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Learning curve of the 67 steps of conventional total knee replacement: an experimental study

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Background: The instrumentation system for total knee replacement (TKR) has been there since the 1970s. The many steps and instruments are the main features despite several modifications over the last 50 years. This may lead to the accumulation of errors as certain steps are dependent on others. This study aimed to identify the errors while performing TKR by three trainees at different levels of training.

Methods: Three trainees with different expertise performed the steps of TKR on bone models. One senior supervisor recorded the outcomes, including operative time and errors made during the experiment. Errors were further categorized into correctable and uncorrectable ones.

Results: Most of the errors were made by the trainee with the least experience during the stages of femoral cutting, sizing, and rotation. The first-year resident has taken 1.25 times longer than the fellow in preparing the femur and 1.11 times in preparing the tibia. The recorded mistakes were 28, 8, and 3 for the first-year resident, the second-year resident, and the fellow surgeon, respectively. Fifteen of the mistakes were uncorrectable, and none of them were from the senior surgeon.

Conclusion: The results of this study highlight the type of errors made by different trainees. This shows the steep learning curve of conventional instrumentation systems for trainees. Increasing cognitive skills and applying computer-assisted technologies may help trainees overcome this steep learning curve.

Keywords: conventional instrumentation, learning curve, surgical training, total knee replacement

Introduction

As the world population is reaching new limits of life expectancy, the wearing and tearing of joints have also significantly increased. Moreover, the rates of total knee replacement (TKR) surgery are currently showing exponential growth, and the growing concern about extending the life span of endoprosthesis has clouded the thoughts of surgeons over the last few decades[1].

Throughout the history of conventional replacement, it was evident that this surgery involves both many steps and instruments used[2]. These steps typically involve sizing, adjustment of both rotation and alignment, and finally, bone cutting. If any mistake is made during any of these steps, it is usually cumulative and impacts the outcome of the procedure[3]. Several factors affect the knee joint flexion angle, and consequently, the maximal functionality of the new joint. These factors include posterior condylar offset and joint line adjustment[4–7]. Most of these steps are impacted by the ability of the surgeon to execute a specific surgical skill correctly. Specific training and practices are required to develop such cognitive skills and help the surgeon to be able to judge their actions[8].

Although it is speculated that the level of expertise directly impacts surgery outcomes, very few studies characterize and quantify the relationship between the initial skill level, learning rate, and final skill level[9,10]. Quantification of these variables is going to help surgeons identify the points of weakness in the learning curve of each technique and individualize the training for quicker and more efficient training. In turn, this will directly affect the patient outcomes of replacement surgery.

Since the errors made during TKR are cumulative, it is difficult to trace them back to the step at which the error occurred. In this article, we aim to track the errors and their impact during TKR experiments performed by three trainees at different levels of orthopedic training.

HIGHLIGHTS

- The accumulation of errors in knee replacement happens facilely.
- Most errors in knee replacement are made during tibial sizing and cutting.
- There is a need to develop knee replacement techniques that can enhance learning.

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Table 1

Level of competence of residents in the training program.

Name of procedure	Competence level	Number of cases
Hip Hemiarthroplasty	5	15
Total hip replacement	4	7
Complex total hip replacement	3	3
Revision total hip replacement	2	3
Unicompartmental replacement	1	2
Total knee replacement	4	7
Complex total knee replacement	3	3
Revision total knee replacement	2	3
Shoulder replacement	1	2
Computer-assisted hip replacement (digital templating)	5	15
Navigation total knee replacement	1	2
Patient-specific instrumentation	1	2
Osteotomy (small or large joint)	2	3
Fusion (small or large joint)	2	3

1: observes; 2: assists; 3: performs part of the operation; 4: performs surgery under supervision; 5: competent without supervision.

Methods

Our orthopedic training program consists of 5 years of residency. At the end of this period, the candidate should have obtained a Master's degree or a fellowship in orthopedics. In the first 3 years, the trainees are taught the basic and general procedures and management plans in orthopedics. In the fourth and fifth years, specialized training in replacement is delivered. To climb the ladder of competence level, each candidate should attend, assist, and solely operate a certain number of replacement surgeries (Table 1).

The first participant was a first-year resident -postgraduate year (PGY-1)- and had no experience doing the TKR independently; however, he had assisted in multiple TKR surgeries before the experiment. The second participant was a third-year resident (PGY-3), who had assisted in over 50 TKR surgeries and performed 10 complete TKRs independently (yet under direct supervision) before experimentation. On the other hand, the third participant was a clinical fellow who could already perform TKR independently without direct or indirect supervision by a consultant.

