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Original Research

Factors Affecting Successful Restricted Kinematic Alignment With Robotic Assisted Total Knee Arthroplasty in Patients With Severe Varus Preoperative Alignment

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ABSTRACT

Background: Total knee arthroplasty (TKA) remains challenging in severe varus knees. We evaluated the impact of hip-knee-ankle varus deformity and osteophyte size on achieving restricted kinematic alignment (rKA) in robotic-arm-assisted TKA.

Methods: This retrospective study included 244 knees (194 patients) that underwent robotic-arm-assisted TKA for varus primary knee osteoarthritis at an academic institution. Intraoperative hip-knee-ankle angle (HKA) and soft tissue balance were monitored to assess the success of rKA with osteophyte resection alone. For those that failed, medial collateral ligament needle pie-crusting was performed.

Results: Mean age was 65.3 years (range, 48-83). Mean preoperative HKA was 11.9° varus (range, 1.0°-32.0°), and HKA after osteophyte resection was 5.1° varus (range, 0°-19.0°). Mean HKA correction was 6.8° (range, 0°-18.0°). rKA was achieved in 36.9% at a boundary of ≤3° varus and up to 72.1% at ≤6° varus. Preoperative varus HKA was lower in successful cases across all target alignments ($P < .05$). Medial tibial osteophyte size was 6.1% ± 2.9% and was smaller in all groups that achieved rKA ($P < .05$). Both were positively correlated with degree of deformity correction, $r = 0.718$ ($P < .01$) and $r = 0.281$ ($P < .01$), respectively.

Conclusions: This study highlighted the importance of varus deformity and medial tibial osteophytes when adopting rKA. They were associated with increased failure to achieve rKA. rKA was reliably achieved in minimal varus deformities (HKA ≤ 5°), we recommend an expanded protocol of HKA ≤ 6° varus for mild deformities (HKA 6°-10°), and consider medial soft tissue release for moderate (HKA 11°-15°) and severe deformities (HKA ≥ 16°).

Introduction

Various philosophies of alignment have been proposed for total knee arthroplasty (TKA). Mechanical alignment first proposed by Freeman and Swanson [1] has been considered the gold standard for the past decades, restoring a neutral lower limb alignment with hip-knee-ankle angle boundaries of 0 ± 3° with the goal of maximizing durability of components and pain relief [2]. Mechanically aligned total knee arthroplasty has a history of good long-term survivorship [3]. However, despite advancements in implant design and surgical precision, there still remains high incidence of residual symptoms and functional problems ranging from 33% to 54% [4].

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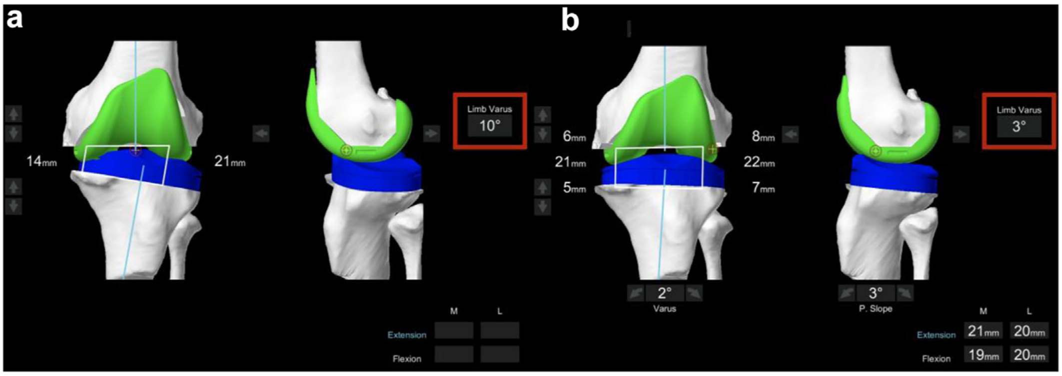

Figure 1. Intraoperative coronal alignment assessment by Mako Robotic Arm-Assisted Surgery System software (Mako Surgical Corp., Stryker, Fort Lauderdale, FL). (a) coronal alignment before osteophyte resection. (b) coronal alignment after osteophyte resection.

