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Less iatrogenic soft-tissue damage utilizing robotic-assisted total knee arthroplasty when compared with a manual approach

A BLINDED ASSESSMENT

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Objectives

The use of the haptically bounded saw blades in robotic-assisted total knee arthroplasty (RTKA) can potentially help to limit surrounding soft-tissue injuries. However, there are limited data characterizing these injuries for cruciate-retaining (CR) TKA with the use of this technique. The objective of this cadaver study was to compare the extent of soft-tissue damage sustained through a robotic-assisted, haptically guided TKA (RATKA) *versus* a manual TKA (MTKA) approach.

Methods

A total of 12 fresh-frozen pelvis-to-toe cadaver specimens were included. Four surgeons each prepared three RATKA and three MTKA specimens for cruciate-retaining TKAs. A RATKA was performed on one knee and a MTKA on the other. Postoperatively, two additional surgeons assessed and graded damage to 14 key anatomical structures in a blinded manner. Kruskal–Wallis hypothesis tests were performed to assess statistical differences in soft-tissue damage between RATKA and MTKA cases.

Results

Significantly less damage occurred to the PCLs in the RATKA *versus* the MTKA specimens ($p < 0.001$). RATKA specimens had non-significantly less damage to the deep medial collateral ligaments ($p = 0.149$), iliotibial bands ($p = 0.580$), poplitei ($p = 0.248$), and patellar ligaments ($p = 0.317$). The remaining anatomical structures had minimal soft-tissue damage in all MTKA and RATKA specimens.

Conclusion

The results of this study indicate that less soft-tissue damage may occur when utilizing RATKA compared with MTKA. These findings are likely due to the enhanced preoperative planning with the robotic software, the real-time intraoperative feedback, and the haptically bounded saw blade, all of which may help protect the surrounding soft tissues and ligaments.

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Keywords: Total knee arthroplasty, Robotic-assisted arthroplasty

Article focus

- This study examined the extent of soft-tissue damage sustained during total knee arthroplasty (TKA) through a haptically guided, robotic-assisted TKA (RATKA) *versus* a manual TKA (MTKA) approach.

Key messages

- RATKA resulted in less soft-tissue damage than MTKA, especially for the posterior cruciate ligament.
- Findings are likely attributed to the haptically bounded saw blade used with RATKA.

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Strengths and limitations

- This was the first prospective, blinded cadaver study to quantify soft-tissue damage in cruciate-retaining TKA using a robotic-assisted and manual approach.
- Caution should be taken in the interpretation of these findings, which may not necessarily translate clinically.

Introduction

Although manual total knee arthroplasties (MTKAs) have demonstrated excellent clinical results, intraoperative damage to soft tissues can occur. Soft-tissue injury to the medial or lateral collateral ligament (MCL or LCL), posterior cruciate ligament (PCL), or extensor mechanism may compromise postoperative clinical outcomes, through reduced stability and decreased implant survivorship.[1-5] Studies have shown that a full transverse tibial cut may lead to damage to the PCL[6-8] and even to the deep MCL.[9] PCL avulsion has been shown to be more likely with increased sagittal slope.[10] Therefore, it must be emphasized that avoidance of soft-tissue damage during TKA is important for the success of the procedure.[11] For MTKA, techniques such as leaving a bone island,[12,13] making a conservative tibial resection,[14,15] or reducing posterior slope[14,15] have been suggested to help preserve the PCL.

Robotic-assisted TKA (RATKA) was developed to help improve the accuracy and precision of bone cuts, as well as to enhance implant placement according to the surgical plan. Another advantage of this technique is that the use of the haptically bounded saw blade can help limit surrounding soft-tissue injuries. These benefits have been clinically demonstrated for RATKA in posterior-stabilized (PS) TKAs.[5] However, there is limited data characterizing soft-tissue injuries for cruciate-retaining (CR) TKAs with the use of this technique. In a recently published study, Khlopas et al[16] compared the amount of soft-tissue damage in 13 cadaver knees that had either a MTKA or a RATKA performed. They found that all six RATKA cases were left with a bone island on the tibial plateau, which surrounded the PCL. In two of the seven MTKA cases, there was slight disruption noted of the PCL *versus* no damage in the RATKA. These results were encouraging, but represented a small, semiquantitative to qualitative initial pilot study.

