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Research article

Robot-assisted knee arthroplasty: Analyzing the learning curve and initial institutional experience

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ABSTRACT

Robot-assisted total knee arthroplasty (rTKA) involves a learning curve for orthopedic surgeons. The aim of the present study was to assess the surgical times of rTKA procedures performed by initial stage and proficiency stage surgeons in comparison with times of conventional total knee arthroplasty (cTKA). The results reveal that the learning curve for rTKA varies considerable between surgeons, suggesting that the skill and aptitude of the individual to adapt to the robotic system play key roles in the learning process. Proficiency stage surgeons were able to reduce rTKA surgical times to levels comparable with those of conventional surgeries after performing approximately 30 to 40 robotic procedures. Ongoing research has shown promising outcomes in terms of improved clinical results and reduced complications following the application of advanced robotic technology to total knee arthroplasty.

1. Introduction

Knee osteoarthritis is a prevalent and debilitating condition that has a significant negative impact on the quality of life. Recent statistics have revealed a growing incidence of knee osteoarthritis, most especially among the aging population [1]. This increase poses significant challenges to healthcare systems worldwide since the condition often leads to disability and reduced capacity to perform daily activities [2].

Total knee arthroplasty (TKA) has emerged as a highly effective surgical intervention for managing severe knee osteoarthritis and has become pivotal in restoring mobility and alleviating pain for patients suffering from such degenerative joint disease [3]. Currently, thousands of patients undergo this surgical procedure every year and the vast majority report substantial improvements in joint function and overall quality of life [3,4].

The development of robotic surgery in the realm of orthopedics, and particularly in TKA, has engendered significant advancements in surgical precision and patient outcome. Robotic total knee arthroplasty (rTKA) employs computational algorithms to translate anatomical data acquired through pre-surgical images into a patient-specific three-dimensional virtual reconstruction of the knee joint. In addition to pre-surgical planning, an intraoperative robotic device assists the surgeon in the resection of femoral and tibial bone and in positioning the implant with an enhanced level of accuracy [5]. Moreover, since rTKA involves smaller incisions than the conventional procedure (cTKA), the level of tissue trauma is reduced resulting in speedier functional recovery, shorter hospitalization, lower risk of implant failure and, potentially, improved long-term outcome [6–10]. However, mastering robotic-assisted procedures necessitates a thorough understanding and adaptation to new surgical techniques and equipment. Thus, the integration of robotic technology in TKA presents a learning curve for orthopedic surgeons [11,12], and this learning phase is crucial as it

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impacts directly on surgical efficiency, patient safety and overall surgical outcomes [11–16].

The aim of the present study was to assess the learning curve associated with the innovative rTKA procedures that have been adopted recently by the orthopedic center of a private hospital in Brazil. The specific goals of the study were: (i) to investigate the learning curve for rTKA in relation to surgical time; (ii) to compare surgical times between surgeons in the proficiency stage and those in the initial (learning) stage of rTKA; (iii) to compare surgical times recorded for the first 10 rTKAs, the last 10 rTKAs and the cTKAs performed; and (iv) to analyze the profiles and outcomes of patients who had been submitted to rTKA or cTKA surgery. Analysis of the experiences of the surgeons involved and the patient outcomes achieved revealed valuable insights into the integration process of robotic surgery in orthopedic practice, thereby contributing to the broader understanding and effective implementation of this technology in clinical settings.

2. Methods

2.2. Study design and participants

This retrospective study assessed a consecutive series of patients who had undergone primary elective unilateral TKA at a private tertiary referral hospital in Latin America. This hospital is considered to be an orthopedic reference centre and is open to external surgeons. Patients who had been submitted to a TKA procedure for end-stage knee osteoarthritis were included in the study, while those who had received surgery by reason of orthopedic trauma or tumor, or had undergone TKA revision, were excluded. The records of all patients were available since the hospital routinely collects and stores demographic and pre-surgical data along with surgical notes, length of stay, peri-surgical adverse events up to 30 days, and clinical and functional scores. In order to avoid information bias related to inaccurate data derived from retrospective entries, we used the institutional database recorded by the team that manages and organizes all TKA cases at our institution.

