Time-Based Learning Curve for Robotic-Assisted Total Knee Arthroplasty: A Multicenter Study

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Abstract

Robotic-assisted total knee arthroplasty (RA-TKA) has been shown to improve the accuracy of bone resection, reduce radiographic outliers, and decrease iatrogenic injury. However, it has also been shown that RA-TKA surgical times can be longer than manual surgery during adoption. The purpose of this article was to investigate (1) the characteristics of the operative time curves and trends, noting the amount of surgeons who improved, for those who performed at least 12 cases (based on initial modeling); (2) the proportion of RA surgeons who achieved the same operative times for RA-TKA as compared with manual TKAs; and (3) the number of RA-TKA cases until a steady-state operative time was achieved. TKA operative times were collected from 30 hospitals for 146 surgeons between January 1, 2016, and December 31, 2019. A hierarchical Bayesian model was used to estimate the difference between the mean RA-TKA times by case interval and the weighted baseline for manual times. The learning curve was observed at the 12th case. Therefore, operative times were analyzed for each surgeon who performed at least 12 RA-TKA cases to determine the percentage of these surgeons who trended toward a decrease or increase in their times. These surgeons were further analyzed to determine the proportion who achieved the same operating times as manual TKAs. A further hierarchical Bayesian model was used to determine when these surgeons achieved steady-state operative times. There were 60 surgeons (82%) who had decreasing surgical times over the first 12 RA-TKA cases. The remaining 13 (18%) had increasing surgical times (mean increase of 0.59 minutes/case). Approximately two-thirds of the surgeons (64%) achieved the same operating times as manual cases. The steady-state time neutrality occurred between 15 and 20 cases and beyond. This study demonstrated the learning curve for a large cohort of RA-TKAs. This model demonstrated a learning curve between 15 and 20 cases and beyond. These are important findings for this innovative technology.

Keywords
- total knee arthroplasty
- robotic-assisted
- learning curve
- multicenter
- Bayesian model

Robotic-assisted total knee arthroplasty (RA-TKA) was developed in an attempt to improve on the results of manual TKAs. It has been shown to improve the accuracy of bone resection to reduce radiographic outliers and decrease iatrogenic soft tissue and bone injury.[1–7] Nevertheless, as is commonly found for any newly introduced surgical procedure, this technique initially takes longer to perform.[1,8]

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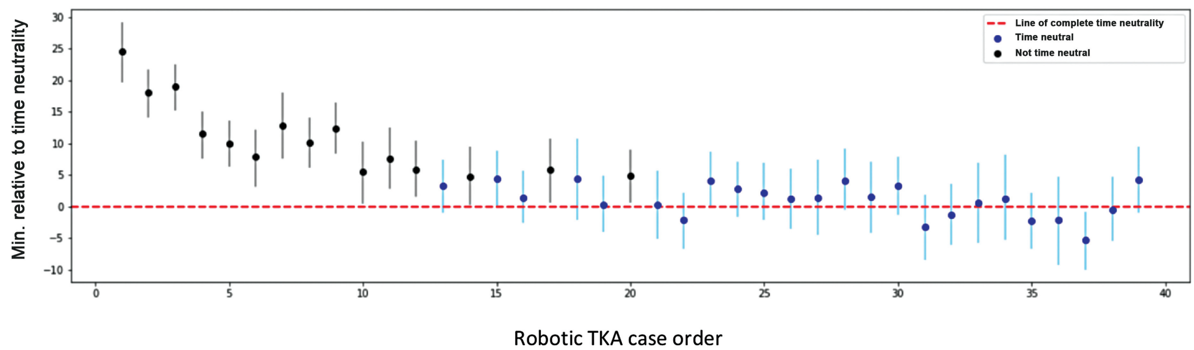

Fig. 1 The model shows that the shift to time neutrality occurs between 10 and 14 cases with an inflection point at case 12. TKA, total knee arthroplasty.

There are studies on the learning curve for RA-TKA but they are limited. The few reports include small, single- or multicenter surgeon experiences.[9,10] Sodhi et al demonstrated a learning curve of 20 cases for two surgeons by analyzing 240 cases.[11] In this analysis, one surgeon's mean first 20 robotic case operative time of 81 minutes was significantly longer than his mean manual case time of 68 minutes ($p < 0.05$), but his mean last 20 robotic case operative time of 70 minutes was similar to his manual cases. The second surgeon's mean first 20 robotic operative times of 117 minutes was significantly longer than his mean manual case time of 95 minutes ($p < 0.05$), but his mean last 20 robotic operative time of 98 minutes was also similar to his manual case times. Nevertheless, this study only included a two-surgeon experience.