Kinematic alignment (KA), proposed by Howell et al [5], aims to restore the native limb alignment, allowing for more physiological joint line obliquity and reducing the need for ligament release. The ideal alignment strategy still remains controversial; KA has been reported to offer improved functional outcomes and reduced incidence of pain associated with TKA compared to mechanical alignment [6,7], while others have reported no difference in clinical and functional outcomes between the 2 groups [8,9]. The implantation of KA without restriction remains controversial due to the concerns of increased aseptic loosening in outlier knee anatomy at extremes of HKA alignment [10,11]. To limit the impact on the mechanics and wear patterns of implants, restricted protocols for the HKA or restricted kinematic alignment (rKA) have been proposed by various authors with HKA 3° valgus to 6° varus [12,13].

Achieving restricted KA boundaries with osteophyte excision alone remains challenging in knees with severe varus deformity. The purpose of this study is to evaluate the impact of varus deformity severity and osteophyte size on deformity correction and to determine the success of achieving rKA boundaries on varus osteoarthritic knees with the use of robotic-arm-assisted TKA.

Material and methods

Study design

This is a retrospective cohort study to assess the effect of preoperative deformity and osteophyte size on achieving restricted kinematic alignment with robotic-assisted total knee arthroplasty in patients with varus osteoarthritis. The study was approved by our institutional review board (HKU/HA HKW IRB number: UW23−595).

Two hundred forty-four knees (121 left and 123 right) from 194 patients undergoing robotic-arm-assisted primary total knee arthroplasty in an academic institute between January 2019 and December 2021 were included. Patients with bilateral TKA were not excluded, with each knee counted as an independent entry. Inclusion criteria included patients diagnosed with primary knee osteoarthritis with varus HKA angle. Patients with preoperative valgus alignment and secondary causes of knee osteoarthritis were excluded.

The mean age is 65.3 years (range, 48-83). One hundred twenty-one patients were women and 70 were men with a ratio of 1.7:1.

Figure 2. Radiological measurement of osteophyte size. (a) Width of tibial plateau. (b) Width of medial tibial osteophyte. (c) Width of femoral condyles. (d) Width of medial femoral osteophyte.

Table 1
Varus knee severity grouping.

Varus knee severity	Frequency	Percentage (%)
Minimal (≤5°)	28	11.5
Mild (6°-10°)	68	27.9
Moderate (11°-15°)	93	38.1
Severe (≥16°)	55	22.5

Robotic-assisted restricted kinematic alignment TKA surgical technique

All robotic-arm-assisted TKA surgeries were performed using a standardized technique and the Mako Robotic-Arm-Assisted Surgery System (Mako Surgical Corp., Stryker, Fort Lauderdale, FL) with the Triathlon primary total knee system with X3 polyethylene (Stryker, Fort Lauderdale, FL). Two hundred thirteen knees received cruciate retaining implants, and 31 received posterior-stabilizing implants. Individual preoperative computer tomography scans were performed for 3D segmentation and surgical planning. Femoral and tibial component plans started at neutral to the mechanical axis. Initial bone cuts were planned for a 9 mm polyethylene and assumed a 2 mm cartilage thickness. Cut thickness was set at 7 mm on both the distal femur and the proximal tibia. The component plans were then individualized intraoperatively to a rKA boundary of neutral to 6° varus HKA with balanced soft tissue envelope at extension and 90° flexion.

Native knee alignment was assessed and recorded with dynamic referencing of the tibia and femoral positions within the Mako software (Fig. 1). Then valgus stress test was performed to assess maximal corrected alignment before any osteophyte resection. Osteophytes along the medial femoral condyle and medial tibial plateau were then resected, minimizing soft tissue disruption and preserving the soft tissue envelope. Reassessment of the knee alignment and the medial and lateral soft tissue balance at extension and flexion were performed. The surgical plan was accepted if the knee achieved a balanced soft tissue envelope and a HKA alignment within the rKA boundary. For the knees that fell beyond the boundary, medial collateral ligament (MCL) piecrusting at the midsubstance with a 19-gauge needle was performed. Soft tissue balance and HKA alignment were reassessed after 20 punctures.

Radiological assessment

Preoperative anteroposterior weight-bearing long film radiographs were used for radiological assessment of hip-knee-ankle alignment and the size of osteophytes. Osteophyte size was defined as the largest perpendicular distance from the original cortical outline of the medial femoral condyle and medial tibial plateau to the outer margin of the osteophyte, as reported by Moon et al. [14]. Medial femoral and tibial osteophyte sizes were represented as a percentage of the width of the femoral condyles and tibial plateau, respectively (Fig. 2).

Outcome measure

The primary outcome measure was the number of knees that successfully achieved the restricted kinematic alignment boundaries, which were set at HKA ≤3°, ≤4°, ≤5°, and ≤6° varus, respectively. Secondary outcome measures included the preoperative and intraoperative coronal HKA alignment, degree of deformity correction, medial tibial osteophyte size, and medial femoral osteophyte size.