The study cohort comprised 617 patients who had been submitted to surgical procedures performed by 80 different surgeons. Patients were divided into two groups, namely those who had undergone rTKA between January 2021 and April 2023, and those who had been submitted to cTKA between January 2020 and April 2023. The rTKA procedures were performed using either the ROSA (Zimmer Biomet, USA) platform, which was introduced at our hospital in January 2021, or the MAKO (Stryker, USA) platform introduced in February 2022. Patients in the rTKA group were assigned to a particular platform according to the preference of the surgeon.

2.3. Measurements and outcomes

Demographic/pre-surgical data and clinical profiles for all patients were retrieved from hospital records. Pre-surgical and 90 days post-surgery clinical and physical outcomes were collected at a call centre by an interviewer who was not aware of the type of surgery undergone by the respondent. The outcomes recorded included the validated Brazilian version of the EuroQol score [17] and Knee Injury and Osteoarthritis Outcome Score-Physical Function Short-form (KOOS-PS). The EuroQol EQ-5D score assesses evolution of quality of life in five dimensions related to mobility, self-care, daily activities, pain/discomfort and anxiety/depression, and ranges from 1 for perfect health to 0 for death [18,19]. EuroQol also incorporates a visual analogue scale (EQ-VAS) that measures health status as perceived by the respondent and ranges from 0 for worst possible to 100 for best possible. The KOOS-PS (www.koos.nu) is a self-reported measure that specifically evaluates physical function in relation to daily activities and sports/recreation. The tool, which has been adapted and validated for the Portuguese language [20], was designed to assess the clinical improvement of patients with knee injuries and osteoarthritis and generates scores ranging from 0 (severe problems) to 100 (no problems). KOOS-PS, EQ-5D and EQ-VAS scores at 90 days post-surgery for cTKA and rTKA patients were compared in relation to baseline data. Surgical time was defined as the time between initial skin incision to final wound closure, while surgical time was extracted from the electronic file completed during each surgical procedure.

2.4. Training and experience of surgeons in rTKA

All surgeons underwent standard pre-training in robotic-assisted arm TKA as provided by the companies that supplied the platforms. The two-day training program with the ROSA robot comprised an initial theoretical session followed by practical training using the platform under the supervision of a qualified surgeon. Training with the MAKO platform encompassed two days of theoretical and practical sessions on cadavers, also under the direct supervision of a qualified surgeon.

Surgeons were categorized into two groups, namely those in the initial (learning) stage and those in the proficiency stage having completed more than 10 robotic surgeries. A separate analysis was conducted to compare the average surgical time for the first 10 procedures and that for the last 10 procedures performed by each surgeon.

2.5. Statistical analysis

Continuous data were described in terms of mean, median, standard deviation and inter-quartile range and Shapiro-Wilk tests were conducted to determine whether data sets were normally distributed. Mann-Whitney U or Student paired-*t* tests were performed to compare continuous variables, while chi-squared or Fisher exact tests were applied to compare categorical variables. Generalized additive models for location, scale and shape (GAMLSS) were employed to compare pre- and post-surgical clinical scores. Cumulative sum (CUSUM) charts were utilized to evaluate the learning curve of surgeons, while linear regression analyses were performed to evaluate surgical time progression. Dunn's multiple comparison test with Bonferroni adjustment was performed to compare the difference between surgical times between the first and last 10 rTKAs and between the first 10 cTKAs. Statistical analyses were performed by an independent statistician using R Statistical Software version 4.2.1 [21] with the alpha level set at 0.05.

3. Results

The demographic information and American Society of Anesthesiologists (ASA) scores of cTKA and rTKA patients are presented in Table 1. TKA procedures were performed predominantly on female patients (64.3%), typically aged between 65 and 74 years (42.5%) and with BMI values between 25 and 29.99 (43.6%) indicating overweight. In terms of surgical procedure, 47.97% of the patients underwent cTKA while 52.03% underwent rTKA, although the characteristics of the two groups were similar.

Table 2 presents the clinical profile of the patients. Hypertension affected 48.5% of TKA patients and was the most common comorbidity, while 18.6% of TKA patients presented diabetes. Regarding surgical complications, no statistically significant differences were observed between patients of the two surgery groups.