Therefore, the objective of this cadaver study was to expand on previous work by comparing in greater depth and quantification, the extent of soft-tissue damage sustained during TKA through a haptically guided RATKA approach *versus* a conventional MTKA approach.

Materials and Methods

Cadaver characteristics. A total of 12 fresh-frozen pelvis-to-toe cadaver specimens (24 knees) were included in this study. The cadaver demographics included six females and six males, who had a mean age of 81 years (68 to 89), and a mean body mass index of 26 kg/m^2 (20 to 36). Paired knees from the same subject were used to limit any potential baseline variability of the extent of osteoarthritis (OA) and the deformity that can be present if knees from different subjects were compared. Radiographs and the medical social summaries from the donor reports were reviewed to confirm that there were no previous joint arthroplasties or fractures in the specimens utilized.

Cadaver osteoarthritis assessment. For each cadaver knee, a preoperative assessment of the degree of osteoarthritis was performed on supine short-film radiographs. This was graded using the Kellgren–Lawrence classification system.[17] The images were also reviewed to ensure that there were no extra-articular deformities.

Sampling plan. Specimens were preoperatively assigned to the surgeon, surgical application, and right/left legs to evenly distribute the Kellgren–Lawrence OA grades. The operative side (e.g. left or right leg) alternated between RATKA and MTKA, and there was an equal number of left and right cases for RATKA and MTKA procedures. These precautions were taken to further reduce any potential confounding variables.

Cadaver preparation. Four orthopaedic surgeons (including MED and ZY) each prepared three cadaver specimens (three RATKA and three MTKA paired knees) for CR TKAs. All surgeons had prior clinical experience with both RATKA and MTKA. Two surgeons (MED and ZY) had previously performed robotic-assisted cases during a joint reconstructive fellowship, and the other two surgeons had performed a minimum of 35 robotic-assisted cases post-fellowship. The surgeons were blinded to the purpose of the study, but were instructed to take precautions with soft tissues that resembled their standard clinical practice. For each cadaver pair, a RATKA was prepared on either the right or left leg and a MTKA was prepared on the contralateral leg.

Specimen preparation. Specimens were scanned on a Siemens SOMATOM Perspective CT with 64-slice configuration (Siemens Healthcare, Erlangen, Germany) following a specific knee CT scanning protocol (supine feet first; 120 kVp to 140 kVp; AutoExposure Control 200 mA to 400 mA; 512 $\times$ 512 matrix image resolution; display field of view of 500 mm for hip, 250 mm for knee, and 500 mm for ankle; slice thickness of 2 mm to 5 mm for hip, 0.5 mm to 1 mm for knee, and 2 mm to 5 mm for ankle). Implant plans were created prior to the lab and reviewed with the 'assessment surgeons' (surgeons performing the visual evaluation of the tissue damage) for sizing and alignment. However, plans may have been adjusted intraoperatively by the 'conducting surgeons' (surgeons performing the surgical procedures).

RATKA system. The RATKA system (Mako Surgical Corp. (Stryker), Fort Lauderdale, Florida) was utilized in this study (Fig. 1). The system is intended to assist the surgeon by providing haptic boundary constraint based on the operative implant plan. This system included a

Fig. 1

The Mako Robotic-Arm Assisted Total Knee Arthroplasty System (Mako Surgical Corp. (Stryker), Fort Lauderdale, Florida).

robotic arm, camera stand, guidance module, TKA application software, and dedicated instrumentation.

Surgical steps. For both RATKA and MTKA cases, a standard midline incision and a medial parapatellar arthrotomy were performed. The arthritic state was documented using a modification of the Outerbridge Classification.[18] The classification system was modified so that in-between grades were assigned a half score.

Prior to any cuts, the conducting surgeons were instructed to inspect any visible ligaments, including the PCL, MCL, and LCL, without disruption to the cavity and to note any injuries. If there were any observed injuries, photographs were taken using a blunt pointer tool to identify the region of interest. The anterior cruciate ligament (ACL) was removed and the surrounding tissues were again checked by the conducting surgeons to ensure that no damage occurred during removal of the ACL. The PCL was visualized and palpated to check for its integrity.