Since there is a paucity of literature on the learning curve of RA-TKA, we wanted to study this topic using a larger sample size. Therefore, we investigated the learning curve in a multicenter study by reporting on how many RA-TKA cases might be performed before operating times approach manual times. Specifically, we evaluated the following: (1) the characteristics of the operative time curves and trends, noting the number of surgeons who improved, for those who performed at least 12 cases (based on initial modeling); (2) the proportion of RA surgeons who achieved the same operative times as manual TKAs; and (3) the number of RA-TKA cases until a steady-state operative time was achieved.

Methods

TKA operative times were collected from 30 hospitals for 146 surgeons between January 1, 2016, and December 31, 2019. These were obtained from the Stryker Performance Solutions Hospital Reported Outcomes database (Stryker, Mahwah, NJ). This database consists of electronic health record data submitted by organizations participating in the Stryker Performance Solutions analytics service. Procedures were identified using the International Classification of Diseases, 10th Revision (ICD-10) codes and the operating room scheduling case descriptions. The search yielded a result of 23,978 TKA procedures. There were 18,272 manual surgeries and 5,706 RA surgeries utilizing the Mako Robotic-Arm Assisted Total Knee Application (Stryker, Mahwah, NJ). The surgeons performed a mean of 164 TKA procedures (range: 1–1,315), a mean of 125 manual cases (range: 1–1,312), and a mean of 39 RA-TKAs (range, 1–785). Operative time was defined as time in minutes between first incision and wound closure. The mean operative times were 91 ± 27 minutes for all TKAs, 88 ± 26 minutes for manual TKAs, and 99 ± 28 minutes for RA-TKAs.

During this preliminary phase of the analysis, a hierarchical Bayesian model was used to estimate the difference between the mean RA-TKA times by case interval and the weighted baseline for manual times for all 146 surgeons.[12–15] The first RA case averaged 24 minutes longer than the mean manual case time with RA group operative times steadily decreasing. The initial learning curve, as defined by time neutrality to manual TKA, was observed at the 12th case (►**Fig. 1**). Data are only shown through the first 40 cases due to the small number of surgeons who had greater than 40 robotic cases.

After the preliminary analyses, the operative times for surgeons who performed at least 12 RA-TKA cases were analyzed. This included 5,404 RA-TKA cases for 73 surgeons. Curves demonstrating trends of the operative times were created for each of these surgeons to determine the proportion who decreased or increased their operative times. Further analyses were done for these surgeons to determine how many of them achieved the same operating times as manual cases. A further hierarchical Bayesian model was used to determine when these surgeons achieved a steady-state operative time.

Data Analyses

Data processing and statistical modeling were completed using the Python (Python, Beaverton, OR) programing language and Microsoft Excel (Microsoft, Redmond, WA). Mean operative times were calculated and the curves demonstrating the trends of the surgical times and their slopes were plotted. Further analyses were performed to determine the proportion of surgeons who had decreasing or increasing operative times, and those who achieved the same times as manual cases. For the hierarchical Bayesian models, the weighted baseline was defined as the mean reported manual time for a given surgeon compared with the total number of procedures and the overall operative times. Student's *t*-tests were used to compare the mean RA-TKA times by case interval to the weighted baseline for manual TKAs because it is inherently robust for outliers.[12] The programing language utilized the Python (Python, Beaverton, OR) 3.7.2, Pandas 1.0.1, Numpy 1.18.2, seaborn 0.10.0, and pymc3 3.8 libraries and dependencies.

Results

Trend curves demonstrated that the majority of surgeons had decreasing RA-TKA surgical times. Specifically, 82% of surgeons (60 out of 73) had trends with slopes demonstrating decreasing surgical times. The remaining 13 surgeons had trends with slopes demonstrating increasing surgical times for the first 12 RA-TKA cases (mean increase of 0.59 minutes/case; range: 0.02–3.22 minutes/case).

Of the 73 surgeons, 47 (64%) were able to achieve the same operative times as manual TKAs. The mean annual TKA volume for surgeons who achieved the same operative times as manual TKAs was 83 cases (range: 13–785). The mean annual TKA volume for surgeons who did not was 57 cases (range: 12–172). We cannot say the exact reasons why some surgeons become time neutral and others do not. This may be due to a multitude of factors, for example, staff issues, teaching, and others. Nevertheless, we suspect that high yearly caseloads are associated with whether surgeons become time neutral or not, and this is further opportunity for future larger research.