Since robotic platforms were introduced at our hospital relatively recently, it was only possible to analyze the early clinical outcomes of the rTKA procedures (Table 3). The baseline physical function (KOOS-PS) scores of patients in the cTKA and rTKA groups were similar and somewhat low (48.8 and 51.5, respectively; $p = 0.148$). However, patients of both groups showed improvement in physical function and quality of life at 90 days post-surgery regardless of the type of surgery they had received (63.0 and 61.4, respectively; $p = 0.282$). In terms of quality of life, patients in the cTKA group reported slightly lower EQ-5D baseline scores compared with those of the rTKA group (0.58 and 0.68, respectively; $p = 0.075$), although patients of both groups experienced

Table 1
Pre-surgical characteristics of TKA patients.

Variable	Whole cohort	cTKA	rTKA	p value *
Number of surgeries [N (%)]	617	296 (48.0%)	321 (52.0%)	
Age (years) (N = 617)				
Distribution [N (%)]				
< 65 years	137 (22.2%)	77 (26%)	60 (18.7%)	0.164
65 – 74 years	262 (42.5%)	117 (39.5%)	145 (45.2%)	
75 – 84 years	194 (31.4%)	90 (30.4%)	104 (32.4%)	
≥ 85 years	24 (3.9%)	12 (4%)	12 (32.4%)	
Mean ± SD (min-max)]	70.74 ± 8.46 (37-91)	70.42 ± 8.69 (37–91)	71.03 ± 8.23 (44–88)	
Females [N (%)]	397 (64.3%)	196 (66.2%)	201 (62.6%)	0.425
BMI (kg/m^2) (N = 617)				
Distribution [N (%)]				
< 18 kg/m^2	6 (1.0%)	2 (0.8%)	4 (1.3%)	0.911
18.5 – 24.99 kg/m^2	114 (18.6%)	55 (18.8%)	59 (18.5%)	
25 - 29.99 kg/m^2	267 (43.6%)	124 (42.3%)	143 (44.9%)	
30 – 34.99 kg/m^2	153 (25%)	75 (25.7%)	78 (24.5%)	
35 – 39.99 kg/m^2	62 (10.1%)	31 (10.6%)	31 (9.7%)	
≥ 40 kg/m^2	10 (1.6%)	6 (2%)	4 (1.25%)	
Mean ± SD (min-max)]	28.86 ± 5.5 (18.87–64.1)	29.13 ± 5.17 (18.87–44.74)	28.62 ± 5.95 (18.87–64.10)	
ASA score [N = 615; N (%)]				
I	56 (9.1%)	25 (8.5%)	31 (9.7%)	0.244
II	510 (82.9%)	241 (81.7%)	269 (84.1%)	
≥ III	49 (7.9%)	29 (9.8%)	20 (6.3%)	

N, absolute frequency; SD, standard deviation; BMI, body mass index; ASA, American Society of Anesthesiologists; cTKA, conventional total knee arthroplasty; rTKA, robot-assisted total knee arthroplasty

* chi-squared test

Table 2
Clinical profiles of TKA patients.

Condition	Whole cohort [N (%)]	cTKA [N (%)]	rTKA [N (%)]	p value *
Hypertension	299 (48.5%)	139 (47.0%)	160 (49.8%)	0.525
Diabetes	115 (18.6%)	59 (20.0%)	56 (17.5%)	0.491
Smoking	22 (3.6%)	7 (2.4%)	15 (4.7%)	0.184
Previous cancer	20 (3.2%)	11 (3.7%)	9 (2.8%)	0.680
Heart disease	65 (10.6%)	27 (9.2%)	38 (11.9%)	0.334
Surgical infection	5 (0.8%)	3 (1.0%)	2 (0.6%)	0.927
Surgical complications	9 (1.5%)	2 (0.7%)	7 (2.2%)	0.222
DVT / PE	4 (0.7%)	1 (0.3%)	3 (0.9%)	0.674

N, absolute frequency; SD, standard deviation; DVT, deep vein thrombosis; PE, pulmonary embolism; cTKA, conventional total knee arthroplasty; rTKA, robot-assisted total knee arthroplasty

* chi-squared test

an increase in quality of life at 90 days post-surgery and attained the same score of 0.79. However, when the difference in baseline scores is taken into consideration, the increase in EQ-5D score from baseline to 90 days post-surgery was greater in cTKA than rTKA (0.21 and 0.096, respectively; $p = 0.018$). There were no differences in the baseline and 90 days post-surgery EQ-VAS pain scores reported by patients in either of the two TKA groups.