Data analysis

The values in the text were given as the mean and the range. Mann-Whitney *U* test and Spearman's rank order correlation were used to compare data among the 2 groups. The level of significance was set at $P < .05$. Statistical analysis was performed using SPSS 27.0 software (IBM, USA).

Results

The mean preoperative HKA alignment was 11.9° varus (range, 1.0°-32.0°), 12.4° (range 1.0°-23.0°) in men and 11.6° (range, 1.0°-31.0°) in women. Patients were grouped based on severity of initial varus deformity into minimal (≤5°), mild (6°-10°), moderate (11°-15°), and severe (≥16°) (Table 1).

Osteophyte resection alone

The mean HKA alignment after osteophyte resection was 5.1° varus (range, 0°-19.0°), 5.8° (range, 0°-14.0°) in men and 4.7° (range, 0°-19.0°) in women. The mean HKA deformity correction is 6.8° (range, 0°-18.0°). Restricted kinematic alignment was achieved in 36.9% (n = 90) of all operated knees at a boundary of ≤3° varus, 48.0% (n = 117) at a boundary of ≤4° varus, 63.1% (n = 154) at a boundary of ≤5° varus, and up to 72.1% (n = 176) with a boundary of ≤6° varus. More patients in higher severity subgroups failed to achieve rKA boundaries with osteophyte resection alone (Table 2) (Fig. 3).

TKAs that successfully achieved rKA had lower preoperative varus deformity across all 4 target alignment boundaries ($P < .01$) (Table 3).

Preoperative varus deformity was positively correlated with degree of deformity correction after osteophyte resection with a correlation coefficient of 0.718 ($P < .01$) (Fig. 4).

There was no significant difference in the degree of correction after osteophyte resection between the groups in all 4 alignment boundaries.

Table 2
Frequency of varus knees that successfully achieved restricted boundaries for kinematic alignment with osteophyte resection alone.

rKA alignment boundary	All cases	%	Minimal	%	Mild	%	Moderate	%	Severe	%
≤3° Varus	90	36.9	26	92.9	37	54.4	23	24.7	4	7.3
≤4° Varus	117	48.0	27	96.4	47	69.1	36	38.7	7	12.7
≤5° Varus	154	63.1	28	100	62	91.2	51	54.8	13	23.6
≤6° Varus	176	72.1	28	100	66	97.1	65	69.9	17	30.9

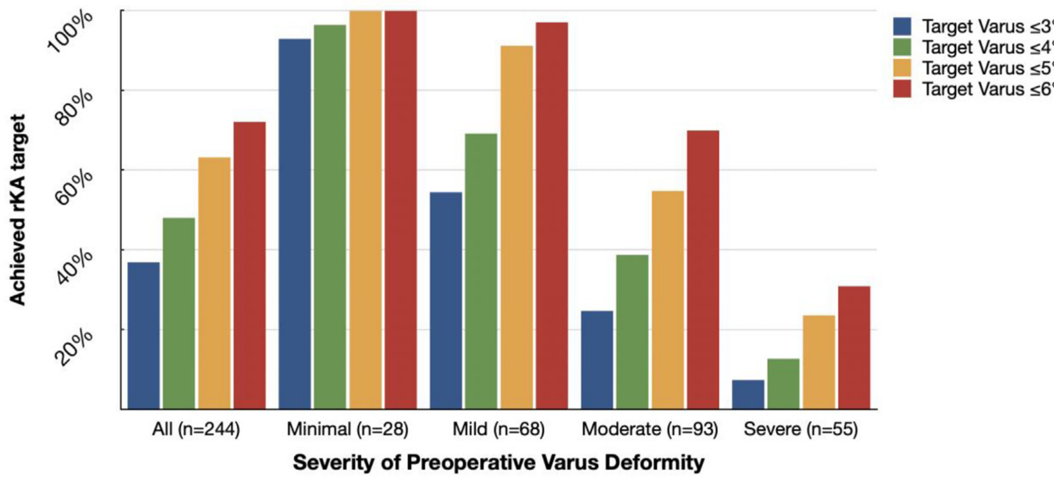

Figure 3. Frequency distribution of varus knees that achieved restricted boundaries for kinematic alignment with osteophyte resection alone.

