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Kinematically Aligned Total Knee Arthroplasty Using Medial Pivot Knee Prosthesis Enhances Medial Pivot Motion: A Comparative Kinematic Study With Mechanically Aligned Total Knee Arthroplasty

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ABSTRACT

Background: Clinical outcomes of kinematically aligned total knee arthroplasty (KA-TKA) have been reported as comparable or superior to those of mechanically aligned TKA (MA-TKA). However, cruciate-retaining prostheses have mostly been used for KA-TKA. This study used medial pivot knee prostheses for KA-TKA, and knee kinematics after KA-TKA were assessed and compared with those after MA-TKA.
Methods: Thirteen knees in 9 patients undergoing primary TKA (8 KAs, 5 MAs) were subjected to two-dimensional (2D) to three-dimensional (3D) registration analysis at 1 year postoperatively. Each patient performed weight-bearing activities, and movements were recorded as intermittent digital radiographic images. Three-dimensional implant positions during activities were analyzed for anterior-posterior translation in the sagittal plane, condylar liftoff and mediolateral translation in the coronal plane, and femoral rotation in the axial plane.
Results: Posterior translation of the lateral femoral condyle from 0° to 100° was larger in KA-TKA than in MA-TKA ($P = .006$). The degrees of condylar liftoff and mediolateral translation were comparable between TKAs. Total external rotation of the femoral component relative to tibial component was significantly greater for KA-TKA (7.7 ± 5.2°) than for MA-TKA (1.3 ± 3.3°; $P = .03$). The kinematic path of the femoral component revealed greater medial pivoting motion in KA-TKA than in MA-TKA.
Conclusions: KA-TKA using a medial pivot knee prosthesis successfully reproduced the medial pivot pattern and achieved larger femoral external rotation relative to the tibia than MA-TKA. KA-TKA was able to maximize the primary concept of the medial pivot knee prosthesis.

Introduction

In mechanically aligned total knee arthroplasty (MA-TKA), the distal femur and proximal tibia are cut perpendicular to each mechanical axis. These cuts change the angle and level of the joint line from the original state and, thus, may cause abnormal tightening or slackening of the collateral ligaments, leading to abnormal knee kinematics. The concept of kinematically aligned TKA (KA-TKA) has been developed to reproduce the flexion-extension axis of the prearthritic knee and maintain the original collateral ligament balance and joint line [1]. The orientation and level of the joint line are anatomically restored, so the resulting knee kinematics are

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closer to those of natural knees [2-4]. Recent systematic reviews and meta-analyses have shown that the clinical outcomes of KA-TKA are comparable or superior to those of MA-TKA [5,6], and several biomechanical studies have suggested satisfactory results from KA-TKA, including cadaveric studies [7,8], computer simulation studies [9-11], and gait analysis [12]. However, few studies to date have investigated in vivo kinematics after KA-TKA in comparison with MA-TKA [13,14].

The medial pivot knee design for TKA is characterized by a medially conforming articulation (ie, ball and socket) that beneficially controls the femoral anteroposterior position. In addition, posterior rollback of the lateral femoral condyle easily occurs around a stable spinning medial femoral condyle, mimicking normal knee kinematics [15]. However, most TKAs with a medial pivot knee design have been performed with the MA technique, and no reports appear to have clarified the effects of the KA technique on medial pivot knee prostheses.

In the present study, patients with end-stage osteoarthritis (OA) were randomly allocated to undergo KA- or MA-TKA using a medial pivot knee prosthesis, and kinematics of weight-bearing movements such as stair climbing and lunge were compared between the two TKA techniques using two-dimensional (2D) to three-dimensional (3D) registration techniques. We hypothesized that KA-TKA would show larger medial pivot rotation of the femur than MA-TKA, as the fundamental concept of the medial pivot knee prosthesis.