Fig. 1 presents the surgical times recorded for the first 10 and last 10 rTKAs and cTKA surgeries relating to the five surgeons who had performed a sufficient number of procedures. According to the Kruskal-Wallis test, the surgical times of the first 10 rTKAs and the cTKAs showed statistically significant differences ($p < 0.001$). Moreover, application of Dunn's multiple comparison test with Bonferroni adjustment revealed significant differences in the surgical times between the first and last 10 rTKAs (177.5 min *vs* 145 min; $p = 0.004$), and between the first 10 rTKAs and the cTKAs (177.5 min *vs* 150 min; $p = 0.004$). In addition, it was found that the surgical times of the last 10 rTKAs and the cTKAs were similar. On this basis, surgeons who had performed more than 10 rTKAs were classified as proficiency stage surgeons, while those who had performed fewer than 10 rTKAs were classified as initial stage surgeons.

Analysis of the relationship between surgical times and surgery volume revealed that proficiency stage surgeons logged shorter surgical times compared with initial stage surgeons (145.0 min *vs* 180.1 min, $p < 0.001$) (Fig. 2).

Plots of CUSUM times *vs* rTKA case numbers (Fig. 3) demonstrated that the learning curves of the proficiency stage surgeons 66, 46, 55 and 52 showed distinction turning points after performing 40, 41, 19 and 12 cases, respectively.

Linear regression analysis indicated a significant correlation between the number of rTKAs and the decrease in surgical times (Fig. 4). Additionally, the robotic surgical times fell below those of conventional surgeries after proficiency stage surgeons had performed 30 rTKA procedures (Fig. 5).

4. Discussion

The aims of this study were to assess the learning curve associated with rTKA and to evaluate the outcomes of the procedures. Our findings highlight several critical aspects concerning the integration of robotic surgery into orthopedic practice, several of which have implications for surgical accuracy, patient safety and overall outcomes.

The data indicate that orthopedic surgeons face a significant learning curve when using rTKA as evidenced by the longer surgical times recorded by surgeons at the initial stage compared with those at the proficiency stage. The workflow associated with the performance of robotic-assisted surgery is somewhat different from that of conventional surgery, and this may explain the longer surgical times observed among surgeons at the initial stage. Moreover, with rTKA, additional time is required to capture anatomical landmarks and for the surgeon to assess the alignment and ligament balance of the knee in real time. Additionally, it is necessary for the surgeon to adjust to utilizing the robotic device since the robotic arm may provide visual, audio and, in some systems, even tactile feedback while the surgeon manipulates the saw blade.

Our study has shown that proficiency stage surgeons were able to reduce their surgical times of rTKA below those of cTKA after approximately 30 robotic procedures. This reduction in time is significant and suggests that, with proficiency, robotic surgery can be as efficient, or more efficient, regarding surgical time than conventional methods. Previous studies have also shown a progressive decline in surgical time with rTKA [11,13]. For example, Kayani et al. [11] reported a sharp inflexion in the surgical time after the initial seven cases of rTKA, with time improvements in bone registration and even resection as the surgeon became more responsive to the robotic arm and gained better control of its movements. Although this study described a decrease in surgical time, there was no learning curve for achieving the final alignment of the planned prosthetic components, an actuality that verifies the fundamental safety of the system by limiting surgeon-induced errors in implant positioning.

It is important to note that the point at which the surgical time for rTKA is similar to that for cTKA varies greatly. Thus, while Kenanidis et al. [14] reported that 70 surgeries are necessary for this equalization to occur, other studies declared that the learning curve of rTKA was less

Table 3
Clinical outcomes of TKA patients.