Osteophyte size

The mean medial tibial and femoral osteophyte size was 6.1% (range, 0%-17.1%) and 8.4% (range, 0%-20.0%), respectively. The mean overall osteophyte size was 9.0% (range, 0%-20.0%). Medial tibial osteophyte size was statistically smaller in TKAs that achieved rKA across all alignment boundaries ($P < .05$) (Table 4). It was positively correlated with preoperative varus alignment with a rho of 0.396 ($P < .01$) (Fig. 5) and positively correlated with degree of deformity correction after osteophyte resection with a rho of 0.281 ($P < .01$) (Fig. 6). There was no significant difference in medial femoral osteophyte size between the 2 groups across all alignment boundaries.

Overall medial osteophyte size was statistically smaller in patients that achieve rKA with the target of ≤5 degrees varus ($P < .05$) and ≤6 degrees varus ($P < .05$).

MCL needle pie-crusting

Eighty-one knees required MCL needle pie-crusting to reach the restricted HKA alignment boundary of ≤6 degrees varus, 51.9% (n = 42) from the severe deformity group, 43.2% (n = 35) from the moderate deformity group, and 4.9% (n = 4) from the mild deformity group.

MCL pie-crusting was performed in 33.2% of all operated knees. The rates were significantly smaller in patients with minimal and mild deformity at 0% and 5.9%, respectively ($P < .01$), and significantly greater in the severe deformity group at 76.4% ($P < .01$). Of the patients, 37.6% with moderate deformity required MCL pie-crusting ($P > .05$).

Knees that required MCL pie-crusting had significantly greater mean preoperative HKA varus at 16.0° (range, 9.0°-32.0° varus) ($P < .01$), and larger mean tibial osteophyte sizes 6.9% (range, 0%-17.2%) ($P < .05$). There were no significant differences in final alignment between knees that did and did not require MCL pie-crusting in the mild, moderate, and severe deformity groups ($P > .05$).

Discussion

Kinematic alignment in TKA aims to restore the native prearthritic limb and joint line alignment while avoiding the excessive corrections and ligamentous releases, potentially improving pain and decreasing dissatisfaction associated with TKA. While 10-year implant survivorship was observed to be 97.5% in a cohort of 222 kinematically aligned knees [15], there are few long-term studies on survivorship as compared with mechanical alignment.

Historically, TKAs with mechanical axis within 3° of neutral have reported greater functional outcome and lower rates of aseptic loosening [16-19]. However, recent studies have not demonstrated greater survivorship or functional outcomes in well-aligned prostheses compared to malaligned TKAs [20-23].

Table 3
Comparison of mean preoperative varus deformity between knees that succeeded and failed to achieve the alignment boundaries after osteophyte resection.

rKA alignment boundaries	Mean preoperative varus deformity (°)		Standard deviation (°)		*P* value
	Success	Fail	Success	Fail	
≤3° Varus	8.4	13.9	4.18	4.5	<.01
≤4° Varus	9.1	14.5	4.15	4.5	<.01
≤5° Varus	9.7	15.6	4.26	4.3	<.01
≤6° Varus	10.1	16.5	4.22	4.4	<.01

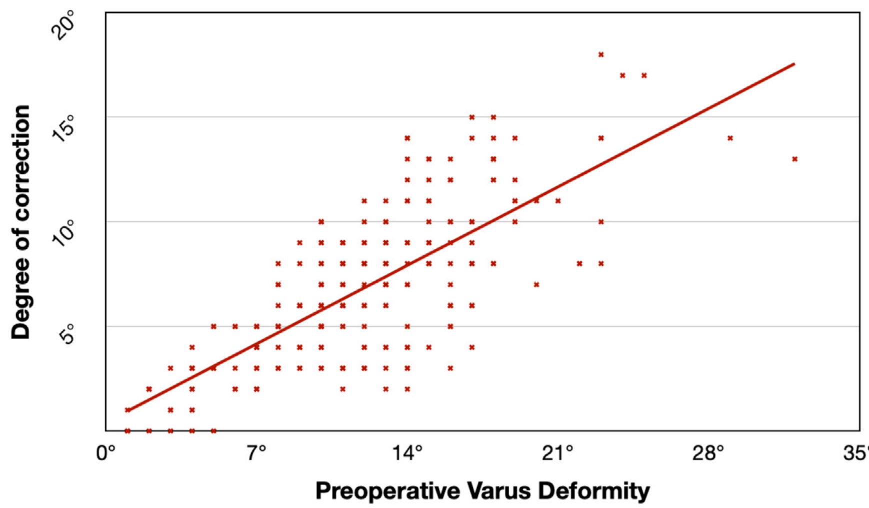

Figure 4. Distribution of degree of deformity correction achieved after osteophyte resection and preoperative varus deformity.