The experimentation was done on plastic knee models (Sawbones Europe, Malmö, Sweden) using the standard bone size normally used in TKR workshops. The investigation was held at our institution. Three trainees were enrolled in this study, and each trainee was assigned to one of the three experiments. Before the initiation of the study, the technique was demonstrated by the head of the department to the three participating surgeons. We had three different knee implants in our department (PFC, NexGen, and Scorpio NRG). The senior two trainees were familiar with these three different implants and the junior trainee was only familiar with Scorpio NRG, Stryker, USA. This was the reason we selected Scorpio NRG for this experiment. The other reason was that it was considered simple and easy by all trainees because it was the most used system in the hospital during their training period. The supervisor demonstrated the surgical technique of Scorpio NRG to all trainees before experimentation. The surgical technique was retrieved from the official website to guide the steps and correctly relate them to the errors made during the experiment. Out of the 67 steps, the experiment was only performed on 59 steps, which are essential and standard for all conventional instrumentation systems.

For simplification, we have divided the experiment into four main steps: Distal femoral cut, Femoral sizing, rotation, and four-in-one cut, Tibial sizing and cutting, and Trial implantation. All outcome data were recorded, which included: the experiment time, the steps of the technique, the errors made, and at which step, and finally, the impact of the error on the outcome. The errors were also categorized into correctable errors and uncorrectable ones. Correctable errors are those that could be corrected while the experiment is resumed without having any significant impact on the outcome. Uncorrectable ones mean that these errors could not be corrected afterward and would result in a detrimental effect on the outcome.

Each experiment conducted by the participants was supervised and evaluated by the head of the department. He recorded each step done by each resident, documented the technical errors, and estimated their effects. Additionally, the time for preparing the

Table 2

Errors performed during distal femoral cut.

	PGY-1	PGY-3	Fellow
Steps of TKR by stryker (Scorpio NRG system)	Technical error	Technical error	Technical error
1. Open the femoral medulla.	Wrong entry point.	Wrong entry point.	No errors were performed.
2. Set the instrument to the desired valgus angle.	Wrong angle (malalignment).		
3. Advance the rod, with attached guide up the intramedullary canal until the desired depth.	Incomplete seating Difficult assembly of the guide Mismatch in right or left.	Rotation of the assembly Reassembly after guide insertion.	
4. Snap the Universal Resection Guide onto the Adjustment Block.	Incorrect fitting.		
5. Insert the posts of the Adjustment Block into the two holes in the Femoral Alignment Guide.	Incomplete fixation.		
6. Place the Femoral Alignment guide in contact with the more prominent distal femoral condyle and align the guide in neutral position.	Incomplete seating Angle change.	Rotation of guide (angle change).	
7. Pin the Distal Resection Guide to the anterior femur.	Use headed pins.		
8. Remove the IM Rod.	Forgetting to remove it before cutting Slight difficulty in its removal.		

Shaded cells mean uncorrectable errors.

Table 3

Errors performed during femoral sizing, rotation, and all in one cut.

		PGY-1	PGY-3	Fellow
	Steps of TKR by stryker (Scorpio NRG system)	Technical error	Technical error	Technical error
9.	Additional checks for rotation may be made by lining up the epicondyles with the reference lines marked "EPI" or assessing Whiteside's line with a pin through the hole in the top of the guide.	Wrong sizing Abnormal rotation.		The desired size was not available (this may differ from one company to another, but no company has all sizes).
10.	Position the assembly flush on the resected distal femur.	Subjective step (differs according to the surgeon).		
11.	Once size confirmation is complete, attach the 1/8″ Peg, drill to the Universal Driver, and create fixation pinholes.	Abnormal sizing Improper fixation.	The step was forgotten.	
12.	Pin the 4:1 Cutting Block in place for stability.	Wrong positioning.		
13.	Pin the PS Box Cutting Guide in place using Headless Pins.	Medialization or lateralization of the guide.	Mediolateral maladjustment.	
14.	Cut the cortical rim on both sides of the posterior-most portion of the intercondylar notch using the oscillating saw and complete the remaining four femoral bone resections.	Overcutting of the posterior-most portion of the intercondylar notch.		
15.	Place by hand (not through impaction) the appropriate size Triathlon PS Femoral Box Trial/ Protector into the prepared box to assure accuracy of the box preparation.	Over-impaction.		
16.	Impactor/Extractor and Impaction Handle and assess the fit of the PS or CR Femoral Trial.	Wrong site.		