A Triathlon CR TKA procedure (Stryker, Mahwah, New Jersey) was performed using standard retraction techniques in accordance to the surgical protocol for RATKA and MTKA cases. The bone cut order (tibia-first or femur-first) and retractor usage ('Z' retractor, Hohmann, or other) was based on surgeon preference. Depending on component size, RATKA cases used a narrow PN 116171 (Triathlon sizes 1 to 2) or standard PN 116170 (Triathlon sizes 3 to 8) blade, with an effective width (total cutting tip excursion of the saw blade oscillation) of 18 mm and 25 mm, respectively (all Mako Surgical Corp. (Stryker)). MTKA cases used a Dual Cut Sagittal Blade PN 4118-127-090 (dimensions: 18 mm $\times$ 90 mm $\times$ 1.27 mm) or PN 4125-119-090 (dimensions: 25 mm $\times$ 90 mm $\times$ 1.19 mm) (all Stryker Instruments, Kalamazoo, Michigan). The implant plans and targets were based on mechanical alignment and confirmed with the conducting surgeons prior to beginning the case.

For MTKA cases, the conducting surgeons had the option to review the CT scout or anteroposterior radiographs. For RATKA cases, extended haptic boundaries were only used when requested by the operating surgeon. Conducting surgeons followed their preferred balancing workflow consistent with the approved user guide.

The conducting surgeons performed the RATKA and MTKA procedures through trialling and assessing the final gap balance. If the gaps were not equal, surgeons were instructed to make soft-tissue releases or bony recuts as necessary. At the end of each case, a note-taker confirmed all recorded data with the surgeon. Peg and keel preparation were also completed by the conducting surgeons.

Conducting surgeons were asked to take additional measures to ensure adequate blinding by the assessment surgeons performing the soft-tissue assessments. In robotic cases, they were asked to drill an intramedullary hole in the femur, as well as holes where the fixation pins would insert for the MTKA cutting guides. In MTKA cases, the conducting surgeons were asked to insert checkpoints into the femur and tibia as would have been performed in RATKA cases. Incisions were also made on the MTKA cases and covered with Coban self-adherent-wrap (3M, St. Paul, Minnesota) to mimic the incisions where extra-articular arrays would have been placed in RATKA cases.

Table I. Kellgren–Lawrence and Outerbridge grades

Compartment	RATKA: median (IQR)	MTKA: median (IQR)	p-value*
Kellgren–Lawrence	2.5 (2.0 to 3.0)	2.0 (2.0 to 3.0)	0.643
Medial femoral condyle	3.0 (2.0 to 4.0)	2.8 (2.0 to 3.8)	0.121
Lateral femoral condyle	2.0 (1.6 to 3.0)	1.8 (0.3 to 2.4)	0.407
Trochlea	3.0 (1.3 to 4.0)	2.8 (1.0 to 3.0)	0.360
Medial tibial plateau	2.8 (2.0 to 3.0)	2.0 (2.0 to 3.0)	0.229
Lateral tibial plateau	2.3 (0.5 to 3.0)	2.3 (0.5 to 3.0)	0.882

*Kruskal–Wallis test
RATKA, robotic-assisted, haptically guided total knee arthroplasty; IQR, interquartile range; MTKA, manual total knee arthroplasty

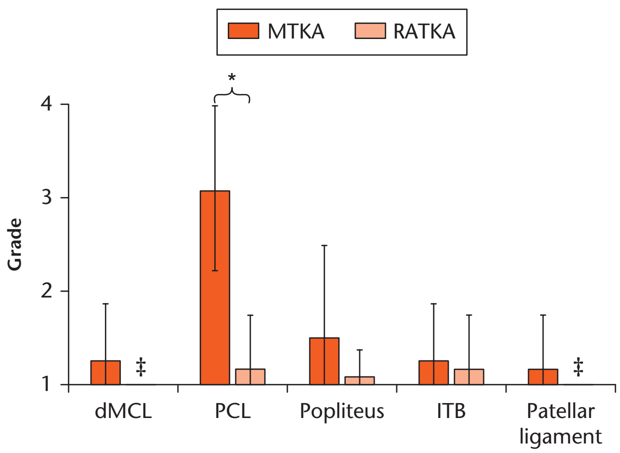

Fig. 2

Bar chart showing the mean grade 1 to 4 damage for the deep medial collateral ligament (dMCL), posterior cruciate ligament (PCL), popliteus, iliotibial band (ITB), and patellar ligament in manual total knee arthroplasty (MTKA) and robotic-assisted, haptically guided total knee arthroplasty (RATKA) specimens. Error bars indicate standard deviations. *Statistically significant difference ($p < 0.001$, Kruskal–Wallis test). ‡The grade mean was 1 (SD 0).