In Asian osteoarthritic knees, there was a greater proportion of varus knee alignment and apex distal joint line orientation, leading to a shift to phenotype I on the coronal plane alignment of the knee classification matrix compared with western knees [24-27]. Mean constitutional alignment of the lower limb in healthy Chinese population was 2.2° in men and women [28]. Our results show that the mean constitutional varus in our Chinese arthritic varus knees were 5.1° varus, 5.8° varus in men, and 4.7° varus in women.

Achieving the HKA boundary of ≤3° varus in Chinese varus knees was more difficult when compared with the Canadian group by Almaawi et al (2017) [12]. Only 36.9% of Chinese knees achieved the target alignment, compared to 51% after osteophyte resection alone in the Canadian group. With expansion of the HKA boundaries, 63.1% were able to achieve a coronal alignment of ≤5° varus; only up to 72% achieved a varus of <6°.

When adopting a restricted kinematic alignment protocol, there were 2 main factors that predicted the success of achieving the desired boundaries during preresection soft tissue balancing. The first was the preoperative varus deformity. Knees that successfully achieved rKA had lower preoperative varus deformity across all alignment boundaries ($P < .01$). Grouping patients based on severity of the deformity, there was lower rate of success in achieving a rKA boundary of ≤3° varus in the moderate (11°-15° varus) and severe (≥16° varus) groups with only 24.7% and 7.3%, respectively; the success rate remained low even with an extended boundary of ≤5° varus at 54.8% and 23.6%, respectively.

The second factor was the size of the medial tibial osteophyte. Mean medial tibial osteophyte size was measured at 6.11% of the tibial plateau width. Medial tibial osteophyte size was statistically smaller in knees that achieved rKA across all alignment boundaries ($P < .05$). Its size was positively corelated with the preoperative varus deformity. Medial osteophyte resection alone resulted in a mean HKA deformity correction of 6.8°; it was comparable to the 6.3° correction achieved in the Japanese cohort by Iizawa et al [29]. Although resection of larger medial tibial osteophytes was correlated with a greater degree of deformity correction, the mean size of these osteophytes was significantly larger in the knee that required pie-crusting ($P < .05$).

We postulate that the difficulty in correction with osteophyte resection alone was due to the significantly greater mean preoperative HKA varus in these knees ($P < .01$). Bellemans et al demonstrated that shortening and contracture of the medial soft tissue envelope occurred when the coronal plane deformity exceeded 10° of varus [30]. For the knees that required MCL needle pie-crusting 95.1% were in the moderate (11°-15° varus) and severe (≥16° varus) deformity groups. There was also a significantly higher rate of MCL needle pie-crusting in the severe deformity group at 76.4% to achieve the desired rKA boundary. MCL needle

Table 4
Comparison of mean medial tibial osteophyte size between knees that succeeded and failed to achieve the alignment boundaries after osteophyte resection.

rKA alignment boundaries	Mean medial tibial osteophyte size (%)		Standard deviation (%)		P value
	Success	Fail	Success	Fail	
≤3° Varus	5.5	6.5	2.9	2.9	<.01
≤4° Varus	5.7	6.5	2.7	3.0	<.05
≤5° Varus	5.6	7.0	2.8	2.9	<.01
≤6° Varus	5.6	7.3	2.7	3.0	<.01

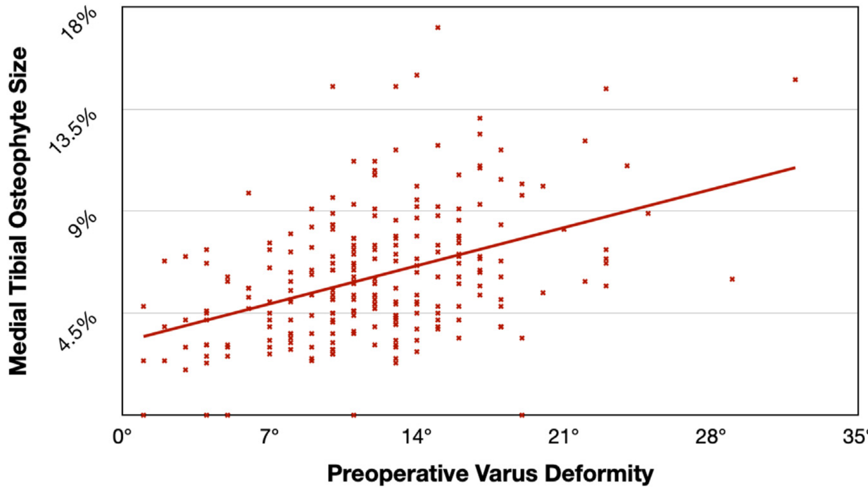

Figure 5. Distribution of medial tibial osteophyte size and preoperative varus deformity.

pie-crusting allowed for progressive release and control of medial soft tissue balance; cadaver studies have demonstrated an increase of medial extension gap by 3 mm with 15-25 needle punctures, which equates to 3° of deformity correction [31,32].