Shaded cells mean uncorrectable errors.

femur was counted, starting from opening the medulla until finishing all cuts of the bone, while the time for preparing the tibia started from applying the extramedullary alignment rods till finishing the tibial cuts. Then the implantation errors of both the femur and tibia were recorded.

Results

The first-year resident (PGY-1) has managed to finish cutting the femur and the tibia in 25 and 20 min, respectively, in a total of 59 steps. Of the 59 steps, he made 28 technical errors. The PGY-3 trainee finished the femoral and tibial preparation in 22 and 20 min, respectively, made eight technical errors, and missed two steps. As for the fellow, he was able to finish preparing both bones in 20 min for the femur and 18 min for the tibia, with only three technical errors. TKR steps and errors are listed in Tables 2–5.

The number of errors was variable according to the level of expertise and they were 28, 10, and 3 for PGY-1, PGY-3, and the fellow, respectively. Each error has its outcomes ranging from simple errors that could be corrected up to serious errors that are not correctable, for example, aggressive cuts leading to excessive bone loss and the wrong angle of cut in the distal femur and proximal tibia leading to malalignment. Such errors could have a serious impact on the function and survival of TKR. Some steps were more susceptible to errors like steps number 9, 18, and 20, where all trainees were not able to avoid falling into these errors.

We have found that 39 errors were made in total, and two steps were forgotten. During the stage of the distal femoral cut, 11

Table 4

Errors performed during the Tibial sizing and cutting.

		PGY-1	PGY-3	Fellow
17.	Put tibial retractor to retract tibia anteriorly.	Aggressive positioning.		
18.	Tibial slope is checked, and medial/lateral offset is adjusted.	Faulty measuring (inability to localize bone from incompletely removed osteophytes).	This step was forgotten.	Inaccurate sloping degree.
19.	Place the ankle clamp around the ankle and unlock the locking switch.	Wrong site.		
20.	Rotate the entire assembly to ensure that the base of the assembly is aligned with the center of the ankle.	Difficulty in fitting the guide.	Wrong level.	Assembly fixed proximal first Assembly not fixed at the center over the ankle.
21.	Establish Tibial Resection Level.	Wrong level.	Wrong level.	
22.	Pin the Tibial Resection Guide in place.		Incorrect choice of pin hole.	
23.	Remove all alignment instruments leaving only the Tibial Resection Guide in place.		Difficult removal.	
24.	Place the assembly on the resected tibial plateau and choose the size that best addresses rotation and coverage.	Incorrect sizing Improper rotation.		

Shaded cells mean uncorrectable errors.

Table 5

Errors performed during the implantation stage (final trial of femur and tibia).

	PGY-1	PGY-3	Fellow
Steps of TKR by stryker (Scorpio NRG system)	Technical error	Technical error	Technical error
25. Place the PS Femoral Trial on the femur.	Abnormal rotation.	No errors were performed.	No errors were performed.
26. Allow the Keel Punch Guide to sit flat on the Universal Tibial Template and lock it.	Improper siting.		
27. Place the appropriate Keel Punch into the Keel Punch Guide.	Excessive impaction.		
28. Check the femoral cuts in both knee flexion and extension.	The cuts need downsizing/oversizing.		
29. With the knee flexed, insert progressively thicker spacer alignment guides until proper soft tissue tension is reached.	Inadequate soft tissue tension reached.		
30. Attach the Femoral Impactor/Extractor to the Impaction Handle and attach to the appropriate size and side Femoral Component.	Aggressive removal.		

Shaded cells mean uncorrectable errors.

errors were made by the first two participants. Additionally, in the second stage of femoral sizing, rotation, and four-in-one cut, the three surgeons committed 10 errors. In the third stage of tibial sizing and cutting, the three participants made 12 errors. Lastly, six errors were made only by the first-year resident during the last stage of trial implantation. Finally, these errors were further categorized into correctable and uncorrectable ones.