Material and methods

The present study enrolled 20 knees from 16 patients with knee OA (2 males, 14 females) who underwent primary TKA between January 2017 and June 2018. The only inclusion criterion was significant disabling pain due to end-stage medial knee OA. Exclusion criteria comprised knees with previous operations including high tibial osteotomy, valgus knee OA, inflammatory arthritides such as rheumatoid arthritis, history of fracture, and revision TKA. *A power analysis was performed to calculate the minimum sample size for the study, and we calculated the sample size with a probability of 0.05, effect size of 0.5, and power of 0.8. The analysis revealed that a minimum sample size of 28 was required for the study. However, we were only able to enroll 20 knees from 16 patients*. Sixteen patients were informed about the purpose of the randomized study and provided written informed consent. Of the 16 patients, 8 were randomly allocated to the KA-TKA group and the other 8 to the MA-TKA group. Two patients in each group underwent bilateral TKA, so the study finally comprised 10 KA-TKAs and 10 MA-TKAs. For all 20 TKAs, the same asymmetric, medial pivot bearing *made of highly cross-linked polyethylene*, cruciate substituting component (Evolution; MicroPort CRM Japan, Tokyo, Japan) was used. Among the 16 patients, 7 refused to undergo computed tomography postoperatively because of concerns about radiation exposure. A final total of 13 knees from 9 patients (8 KA-TKAs, 5 MA-TKAs) were thus subjected to 2D-3D registration analysis at 1 year postoperatively. Detailed demographic characteristics of participants are shown in Table 1. All surgeries were performed by two expert surgeons who had *greater* 20 years of experience with TKA. After 3D planning of the bone cut angle and thickness, KA-TKAs were performed as reported previously [12]. Briefly, the position of the cylindrical axis of the femur was initially measured, and the femur was cut so that both coronal and axial joint lines were parallel to cylindrical axis. Basically, bone cut thickness was equal to each region of the femoral component. When planning tibial plateau orientation, CT data for the contralateral knee were used if that knee was left unaffected by OA. In cases with bilateral knee OA, tibial plateau orientation was determined based on the growth plate axis [16] or decided intraoperatively based on the intraoperative gap balance. The study protocol was approved by the ethics committee at our university (institutional review board ID#20140319).

Table 1
Demographic characteristics of patients.

Variable	KA-TKA	MA-TKA	Significance
No. of participants (male/female)	6 (2/4)	3 (0/3)	
No. of knees	8	5	
Age (y)	76.3 ± 8.4[a]	75.0 ± 1.0	$P = .548$
BMI (kg/m^2)	26.2 ± 2.8	27.3 ± 3.5	$P = .714$
Preoperative KSS score			
Total knee score (180)[b]	78.8 ± 26.6	97.0 ± 15.7	$P = .284$
Total activity score (100)	43.8 ± 16.0	60.6 ± 16.3	$P = .093$
Patient satisfaction score (40)	17.6 ± 6.5	12.8 ± 2.7	$P = .151$
mMPTA (°)	83.6 ± 2.8	82.9 ± 2.9	$P = .324$
HKA angle (°)	-12.7 ± 6.3	-12.1 ± 7.7	$P = .943$

BMI, body mass index; HKA, hip-knee-ankle angle; KSS, Knee Society Score.
[a] Values are expressed as mean ± standard deviations.
[b] Values in parentheses indicate maximum score in each category.

On 2D-3D registration analysis of implant position and knee kinematics, each patient underwent two weight-bearing activities: stair climbing and lunge movement. The patient practiced each activity several times before recording. Movements were recorded as intermittent digital radiographic images at 10 frames/s using a flat panel detector system (42-cm field of view, 1536 × 1536-pixel images, Ultimax-i DREX-UI80; Canon Medical Systems, Tokyo, Japan). Positioning of the 3D femoral and tibial components was calculated from 2D sequential images. Nonlinear least-squares optimization was used for 2D-3D registration, and an open-source software program (JointTrack; University of Florida, Gainesville, FL) was used for registration. The 2D-3D registration process has been reported to involve standard errors of approximately 0.5–1.0° for rotations and 0.5–1.0 mm for translations in the sagittal plane [17]. We used the Euler/Cardan angles representing three sequential rotations about the anatomical axis of the distal component to describe component-to-component rotations of the femoral component relative to the tibial component around each axis. The following movements were measured: femoral component rotation of each axis relative to the tibial component; anteroposterior, superoinferior, and mediolateral (ML) translations of the medial and lateral femorotibial contact points; and kinematic pathways of the medial and lateral femorotibial contact points. Posterior translation and external rotation angle were defined as changes in values from 0° to 100° of knee flexion. Anterior sliding was defined as a change in the value at the midflexion position ranging from 0° to 30°. Condylar liftoff was measured as a distance from the medial and lateral femoral condyles to the tibial tray at each angle of flexion. Mean and maximum values from 0° to 100° of knee flexion were also recorded. The Mann-Whitney U test was used to compare differences in mean values between the two TKA groups. Analysis was performed at a significance level of $P < .05$, using SPSS version 24.0 software (IBM, Armonk, NY).