Scores		Whole cohort		cTKA		rTKA		p value*
		MD	IQR	MD	IQR	MD	IQR	
KOOS-PS	Baseline	51.5	23.4	48.8	28	51.5	19.3	0.148
	90d	63	16.4	63	16.4	61.4	13.85	0.282
	Bas-90d	12.2	24.05	15.4	30.55	10.4	18.93	0.126
EQ 5D	Baseline	0.67	0.33	0.58	0.35	0.68	0.26	0.075
	90d	0.79	0.13	0.79	0.31	0.79	0.12	0.491
	Bas-90d	0.12	0.27	0.21	0.32	0.096	0.31	0.018
EQ-VAS	Baseline	80	20	80	20	80	20	0.419
	90d	80	20	80	15	80	20	0.091
	Bas-90d	0	20	0	20	0	20	0.7

MD, median; IQR, interquartile range; cTKA, conventional total knee arthroplasty; rTKA, robot-assisted total knee arthroplasty; KOOS-PS, knee injury and osteoarthritis outcome score–physical function short-form; EQ-5D, EuroQol-five-dimension score; EQ-VAS, EuroQol-vertical visual analog scale; 90d, 90 days post-surgery; Bas-90d, baseline to 90 days post-surgery.

* Mann-Whitney test or Student's *t* test

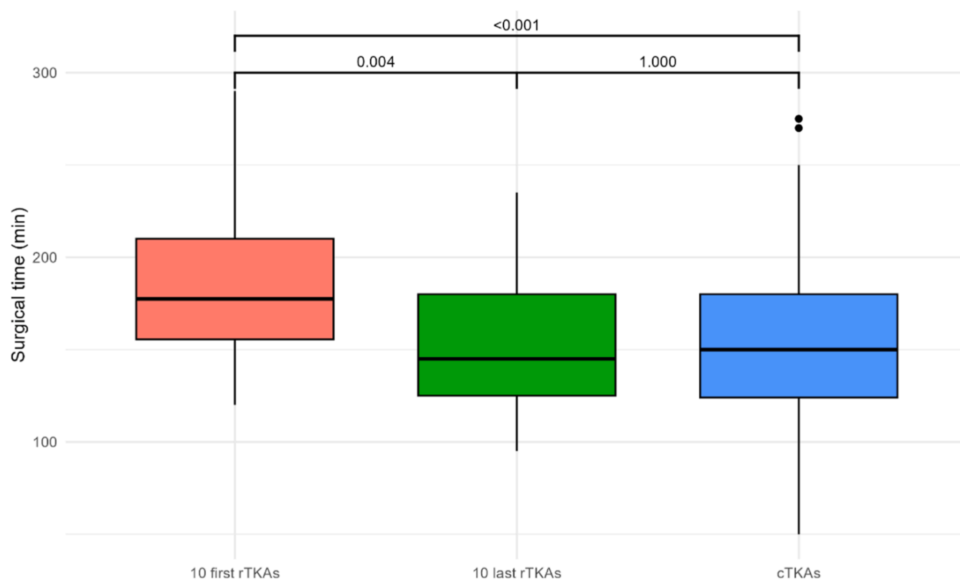

Fig. 1. Surgical times of conventional total knee arthroplasty (cTKA) compared with those recorded for the first 10 and the last 10 robot-assisted procedures (rTKAs) performed by 5 surgeons. Differences assessed by Dunn's multiple comparison test with Bonferroni adjustment.

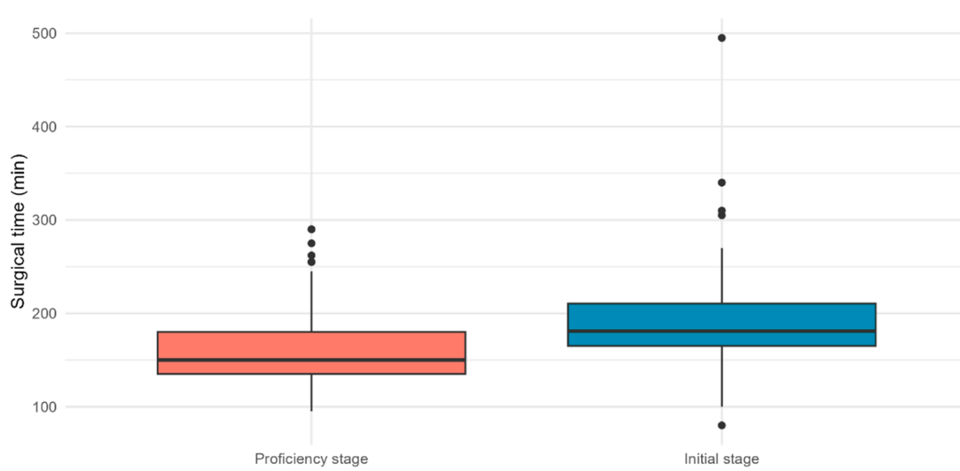

Fig. 2. Surgical times of robot-assisted total knee arthroplasties distributed according to the level of expertise of the surgeon.