Soft-tissue damage assessments. Two additional orthopaedic surgeons (GW and MAM), who were not involved with the surgical procedures (assessment surgeons), performed the visual evaluation of the tissue damage. The assessment surgeons were blinded to the type of surgery, robotic-assisted or manual, that was performed. Direct visual grading and arthroscopic imaging were used to assess the extent of damage. Damage was defined as tissue fibres that were visibly torn, cut, frayed, or macerated over the total cross-sectional area. For a transected ligament/tendon/muscle, the percentage of damage was estimated as the affected area over the total cross-sectional area. The damage was assessed at the approximate level of the femoral or tibial resection to capture damage due to the excursion of the saw blade.

Tissue damage was recorded for the following 14 structures: deep MCL, superficial MCL, posterior oblique ligament, semimembranosus muscle tendon, gastrocnemius muscle medial head, PCL, iliotibial band, lateral retinaculum, LCL, popliteus tendon, gastrocnemius muscle lateral head, patellar ligament, quadriceps tendon, and extensor mechanism. A dry arthroscope (Stryker Endoscopy, San Jose, California) was used to help visualize and to take photographs of the damage. A Castroviejo straight bone caliper (6.5" straight 0 mm to 40 mm) (gSource, LLC, Emerson, New Jersey) was used for measurement of the damage and to capture an estimated overall width of the structure and damaged tissue. These values were then used to estimate the percent damage.

Ligaments were assessed in the same order for all knees. With the knees in extension, assessment surgeons evaluated the medial side with a taut laminar spreader across the lateral side, and then evaluated the lateral side with a taut laminar spreader across the medial side. Assessment surgeons also digitally palpated the structures to check for their integrity. The patella was then everted with the patellar and quadriceps tendons assessed. The laminar spreader was removed, the knee was flexed to 90°, and the same assessments were repeated in flexion. Structures were measured under relatively equal joint tensions in both flexion and extension.

Assessment surgeons independently assigned a percentage of damage value to each structure. The difference between the means of both surgeons was determined, and if the difference was > 10%, the surgeons were asked to further review photographs or the actual specimens to determine any discrepancies and to agree on a value. A mean of the percentages was then taken between the surgeons, and a grade was assigned according to a modified macroscopic soft-tissue injury (MASTI) classification system, which was shown to be a reproducible grading scheme for describing knee soft-tissue injuries.[5] The classification system was modified to quantify the injury assessments for each structure on a 1 to 4 scale: grade 1, complete soft-tissue preservation to ≤ 5% damage; grade 2, 6% to 25% damage; grade 3, 26% to 75% damage; grade 4, 76% to 100% damage. Notes were reviewed to determine whether or not the assessment surgeons noted the presence of a tibial bone island.

Statistical analysis. Hypothesis testing was performed to assess MTKA and RATKA data on preoperative Kellgren–Lawrence grades, intraoperative osteoarthritis assessments using the Outerbridge Classification, and soft-tissue damage of 14 structures using Kruskal–Wallis tests. The α significance level for the test was 0.05 with a 95% confidence level and adjusted for ties. A tie occurred when the same value was in more than one sample. If the p-value was > 0.05, then the data provided insufficient evidence to