Results

Preoperatively, total knee score and activity score tended to be higher in the MA-TKA group, but no significant differences were identified in mean age, body mass index, or all categories of Knee Society Scores between the two TKA groups. After TKA, the total activity score was significantly higher in the MA-TKA group than in the KA-TKA group, as reflected by preoperative status. However, no significant differences between the two groups were found in improvements of total knee score or total activity score from preoperative to postoperative stage (Table 2).

Table 2
Knee scores and radiographic implant positionings after TKA.

Variable	KA-TKA	MA-TKA	Significance
Postoperative			
Total knee score (180)[a]	130.5 ± 17.9[b]	147.4 ± 15.5	$P = .222$
Total activity score (100)	67.6 ± 14.0	81.0 ± 6.7	$P = .045$
Patient satisfaction score (40)	27.3 ± 3.0	32.8 ± 8.2	$P = .435$
HKA angle (°)	-3.00 ± 2.4	-1.22 ± 3.5	$P = .127$
Total knee score improvement rate (%)	28.8 ± 15.2	28.0 ± 6.7	$P = .943$
Total activity score improvement rate (%)	23.9 ± 13.6	20.4 ± 10.8	$P = .523$
Component angle			
mLDFA (°)	89.4 ± 2.5	91.0 ± 0.8	$P = .524$
mMPTA (°)	83.4 ± 1.8	90.1 ± 1.4	$P = .002$
Femoral component flexion (°)	1.89 ± 1.0	2.06 ± 1.3	$P = .833$
Tibial posterior slope (°)	87.0 ± 1.5	86.6 ± 2.0	$P = .833$

HKA, hip-knee-ankle angle; mLDFA, mechanical lateral distal femoral angle; mMPTA, mechanical medial proximal tibial angle.
[a] Values in parentheses indicate maximum score in each category.
[b] Values are expressed as mean ± standard deviation.

Regarding implant positioning, mechanical medial proximal tibial angle (mMPTA) was significantly smaller with KA-TKA than with MA-TKA ($P = .002$), supporting the KA-TKA concept of reproducing the original joint line (Table 2). No significant differences were found regarding other implant position parameters, including mechanical lateral distal femoral angle, femoral component flexion angle, and tibial posterior slope angle.

In vivo knee kinematics as assessed by 2D-3D registration techniques were expressed as changes in locations of the closest points on the femoral component relative to the tibial component based on the knee flexion angle (Fig. 1). Anterior sliding, defined as a change in the closest point from 0° to 30°, was confirmed in both groups, and no significant difference was observed between groups (Table 3). The lateral closest point indicated that posterior translation from 0° to 100° was larger in the KA-TKA group (*5.01 ± 3.86 mm*) than in the MA-TKA group (*0.02 ± 1.80 mm*) ($P = .006$). Degrees of liftoff of medial and lateral closest points were comparable between groups. Total external rotation of the femoral component from 0° to 100° was 7.67 ± 5.18° for the KA-TKA and 1.31 ± 3.30° for the MA-TKA, showing a significant difference between groups. ML translation of the femoral component was comparable between groups (Fig. 1D). The kinematic path of the femoral component revealed greater medial pivoting motion with KA-TKA than with MA-TKA (Fig. 2).