than 25 cases [15,16]. The CUSUM analysis performed in the present study showed that the moment at which surgeons reached proficiency varied considerably, indicating that the learning curve is not the same for everyone and likely depends on individual skill and adaptation to the different robotic devices available.

Regarding clinical outcomes, the rTKA and cTKA groups showed

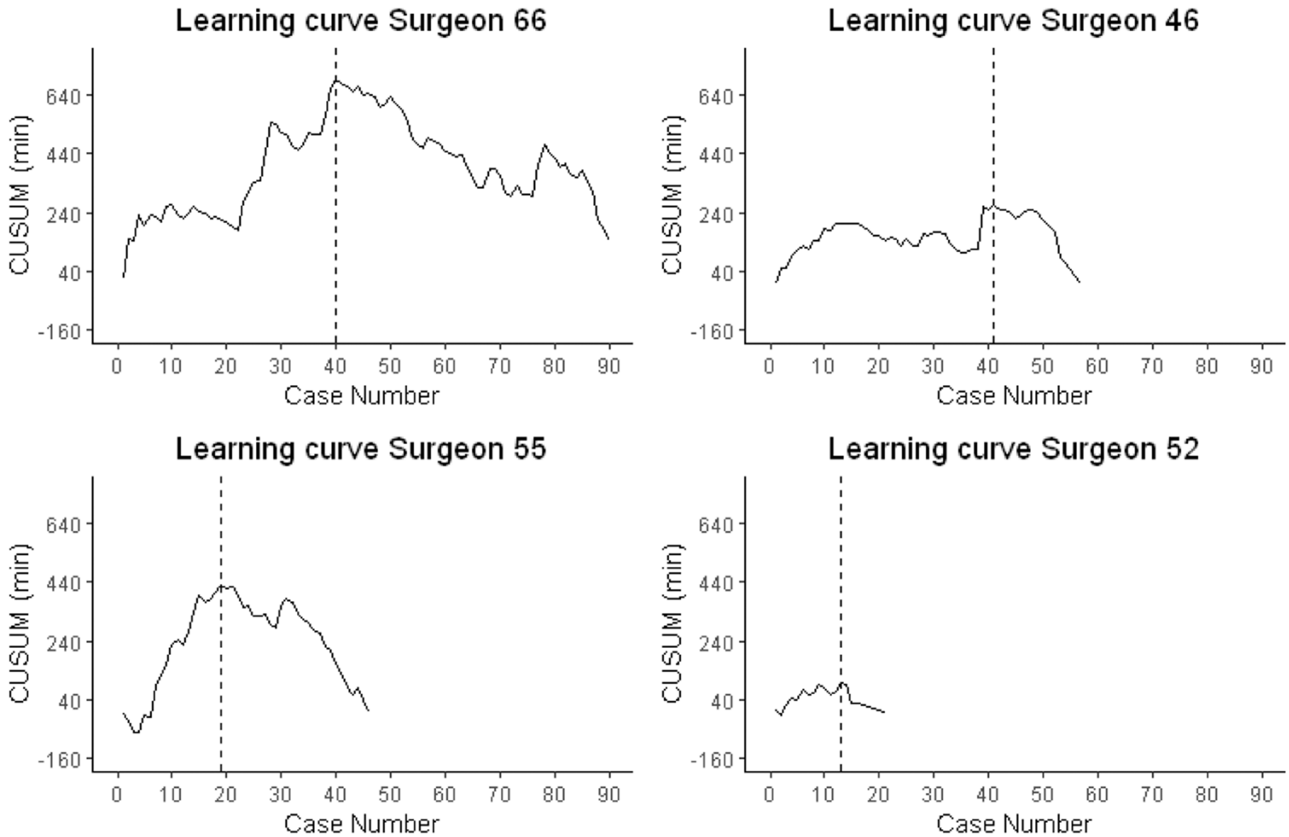

Fig. 3. Cumulative summation (CUSUM) of surgical times of robot-assisted total knee arthroplasties in relation to the number of procedures performed by four surgeons.