The further Bayesian model demonstrated steady state time neutrality between 15 and 20 cases. No significant differences in mean operating times between RA-TKA and manual TKA were demonstrated beyond the 20th case (Bayesian credible intervals shown in ►**Fig. 2**).

Discussion

RA-TKA has been shown to improve the accuracy of bone resection to plan, reduce radiographic outliers, decrease iatrogenic soft tissue and bone injury, and improve clinical outcomes.[1,16] However, it has also been demonstrated that as with most new technologies, initially, there is an primary increase in operating times.[8] The few studies that exist on the time-based learning curves of RA-TKAs are limited to small, single- or multicenter surgeon experiences.[9,10] Because of this paucity of literature, we endeavored to understand the estimated number of cases needed to reach time neutrality when using RA-TKA. In a large cohort of multicenter time-based study, we observed an initial learning curve of 12 cases (►**Fig. 1**). Greater than 80% of surgeons had decreasing RA-TKA surgical times. The remaining surgeons demonstrated increasing surgical times but only increased by less than 1 minute per case. After 20 cases, there were no significant differences between manual and RA-TKA times. The model demonstrated a reasonable learning curve with consistent time neutrality achieved between 15 and 20 cases, and corroborated the results of previously published smaller studies.[11,17,18]

The study has some limitations. We did not account for some variables including the relative skill of the individual surgeons, the time-lapse between cases and factors that may have increase the complexity of certain cases. Instead of measuring these effects directly, a model that accounted for a high degree of variance was selected. The same model could be applied to new, incoming data to determine whether the observed trends hold constant over time. Individual surgeon performance could also be evaluated using pooling. All of the RA-TKA surgeries were done using the same robotic system, and therefore, the observations from this analysis may not be generalizable to other procedures. It is noted that there could be significant bias in the data, as the data were obtained from an industry-sponsored and maintained database and only includes surgeons who participated in the database. However, the data were collected and analyzed independently to minimize such potential biases. Additionally, an individual surgeon's operative volume should be considered as a surgeon who does one case every 3 months is vastly different than a surgeon who does 12 cases in 3 weeks. In fact, this report was written to account for lower volume, as well as high-

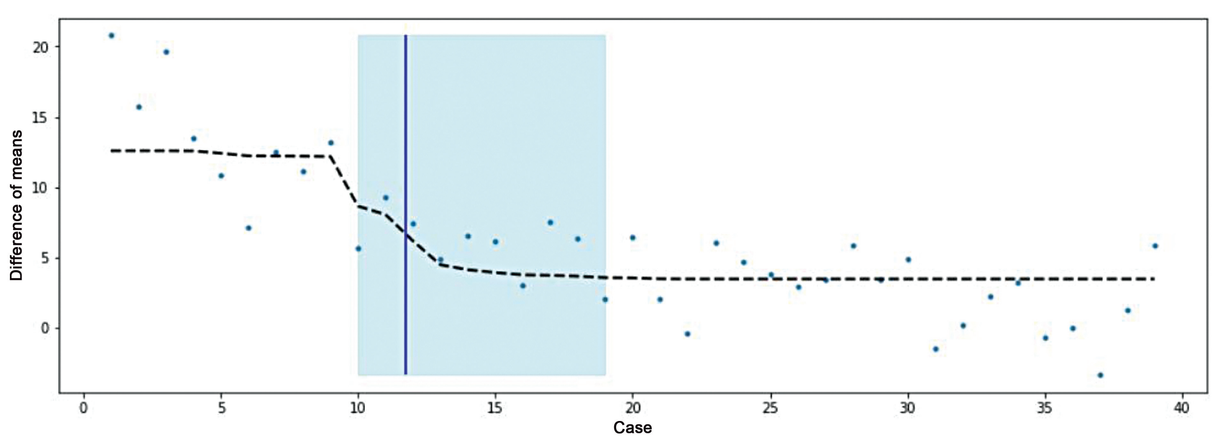

Fig. 2 The difference of means for each incremental case versus the approximate baseline. Vertical bars represent Bayesian credible interval. No statistically significant difference found beyond the 20th case (all credible intervals for cases > 20 contain 0).

volume surgeons, to allow for some degree of generalizability of our results.

