserve and correlates with [29]: (1) Serum albumin levels; (2) Lean body mass; (3) Muscle strength; (4) Tissue healing capacity; (5) Immunological competence. Patients with lower GNRI likely have: (1) Reduced quadriceps strength; (2) Impaired neuromuscular coordination; (3) Delayed rehabilitation response; (4) Lower adaptive capacity to mechanical stress. In such individuals, even minor alignment imperfections may produce disproportionate functional consequences. Robotic assistance, by minimizing mechanical variability, may therefore offer protective benefit in physiologically vulnerable patients.

In the GNRI ≤ 105 subgroup, robotic assistance resulted in significantly higher postoperative KSS, despite no major differences in measured alignment deviation compared with conventional UKA. This suggests that: (1) Precision may reduce micro-instability; (2) Joint loading may be more physiologically balanced; (3) Soft tissue tensioning may be more consistent. For patients with limited compensatory capacity, these small improvements become clinically relevant. Conversely, patients with adequate nutritional reserve may compensate effectively for mild mechanical variability through: (1) Better muscle strength; (2) Faster neuromuscular adaptation; (3) More efficient rehabilitation.

Why Alignment Matters More in Low GNRI Patients

In the GNRI ≤ 105 subgroup, robotic assistance resulted in significantly higher postoperative KSS, despite no major differences in measured alignment deviation compared with conventional UKA.

This suggests that: (1) Precision may reduce micro-instability; (2) Joint loading may be more physiologically balanced; (3) Soft tissue tensioning may be more consistent. For patients with limited compensatory capacity, these small improvements become clinically relevant. Conversely, patients with adequate nutritional reserve may compensate effectively for mild mechanical variability through: (1) Better muscle strength; (2) Faster neuromuscular adaptation; (3) More efficient rehabilitation. Thus, mechanical superiority does not necessarily translate into measurable functional gain in nutritionally robust individuals.

Conditional Relevance of Robotic Technology

These findings support a broader concept: Robotic precision is not uniformly beneficial; its value may depend on patient-specific vulnerability. From a surgical strategy standpoint, this suggests that: Robotic assistance should not be universally mandated, Patient selection may optimize cost-effectiveness and Nutritional screening may serve as a practical stratification tool. This approach aligns with precision medicine principles in orthopedics.

Comparison With Previous

Previous randomized and cohort studies have demonstrated improved alignment with robotic UKA but inconsistent functional benefit [30,31]. Most investigations evaluated general populations without considering biological modifiers. This study demonstrating that GNRI modifies the relationship between robotic precision and functional outcome in UKA. Previous study showed malnutrition has been associated with: (1) Increased complications; (2) Delayed recovery; (3) Inferior functional outcomes. Our

findings extend this concept by showing that nutritional reserve not only affects complication risk but may influence the functional sensitivity to surgical precision.

Clinical Implications

From a clinical perspective, robotic systems increase operative cost and operative time [32]. Therefore, identifying patients most likely to benefit is essential. Our findings suggest: Patients with GNRI ≤ 105 may derive greater early functional benefit from robotic-assisted UKA. This has several implications: Preoperative GNRI assessment is simple and inexpensive, Nutritional status may inform surgical technique selection and Selective robotic utilization may enhance cost-effectiveness. Rather than viewing robotic systems as universally superior, surgeons may consider a targeted approach for high-risk physiological subgroups.

Limitations

Several limitations must be acknowledged. First, this is a retrospective, single-center study. Selection bias cannot be fully excluded. Second, the robotic group sample size was smaller than the conventional group, which may limit statistical power. Third, follow-up duration was short-term. Whether nutritional status modifies long-term survivorship or revision risk remains unknown. Fourth, GNRI reflects systemic nutritional reserve but does not directly measure muscle mass or frailty indices. Future studies incorporating sarcopenia assessment may further clarify mechanisms.

Conclusion

In conclusion, this study demonstrates that the functional relevance of robotic precision in UKA is influenced by preoperative nutritional status. Mechanical superiority alone does not universally improve early function; rather, its clinical value appears greatest in physiologically vulnerable patients. Nutritional assessment may therefore represent a practical and scalable tool for individualized surgical planning in unicompartmental knee arthroplasty.

Declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of Guangdong Provincial Second People's Hospital (No. 2023-XJS-040-02) and was conducted in accordance with the Declaration of Helsinki.

Consent to participate

Informed consent was obtained from all individual participants included in the study. Informed consent was obtained from all individual participants included in the study.

Consent for publication

Confirm that consent from all participants has been received for publication.

Availability of data and materials

The datasets generated during and analysis during the current study are available from the corresponding author on reasonable request.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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Figures

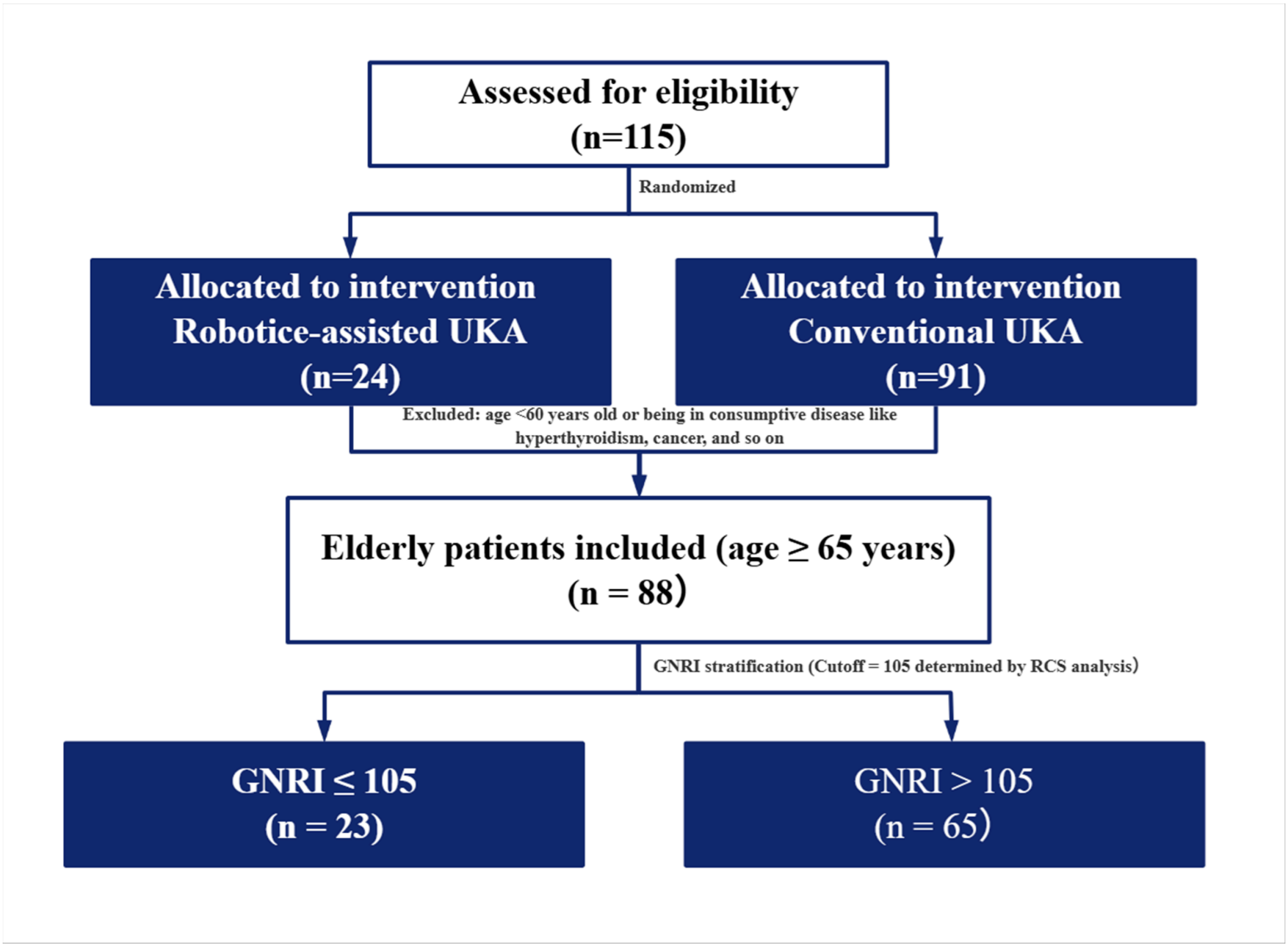


Figure 1

Flow diagram of inclusion/exclusion of study participants.