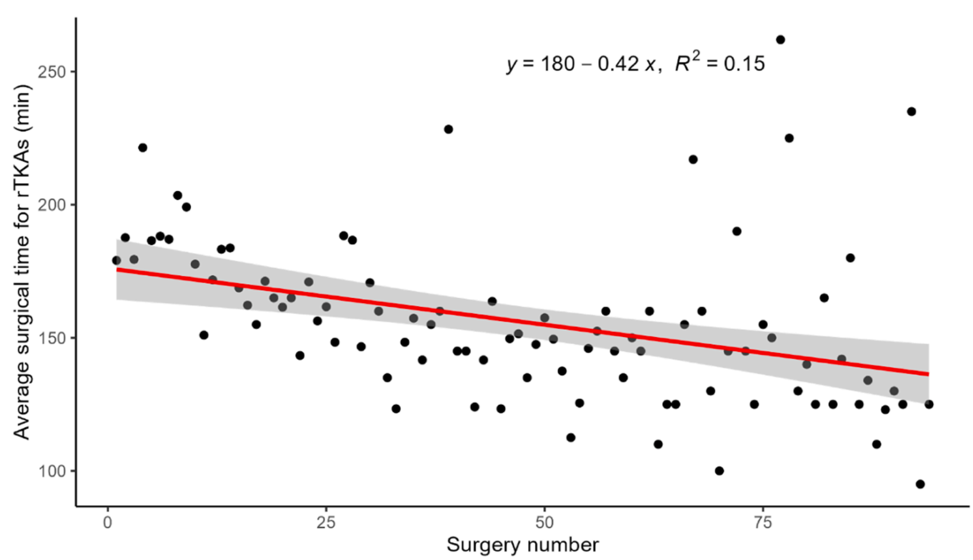

Fig. 4. Scatter plot and linear regression analysis of the average surgical times of robot-assisted total knee arthroplasties (rTKAs) for all surgeons in relation to the number of procedures performed.

similar physical function and quality of life scores both at baseline and at 90 days post-surgery. However, controversy remains as to whether improved accuracy of implant positioning and enhanced post-surgical rehabilitation inherent with rTKA can be reflected in better long-term functional scores compared with cTKA. Nevertheless, findings reported by a number of authors suggest that implementation of rTKA may help to improve other important outcomes. Following a prospective cohort study, Kayani et al.[6] declared that rTKA was associated with decreased pain, improved early functional recovery and reduced time to hospital discharge in comparison with cTKA. In another interesting study, Ali et al. [7] assessed 36 patients who had been submitted to contralateral cTKA and, at a later time, to rTKA, and compared the differences in clinical outcomes relating to the same patient. These authors reported that patients who had undergone rTKA showed early improvement in pain, stiffness and knee flexion at the one year follow-up.