Fig. 3a

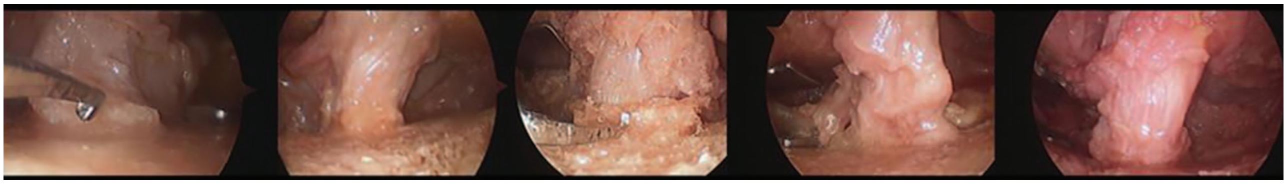

Fig. 3b

Examples of arthroscopic images of a) severed posterior cruciate ligament (PCL) and b) intact PCL, from manual total knee arthroplasty (MTKA) and robotic-assisted, haptically guided total knee arthroplasty (RATKA) specimens, respectively.

reject the null hypothesis (Ho: $s1/s2 = p$) and accept the alternate hypothesis (Ha: $s1/s2 > p$), where $s1 = $ MTKA and $s2 = $ RATKA. This decision was reached because the calculated p-value for the test was more than the preselected α level. If the p-value was $\leqslant 0.05$, then the data provided sufficient evidence to reject the null hypothesis (Ho: $s1/s2 = p$) and to accept the alternate hypothesis (Ho: $s1/s2 > p$) at a significance level of 0.05. This decision was reached because the calculated p-value for the test was less than the preselected α level.

Results

Specimen characteristics. Preoperatively, no statistically significant differences were found between the median Kellgren–Lawrence scores for the MTKA *versus* RATKA cohorts (2.0 (interquartile range (IQR) 2.0 to 3.0) *vs* 2.5 (IQR 2.0 to 3.0); all $p > 0.05$, Kruskal–Wallis test). Intraoperatively, no statistically significant differences were found between the mean OA grades for any of the five compartments, using the modified Outerbridge Classification (all $p > 0.05$, Kruskal–Wallis test) (Table I), using Kruskal-Wallis Tests. In addition, intraoperative inspection of the ligaments by the conducting surgeons characterized the PCL, MCL, and LCL as structurally intact in all specimens.

Retractor and bone cuts preference. Retractor use and placement was at the discretion of the surgeon. In MTKA and RATKA cases, surgeons most commonly used 'Z' and Hohmann retractors (or the retractors compatible with the Leg Positioner Self-Retractor system (Mako Surgical Corp. (Stryker) only in RATKA cases) to protect the collaterals. All RATKA components were sizes 3 to 8 and used the standard (25 mm effective width) saw blade.

The bone cut order was based on surgeon preference. For MTKA cases, three of the four surgeons performed the distal femoral cut first, the tibial cut second, followed by the remaining femoral cuts. One surgeon performed the tibial cut first, the distal femoral cut second, followed by the remaining femoral cuts.

For RATKA cases, one surgeon first performed the distal femoral cut, femoral posterior chamfer cut, tibial cut, and then the remaining femoral cuts last. Two surgeons fully cut the femur first and then the tibia. An additional surgeon performed the tibial cut first and then the distal femoral cut last. For removal of the tibia, surgeons most often used a scalpel to release the bone.

Soft-tissue damage results. Significantly less damage occurred to the PCLs in the RATKA than the MTKA specimens ($p < 0.001$, Kruskal–Wallis test) (Fig. 2). In MTKA specimens, four PCLs were 100% severed (grade 4). Examples of arthroscopic images of a severed PCL and an intact PCL, from MTKA and RATKA specimens, respectively, are seen in Figure 3. RATKA specimens showed non-significantly less damage to the deep medial collateral ligaments ($p = 0.149$, Kruskal–Wallis test), iliotibial bands ($p = 0.580$, Kruskal–Wallis test), poplitei ($p = 0.248$, Kruskal–Wallis test), and patellar ligaments ($p = 0.317$, Kruskal–Wallis test). The superficial medial collateral ligaments, posterior oblique ligaments, semimembranosus muscle tendons, gastrocnemius muscle medial heads, gastrocnemius muscle lateral heads, lateral retinacula, LCLs, quadriceps tendons, and extensor mechanisms were grade 1 in all MTKA and RATKA specimens.

Of note, no intentional soft-tissue releases were performed in either group to balance the knee. Additionally, nine RATKA and two MTKA specimens had a posterior bone island protecting the PCL (RATKA examples indicated by the probe tip in Fig. 3b).