Discussion

The present findings support the hypothesis that KA-TKA exhibit better medial pivot knee kinematics than MA-TKA. As a result of the large lateral posterior translation with minimal medial translation, the femoral component exhibited external rotation with a medial pivot pattern as the knee flexed. In the context of a "medial pivot" knee prosthesis, a highly congruent medial compartment and less-conforming lateral compartment may easily reproduce a medial pivot motion closer to that of the native human knee. KA-TKA techniques further enhanced this medial pivot pattern and femoral external rotation relative to the tibia (Fig. 2). The present data on in vivo kinematics after KA-TKA supported data from previous cadaveric studies [7,8] and computer simulations [9,10]. The kinematic path of the medial pivot pattern was substantially confirmed in MA-TKA but was much smaller than that in normal healthy knees [18]. Based on the perspectives of intraoperative gap balance, greater tibial internal rotation and lateral laxity during knee flexion were observed in KA-TKA than in MA-TKA [19]. In our

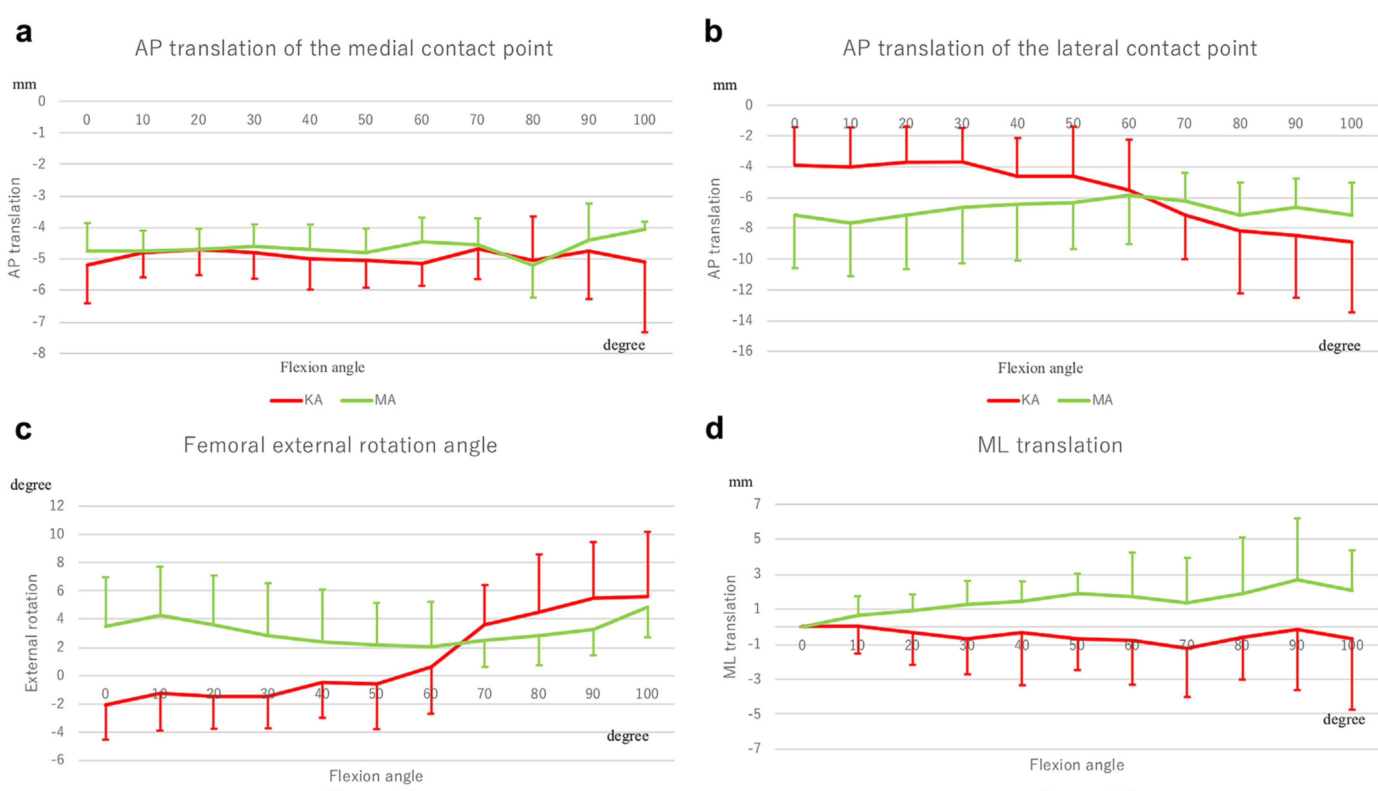

Figure 1. The closest point movements of the medial and lateral femoral components on the tibial coordinate axis according to knee flexion angle. (a) Anteroposterior translation of the medial contact point. (b) Anteroposterior translation of the lateral contact point. (c) Femoral component external rotation angle relative to tibial component. (d) Mediolateral translation of the femoral component. Positive values indicate lateral translation, and negative values indicate medial translation.