While it has been previously stated that a small number of surgeons included in this study had greater than 40 robotic cases, the long-term characteristics of the learning curve, high-volume surgeons have already been well established in multiple prior studies.[9,11,19] Sodhi et al studied RA versus manual operative times and the overall learning curve of two high-volume joint reconstructive surgeons.[11] Both surgeons operated at programs that perform approximately 500 to 600 lower extremity joint arthroplasties per year. A total of 240 RA-TKA cases (180 for surgeon 1 and 60 for surgeon 2) were analyzed. These cases were sequentially grouped into cohorts of 20, allowing for the comparison of multiple time intervals. These were also compared with random samples of 20 manual cases performed within 3 months of the study. The first surgeon had a significant decrease in mean RA-TKA operative times from their first to last cohort (81 vs. 70 minutes, $p < 0.05$) and a significant difference between the first RA cohort and the manual cohort (81 vs. 68 minutes, $p < 0.05$). However, they had no significant difference in mean operative times between the last RA cohort and manual cohort (70 vs. 68 minutes, $p > 0.05$). Similarly, the second surgeon demonstrated a significant decrease in mean RA-TKA operative times from their first to last cohort (117 vs. 98 minutes, $p < 0.005$) and a significant difference between the first RA cohort and the manual cohort (117 vs. 95 minutes, $p < 0.005$), but no significant difference in mean operative times between the last RA cohort and manual cohort (98 vs. 95 minutes, $p > 0.05$). Therefore, this demonstrated that high-volume surgeons should be able to perform RA-TKAs without increasing their operative times.

In another study, the long-term RA versus manual operative times of a high-volume board-certified surgeon was studied.[19] A total of 140 RA-TKA cases were analyzed. The matching cohort was made up of 60 consecutively performed manual TKA cases and 20 sequentially performed RA cases, representing the RA cases performed by the surgeon in the first month. The study groups contained two cohorts of 60 RA cases (120 total) with the first cohort representing the RA cases completed at approximately 6 months and the second cohort representing the RA cases completed at approximately 1 year. The learning curve was steepest between 1 and 6 months, but still continued to decrease in the subsequent 6 months. RA mean operative times were found to be 81, 65, and 62 minutes at approximately 1 month, 6 months, and 1 year, respectively, and a significant decrease was found between 1 month and 1 year (81 vs. 62 minutes, $p < 0.00001$). This further demonstrated that high-volume surgeons decreased their long-term robotic operative times.

Kayani et al also studied a high-volume surgeon's learning curve for RA-TKA.[9] A total of 120 patients (60 consecutive undergoing manual TKAs followed by 60 consecutive receiving RA-TKAs) between 2016 and 2017 were analyzed. They used a cumulative sum control chart (CUSUM) sequential analysis to assess the learning curve. A sharp inflection point was found after the first seven cases. The operative times of these cases were significantly longer ($p = 0.01$). Thus, their results suggest a learning curve of approximately seven RA-TKA cases for high-volume surgeons.

Despite these limitations, the authors believe that this large-scale analysis represents a valuable contribution to this topic.

Our results are consistent with other studies in demonstrating decreased operative times with each successive RA-TKA for the majority of surgeons, and a point when operative times compared with manual TKAs are no longer significantly different.[17–19] Marchand et al demonstrated that within 6 months of adopting RA technology, mean operative times of a single high-volume surgeon were similar to those of manual procedures.[19] Mean operative times continued to decrease after 6 months, and at 1 year, a majority (88%) of the surgeon's RA cases were less than 1 hour in duration.[19] Similarly, Sodhi et al demonstrated a learning curve of 20 cases for two surgeons by analyzing 240 cases.[11] There was a significant decrease in RA operative times between the first and last 20 cases for each surgeon (mean = 99 minutes compared with 84 minutes, $p < 0.005$) and no significant procedural time difference between the final 20 RA cases and the manual cases (mean = 84 minutes compared with 81 minutes, $p > 0.05$).[11] Kayani et al reported that the expected learning curve for RA-TKA was seven cases for a single surgeon at a single center, using the same technology as the present study.[9] In summary, the results of our study are in agreement with previous literature evaluating the learning curve of RA-TKA.

Some studies evaluating the learning curve of RA TKAs revealed slightly differing estimates than ours. Vermue et al reported a single-surgeon inflection point of 22 cases when analyzing 111 RA-TKAs, performed using the same RA technology as in the present study. The authors performed a cumulative summation analysis, and reported an inflection point of 43 cases after analyzing 74 RA-TKAs with the same methodology.[17] This higher inflection point may be due to differences between individual surgeons. King et al reported an increased mean operating time of 9.3 minutes when studying a single surgeon who over a 39-month period performed 290 RA-TKAs using the same system as the present study.[8]

Conclusion

In conclusion, the burden of potential increased operating times using RA-TKA should be decreased within the first 15 cases that a surgeon performs.[8,20] Most surgeons (82%) improved their RA surgical times and nearly two-thirds achieved time neutrality to manual cases. All of these are important findings for this innovative technology.

Conflict of Interest
None declared.

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