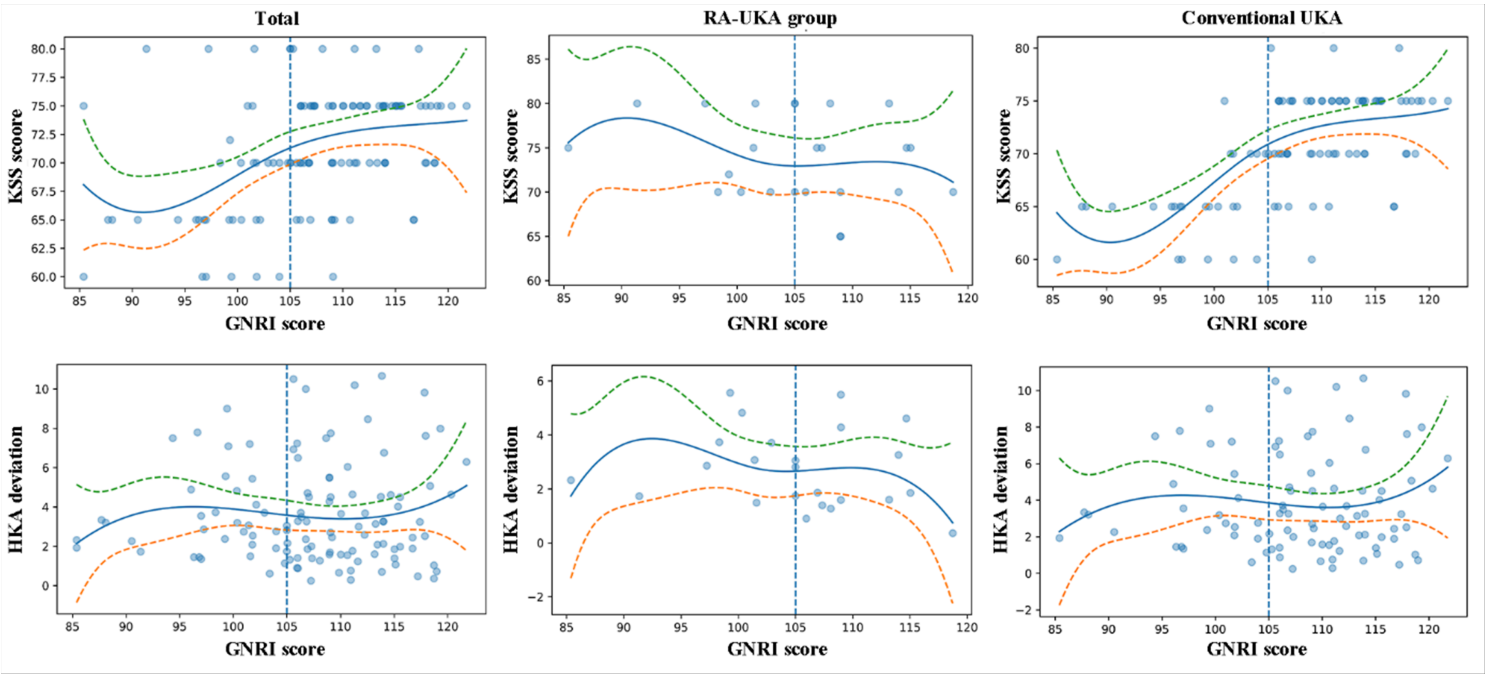


Figure 2

Restricted cubic spline analyses of GNRI in relation to postoperative KSS score and HKA deviation. Panels A–C illustrate the relationship between GNIF and postoperative Knee Society Score (KSS): (A) total cohort; (B) robot-assisted UKA group; (C) conventional UKA group. D–F illustrate the association between GNIF and postoperative hip–knee–ankle (HKA) angle deviation (absolute deviation from 180°: (D) total cohort; (E) robot-assisted UKA group; (F) conventional UKA group.