We propose the following workflow when implementing rKA in TKA: In knees with minimal varus deformity (≤5°), ≤3° varus boundaries were achieved in 92.9% of knees and can be readily utilized. With mild varus deformity (6°-10°), we recommend an extended alignment boundary of ≤5° varus in patients without the use of additional medial soft tissue release. For knees with moderate varus deformity (11°-15°), MCL pie-crusting with 19-G needle punctures can be considered in addition to the expanded boundaries. In cases of severe varus deformity (≥16°), there were high rates of failure to achieve rKA target, only up to 25.5% at a ≤5 alignment boundary with bone cut adjustments. We recommend planning for MCL pie-crusting or performing a medial reduction osteotomy.

This study has several limitations. The radiological assessment of the osteophyte size was performed using conventional radiographs. Although the method outlined by Moon et al [14] has been reported to reliably assess osteophyte size with strong-to-moderate correlations with the size and area on computed tomography [33], quantitative computed tomography evaluation would provide a more accurate assessment in terms of area and volume. In addition, while our results highlighted the importance of HKA varus deformity and medial tibial osteophytes when adopting rKA, further research is needed to assess the clinical and patient-reported function outcome of patients who achieved rKA with osteophyte resection alone and those that required MCL needle pie-crusting.

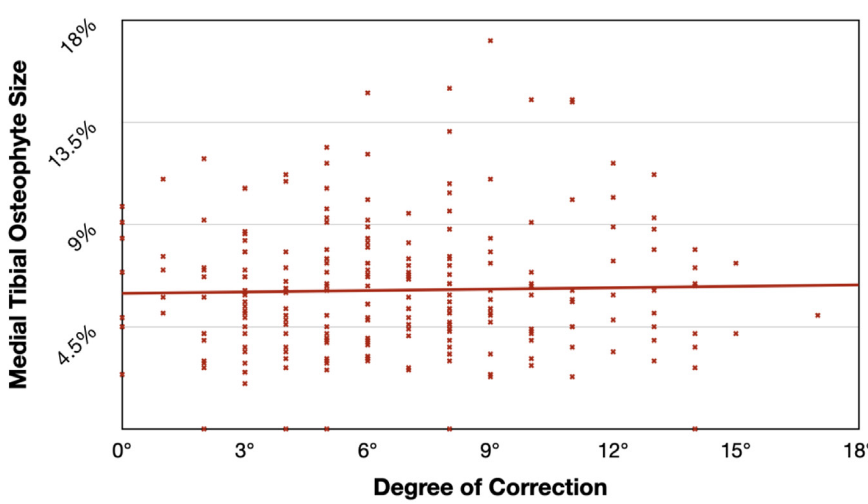

Figure 6. Distribution of medial tibial osteophyte size and degree of deformity correction.

Conclusions

Preoperative coronal plane varus deformity and medial tibial osteophyte size were important factors to consider when adopting rKA protocols for TKA.

Larger preoperative varus deformities were associated with increased failure to achieve restricted kinematic alignment across target ranges. While rKA can be reliably achieved in minimal varus deformities, we recommend that an expanded protocol be employed in those with mild deformities. In patients with moderate to severe varus knee deformities, alternative techniques including medial soft tissue release and reduction osteotomy should be considered to aid in achieving restricted kinematic alignment.

Conflicts of interest

The authors declare there are no conflicts of interest.

For full disclosure statements refer to https://doi.org/10.1016/j.artd.2024.101490.

CRediT authorship contribution statement

Samuel Yan Jin Fang: Writing − review & editing, Writing − original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kwong Yuen Chiu:** Supervision, Project administration, Conceptualization. **Wai Kiu Thomas Liu:** Data curation. **Amy Cheung:** Supervision, Methodology. **Ping Keung Chan:** Validation, Supervision, Project administration, Methodology, Conceptualization. **Henry Fu:** Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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