Discussion

Robotic-assisted technology has been shown to facilitate more accurate positioning to plan[19-23] and to enhance patient reported outcomes.[24-28] Conventional MTKA procedures have also demonstrated clinical success in terms of pain relief and survivorship, but intraoperative complications, such as soft-tissue injury, can occur.[29] Therefore, this study was conceived to compare the amount of soft-tissue damage found after performing RATKA *versus* MTKA techniques. Our results showed that less soft-tissue damage may occur utilizing RATKA. The findings are likely due to the enhanced preoperative planning with the robotic software, the real-time intraoperative feedback, and the haptically bounded saw blade. Furthermore, these findings could be attributed to the smaller effective width (or total cutting tip excursion) of the RATKA saw blade oscillations. As noted above, the RATKA saw blades used in this study had a total cutting tip excursion of 25 mm, whereas the MTKA blades were 25 mm or 18 mm wide before oscillation. These features all may have helped to protect the surrounding soft tissue and ligaments. The reduced soft-tissue injury may also partly be due to the tendency to create a full transverse tibial resection in MTKA procedures, whereas the RATKA procedure is designed to leave a posterior tibial bone island to help protect the PCL.

Studies have evaluated the importance of the PCL through simulations and passive testing.[30-32] The PCL is the primary restraint to posterior translation of the tibia and plays a role in joint compression.[31] Sekiya et al[30] used stress radiography on 20 cadaver knees to measure the change in posterior translation during a 200 N posterior drawer at 90° flexion before and after the sequential resection of the PCL, and showed that sectioning of the PCL resulted in corrected posterior displacement up to 10 mm.

In a knee simulation model, one study demonstrated that a loose PCL induced paradoxical anterior movement and greater patellofemoral forces, whereas a tight PCL was related to excessive rollback and increased tibiofemoral forces.[31] Kang et al[32] used a validated knee model to simulate force-dependent kinematics under gait- and squat-loading conditions with and without PCL deficiency. They found forces on the posterolateral corner structures, and tibiofemoral and patellofemoral contact forces, to be increased with PCL deficiency under gait- and squat-loading conditions.[32]

In addition to the previously mentioned study by Khlopas et al,[16] there have been other reports describing the degree of soft-tissue injury occurring when RATKAs are compared with MTKA techniques.[5,33] Kayani et al[5] assessed the extent of unintended soft-tissue damage in a prospective cohort of 30 consecutive PS conventional TKAs followed by 20 consecutive PS RATKA. Results indicated that RATKA had reduced medial soft-tissue injuries and improved MASTI scores ($p < 0.05$) when compared with the manual TKA group.

The enhanced soft-tissue protection seen with RATKA may be one of the main reasons that in a recent study, patients demonstrated enhanced outcomes, less pain, faster therapy, and less narcotic use.[27] In a prospective cohort study of 40 consecutive patients undergoing conventional jig-based TKA followed by 40 consecutive patients receiving robotic-assisted TKA, the latter group was associated with reduced postoperative pain levels ($p < 0.001$), decreased analgesia requirements ($p < 0.001$), decreased reductions in postoperative haemoglobin levels ($p < 0.001$), shorter times to straight leg raise ($p < 0.001$), decreased numbers of physiotherapy sessions ($p < 0.001$), and improved maximum knee flexions at discharge ($p < 0.001$).[27] Multiple other studies have demonstrated early benefits of this RATKA system.[34-47]

There were several limitations of the present study. We utilized cadavers instead of live patients, which may not allow for results to be translated clinically. Furthermore, the damage was postoperatively assessed, so it was not always known whether the damage occurred from the saw blade or the removal of the tibial osteotomy with a scalpel, although it is believed that damage most likely arose from the saw blade based on location and visual characteristics. The sample size was relatively small (12 RATKA and 12 MTKA cases). However, even with this number of cases, we were able to demonstrate statistical differences in soft-tissue injury for the PCL. In addition, our results are promising in their demonstration of less soft-tissue injuries for RATKA.

In conclusion, the results of this study indicate that RATKA may result in less soft-tissue damage than MTKA, especially for the PCL. However, since any damage was postoperatively assessed and in a cadaver model, further investigations on soft-tissue damage from patients who have clinical outcomes should be performed. Nevertheless, this work provides a basis from which future clinical studies can be performed.

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