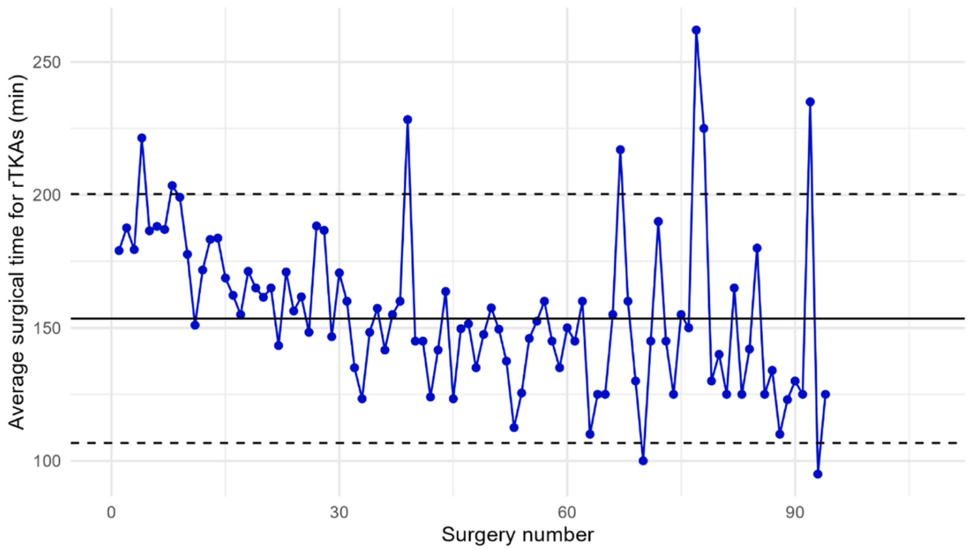

Fig. 5. Average surgical times of robot-assisted total knee arthroplasties (rTKAs) for all surgeons in relation to the number of surgeries and the average time of conventional surgeries. The solid line represents the average surgical time of conventional TKAs (cTKAs), while the dashed lines represent the standard deviation of cTKAs.

The use of robotic technology in TKA is associated with improved accuracy in implant positioning and in achieving correct alignment of the joint line and lower limb [22], factors that are considered important in terms of implant survival and patient satisfaction [8–10]. In this manner, rTKA offers important advantages in relation to cTKA, especially since the former affords greater surgical precision and reduced tissue trauma, which can potentially improve tong-term outcomes [11, 23]. However, our findings serve to highlight the importance of a structured training program to accelerate the learning process and maximize the benefits of robotic technology in orthopedic surgery.

Although our study provided valuable insights into the integration of robotic surgery in orthopedic practice, it was subject to several limitations. Firstly, surgeons were classified as proficient in rTKA based solely on their use of the robotic platform within our institution. It is important to note that, in our city, surgeons often perform operations in several hospitals and, consequently, some surgeons categorized as non-proficient at our center might have substantial experience with robotic surgeries conducted elsewhere. Whilst this factor could potentially skew the interpretation of the learning curve associated with rTKA, further analysis revealed that this situation was infrequent among the surgeons in our sample. Secondly, the severity of knee osteoarthritis in the patient cohort was not evaluated systematically. Surgical duration can vary significantly with the complexity of the case and is often correlated with the severity of the pathology. Detailed knowledge about the influence of severity of knee osteoarthritis on surgical times, and whether this factor might differentially impact rTKA procedures compared with conventional surgeries, would provide a more refined understanding of the efficiency and applicability of robotic-assisted techniques. Thirdly, since our study did not allow the evaluation of long-term clinical outcomes, the ongoing controversy as to whether rTKA leads to superior clinical outcomes compared with conventional methods remains unresolved. Assessment of clinical outcomes, particularly those of patients under the care of surgeons in the early stages of a learning curve with robotic technology, would be invaluable in determining the real-world efficacy and benefits of these advanced surgical procedures.

Whilst rTKA presents appreciable challenges in terms of the learning curve for surgeons, its potential benefits regarding surgical accuracy and patient outcomes are considerable. Our findings underline the importance of a structured training program to accelerate this learning process and to maximize the efficacy of robotic technology in orthopedic surgery. Nevertheless, further studies with larger sample sizes and longer follow-up periods are required to elucidate the long-term benefits of rTKA and optimize training protocols for surgeons.

5. Conclusion

Surgical times decreased after the initial rTKAs performed by an individual surgeon, and the recorded reductions were correlated with the number of robotic procedures carried out, thereby highlighting the importance of experience in maximizing the benefits of robotic assistance. Remarkably, our study revealed that, on average, the surgical time for rTKA was equal to or shorter than that for cTKA after 30 robotic procedures.

Ethical statement

Details of the project were approved by the Institutional Review Board of HIAE (protocol number 73225523.8.0000.0071) prior to the commencement of the study.

CRediT authorship contribution statement

Leandro Ejnisman: Writing – original draft. **Eliane Antonioli:** Funding acquisition, Investigation, Writing – original draft. **Luciana Cintra:** Formal analysis, Investigation. **Pamela Gabriela de Oliveira Souza:** Data curation. **Lauro Augusto Veloso Costa:** Writing – review & editing. **Mario Lenza:** Supervision, Conceptualization.

Declaration of Competing Interest

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

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AuthorAgreement Statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process. He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

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