Discussion

In this experiment, we chose to include three trainees at different levels of training to perform conventional TKR steps on plastic knee models. We aimed to elaborate on how the different levels of expertise correlate with the number of errors and the success of such operations. We found that the trainee with the least experience made most of the errors, which were mostly uncorrectable ones and resulted in changing the sawbones model. Additionally, most of the errors made were in the stage of tibial sizing and cutting. This is logical because a resident in their first training year is not supposed to master every step of such a complex operation. However, it was surprising to us that a three-year resident and a fellow surgeon who practiced surgery for more than five years have also done some mistakes that can increase the operation time and waste surgical resources.

However, this experiment is limited by its performance on plastic knee models, which do not represent real-life circumstances during surgery. Consequently, the errors made in real-life surgery are expected to be higher than in the experiment. It is also worth mentioning that it is always hard to learn the methods of operating with different TKR sets by different companies, even if the surgeon is experienced. Another limitation is that exposure, closure, and soft tissue balancing errors were not considered. A third limitation is that our department is understaffed. This has hindered the inclusion of more residents in this study, limiting the generalizability of this study to some hospitals in low-income countries and also to all hospitals in high-income settings.

It is also crucial to highlight that the results we present in this study are expected as senior residents are supposed to perform better than junior residents. Accordingly, we believe that mastering the techniques of TKR requires adequate training during the residency program and subsequent subspecialty fellowship in arthroplasty.

In 2002, Plaskos *et al.* performed an in vitro study and found that the conventional techniques that lead to bone resection inaccuracy can eventually contribute to implant misalignment. This inaccuracy reaches up to 1.1 degrees in varus/valgus and 1.8 degrees in flexion and extension[11]. Reaching the perfect alignment is quite difficult using conventional methods. Soft tissue balancing is another issue that was pointed out by Griffin *et al.* in 2000, and perfect soft tissue balancing is quite challenging, even with meticulous care[12]. Since precision is the key to this surgery, PSI and robotic surgery were introduced. This technique has transformed intraoperative sizing and implant positioning to a preoperative setting, giving the surgeon more time to reach the best fitting, and consequently, better outcomes[13]. For these reasons, it is believed that PSI and robotic surgery could be of extreme importance to achieve better outcomes.

In 2017, Mushtaq *et al.* conducted a randomized control trial and has shown that there were statistically significant differences in the clinical outcomes of TKR designed by Stryker and Zimmer. Both companies have some differences in the design, steps of the procedure, or functional outcomes in the long run[14]. It was found that both Triathlon and Duracon (both developed by Stryker) cemented knee prostheses did not show any significant difference in stability or maximum total point motion[15]. However, we encourage more future studies to be conducted to compare the outcome of different implants as well as evaluate these conventional methods with PSI.

Lastly, a boot camp for PGY-1 surgical residents was conducted to develop their surgical and cognitive skills. The training was in the form of didactic simulation-based training for the skills needed for basic problem assessment and management of a surgical patient, and the performance data were recorded over 4 years. It was found that cognitive scores and procedural skills in the simulation directly correlated with real-life clinical performance[16]. Another study by Mayden *et al.* has involved computer-assisted surgery simulations performed on orthopedic residents learning TKR. It was found that a junior resident could do better than a senior resident if provided with high-impact educational interventions that promote cognitive flexibility[17].

Conclusion

In this study, we highlighted the difficulty in training orthopedic surgeons on the conventional instrumentation of TKR. This is mainly due to the complexity of the instruments used, the major differences in TKR instrumentation sets offered by different manufacturers, and the need for intraoperative prosthesis sizing.

The results of this study highlight the type of errors made by different trainees and the need to increase the learning curve of such complex procedures by having assistance from advanced technology like PSI and robotic surgery. But as those advances are scarce in low-and-middle-income countries, it is expected from young residents to train on artificial samples like plastic knee or hip models, cadavers, and computer simulators before doing surgery on patients under supervision. Although robotic and navigational surgical techniques are expensive and unaffordable in low-income settings, other computer-assisted techniques such as patient-specific templating are cost-effective and affordable and has already been applied in our low-income settings[2].

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent to publish

All authors agree to the publication of this study in its current form.

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Authors' contribution

M.A.H. accounted for the idea; M.A.H., E.N., and A.N. trained the physicians recruited in the experiment; M.A.H. evaluated the participants, wrote the manuscript and reviewed the literature with the help of A.M.M. and O.M.M. (acknowledged contributors). All authors approved the final version before submission.

Conflicts of interest disclosure

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or nonfinancial interest (such as personal or professional relationships, affiliations, knowledge, or beliefs) in the subject matter or materials discussed in this manuscript.

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