Table 3
Comparison of femoral component positioning between KA-TKA and MA-TKA.

Variable		KA-TKA	MA-TKA	Significance
Anterior sliding[a]	Medial (mm)	0.17 ± 0.19[e]	0.26 ± 0.33	P = .724
	Lateral (mm)	1.09 ± 1.10	1.06 ± 1.02	P = .833
Posterior translation[b]	Medial (mm)	0.04 ± 1.01	-0.67 ± 1.31	P = .622
	Lateral (mm)	5.01 ± 3.86	0.02 ± 1.80	P = .006
Condylar liftoff[c]	Medial (mm)	0.99 ± 0.81 (1.86 ± 1.38)	0.82 ± 0.33 (1.45 ± 0.66)	P = .724 (0.943)
	Lateral (mm)	1.12 ± 0.63 (1.88 ± 1.24)	1.13 ± 1.24 (2.95 ± 4.21)	P = .622 (0.833)
Total external rotation (°)[d]		7.67 ± 5.18	1.31 ± 3.30	P = .03

[a] Values are defined as change in femoral component translation from 0° to 30°.
[b] Values are defined as change in femoral component translation from 0° to 100°.
[c] Values are expressed as mean distance from the medial and lateral femoral condyles to the tibial tray from 0° to 100°. Maximum values are indicated in parentheses.
[d] Values are defined as change in femoral component external rotation from 0° to 100°.
[e] Values are expressed as mean ± standard deviation.

study, the degree of medial pivot motion seemed sufficient in KA-TKA using a medial pivot knee prosthesis, but paradoxical femoral anterior sliding at early flexion still existed. This paradoxical anterior sliding cannot be completely controlled, even though the medial component introduces a ball-and-socket design intended to increase the degree of medial conformity. *We hoped that kinematic alignment with ball-and-socket articulation would be a solution to settle the problem of midflexion instability, but unfortunately, paradoxical anterior sliding in midflexion range was substantially present.* Femoral anterior sliding is undoubtedly a downside of excising the anterior cruciate ligament (ACL) in conventional posterior-stabilized (PS) and cruciate-retaining TKAs [20]. *At present, we introduced robotic technology in bicruciate-retaining KA-TKA. Gait analysis and 2D-3D motion analysis of robotic assisted bicruciate-retaining KA-TKA is underway.*

Regarding ML liftoff in the coronal plane, no significant difference was apparent between KA- and MA-TKAs. Although preoperative hip-knee-ankle angle was comparable between the two TKAs, KA-TKA exhibited about 1.8° more varus, as a more natural joint line inclination was reproduced. Although 1.8° of varus alignment carried a risk of increasing knee adduction moment, condylar liftoff was not observed in our KA-TKA series. This result was different to that of a cadaveric study showing that laxity increased in midflexion more frequently in KA-TKA than in MA-TKA [21].

Regarding ML translation of the femur relative to the tibia, no significant difference was apparent between KA-TKA and MA-TKA. No significant correlation was found between mMPTA and the degree of medial translation ($r = 0.45$, $P = .13$) as assessed by Spearman's correlation test. Increased medial conformity in the medial pivot knee design theoretically decreases ML translation, but a patient with 80° of mMPTA showed medial femoral translation of 1.2 mm, while conversely, patients with >90° of mMPTA showed lateral femoral translation. Subtle amounts of ML translation still occur even in medial pivot knee prosthesis, particularly in the case of excessively small mMPTA. A previous study reported that an inclined joint line with 87° and 85° of mMPTA in PS-TKA increased peak contact force on the post by 2.2- and 3.8-fold of that at 90° of mMPTA, respectively [22]. Accordingly, PS-TKA carries a risk of increasing post-cam contact stress with slight medial inclination, as medial translation of the medial border of the lateral condyle may collide with the lateral aspect of the post. From this perspective, KA-TKA with a medial pivot knee prosthesis offers less ML translation and harmonizes well to reduce the kinematic risk of KA-TKA.

Finally, the present results must be interpreted after considering several limitations. First, the sample size in this study was small, and the statistical power of this study was relatively low. *In theory, a minimum sample size of 28 was required to gain statistical power of 80%.* Many patients opted out of fluoroscopic analyses to avoid radiation exposure, so preoperative activity scores were likely to have been artificially low in the KA-TKA group, and postoperative activity scores were significantly lower than those in the MA-TKA group. However, when the improvement rate of the activity score was analyzed, no significant differences were evident between the two TKA groups, and we appreciated that the two groups had comparable backgrounds. Second, knee kinematics were examined only from 0° to 100° of knee flexion. When the impact of KA techniques on full range of knee flexion is examined, deep knee flexion activities (such as lunge and squat) should be evaluated.

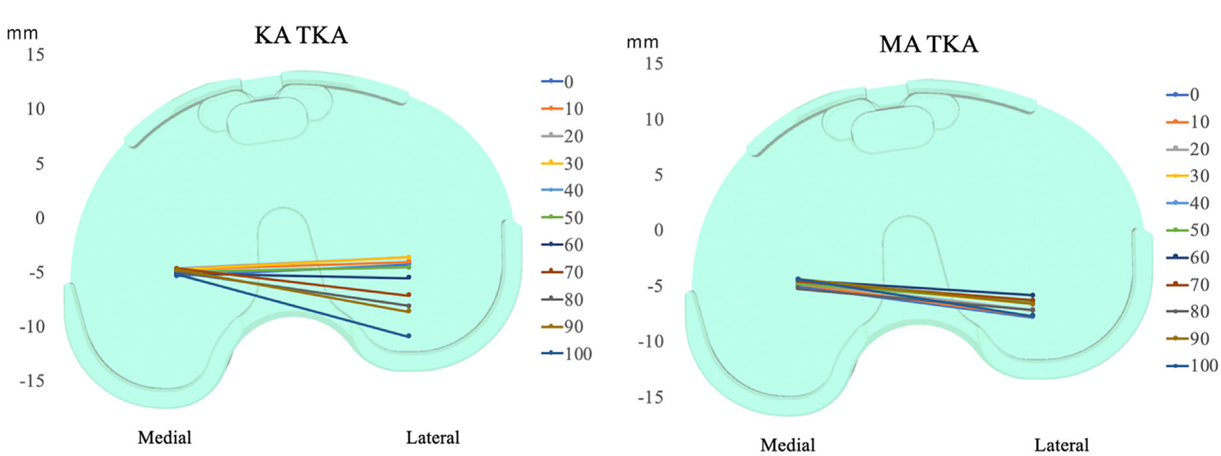

Figure 2. Kinematic path of the tibiofemoral contact point in KA-TKA and MA-TKA. Medial pivot pattern and degree of femoral external rotation relative to the tibia were more pronounced in KA-TKA than in MA-TKA.

Conclusions

KA-TKA using a medial pivot knee prosthesis successfully reproduced the medial pivot pattern and exhibited larger femoral external rotation relative to the tibia than MA-TKA. KA-TKA was able to maximize the primary concept of the medial pivot knee prosthesis. However, paradoxical anterior sliding substantially occurred, potentially due to the lack of ACL. Whether KA-TKA with an ACL-retaining prosthesis could resolve paradoxical knee motions is to be addressed in the future.

Ethics approval and consent to participate

The present study was approved by the Institutional Review Board of the School of Medicine, Keio University (ID#20140319), and informed consent was obtained from all participants.

Authors' contributions

K.K., Y.N., K.H., and T.N. conceived and designed the study. K.K., Y.N., K.H., and S.K. performed the experiments. K.K., Y.N., and Y.K. performed the data analysis and drafted the manuscript. K.K., Y.N., and Y.I. performed image acquisition. All authors edited and approved the manuscript before submission.

Conflicts of interest

Y. Niki has received personal and institutional research support from MicroPort Orthopedics.

Consent for publication

The approval of the institutional review board included the consent for publication of any individual data.

Availability of data and materials

The data sets of the present study are available from the corresponding author on reasonable request.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.artd.2021.10.004.

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