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Article *in* The Journal of arthroplasty · October 2010

DOI: 10.1016/j.arth.2010.08.003 · Source: PubMed

The Journal of Arthroplasty Vol. 26 No. 2 2011

Knee Kinematics of High-Flexion Activities of Daily Living Performed by Male Muslims in the Middle East

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Abstract: Full flexion is critical for total knee arthroplasty (TKA) patients in the Middle East, where daily activities require a high range of motion in the lower limb. This study aimed to increase understanding of the knee kinematics of normal Muslim subjects during high-flexion activities of daily living, such as kneeling, Muslim prayer, sitting cross-legged, and squatting. The early postoperative kinematics for a select group of Muslim, high-flexion TKA patients are also reported. Mean curves were compared between the normal group and the TKA group. During kneeling, the average maximum flexion was 141.6° for the normal group and 140.2° for the TKA group. The normal group's maximum and minimum knee angles (flexion, abduction, external rotation) were reported and, with the exception of maximum extension, were not significantly different from the TKA group, despite short postoperative times. **Keywords:** total knee arthroplasty, knee kinematics, high-flexion activities.

The objective of this study was to determine the normal 3-dimensional knee kinematics of Muslims in the Middle East during high-flexion activities. There is little data on high-flexion activities for Middle Eastern lifestyles, despite that these activities are considered crucial to people in this region. Early postoperative knee kinematics of total knee arthroplasty (TKA) patients are also presented for high-flexion activities. The data presented in this study will increase the knowledge of high-flexion needs in non-Western cultures and provide an initial characterization of the prosthesis kinematics in high flexion.

High Range of Motion Activities of Daily Living

There is a lack of documented research on the functional range of motion of non-Western populations. Several studies have been carried out involving Western, Japanese, Indian, and Chinese subjects, but the availability of published data for Middle Eastern subjects is limited [1]. Of the published studies, few report the range of abduction/adduction (varus/valgus) in either the normal knee or knees with prostheses.

In some non-Western cultures, high range of motion activities are commonplace and culturally significant. A range of motion greater than 120° is critical for activities of daily living, which include kneeling, squatting, and sitting cross-legged [2,3]. Squatting can be maintained by some for hours and is required for activities such as toileting, resting, and conducting activities near the floor [4]. Sitting cross-legged is used for eating meals, meditation, and relaxation. Kneeling is important in much of the Middle East and Asia for religious activities. During prayer, Muslims have been shown to routinely flex the knee between 150° and 165° [5]. Some Muslim subjects in this study indicated that they kneel 20 to 30 times each day and could comfortably remain kneeling or sitting cross-legged for an hour or more. Often, non-Western patients are inclined to refuse TKA because of concerns that the postoperative range of motion will be less than adequate for high range of motion activities of daily living [6]. Compared with Western countries, far fewer TKAs are performed in Saudi Arabia and the Middle East, where TKA is less accepted because the outcome

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Submitted July 25, 2007; accepted August 1, 2010.

This study was funded by National Sciences and Engineering Research Council, Canada and Zimmer Inc., Warsaw, IN.

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0883-5403/2602-0024$36.00/0
doi:10.1016/j.arth.2010.08.003

depends highly on implant design, surgical techniques, and many patient factors [5].

High Range of Motion TKA

Recent improvements in implant design and surgical technique have allowed more TKA patients to reach previously unattainable ranges of motion. With these improvements, surgeons are implanting knee prostheses in more diverse, younger, and more active patients, including Western patients who require a high range of motion for gardening, golfing, and, in some cases, even competitive athletics [1,3,7]. Knowledge of normal knee kinematics is important for understanding joint injuries and diseases and evaluating treatment outcomes [8]. An understanding of knee arthroplasty kinematics, especially in deep flexion, can aid in the prediction of TKA component wear [9].

Subjects and Methods

Subjects

This study was carried out in Dubai, UAE, and ethics approval was obtained from a local institutional review board. Volunteer subjects were recruited at the hospital where the study was to take place and provided informed consent for participation. Data collection required travel to the Middle East and was scheduled to take place for a period of 1 week. All 11 male patients who were scheduled for routine follow-up appointments during that week were asked to participate. Nine patients (82%) agreed to participate and stated that they were able to perform the required activities. Seven of the TKA patients had bilateral TKA, 1 had a right knee arthroplasty only, and 1 had a left knee arthroplasty only. The average time postoperative for the TKA patients was 18 months, ranging from 3 to 29.5 months. Normal, healthy subjects were recruited through advertisements at the hospital. This normal group consisted of hospital employees, patients who were at the hospital for non–joint-related treatment, relatives of admitted patients, and those who were informed of the study by another subject or person at the hospital. Subjects were required to be Muslim, of Middle Eastern descent, and living a Middle Eastern lifestyle. All subjects included in this study were male. The mean age, height, and mass of the 2 subject groups are shown in Table 1. The average passive preoperative range of knee flexion was 135°, whereas the average passive postoperative range of flexion was 148.8°.

Table 1. Subject Characteristics for the 2 Groups

	Normal Group	TKA Group
Age (y)	45.7 (±11.7)	63.9 (±4.5)
Height (m)	1.76 (±0.05)	1.64 (±0.09)
Mass (kg)	90.0 (±11.3)	76.7 (±12.1)
No. of subjects	10 males	9 males

Surgical Technique

All patients received high-flexion, mobile-bearing knee prostheses. All surgeries were performed by the same surgeon via the subvastus approach with quadriceps releases carried out in cases where flexion was less than 100°. A median parapatellar incision was made while maintaining the attachment of the vastus medialis on the patella and leaving it intact. Dissections were carried out on the vastus medialis until it was laterally mobilized. If the patient had limited movement, a quadriceps release was carried out, where the quadriceps muscle was dissected free from the anterior surface of the femur. The release was done manually and bluntly as far proximally as needed until a flexion of 130° was obtained. This procedure allowed more quadriceps excursion and enabled the surgeon to sublux the patella laterally. No attempt was made to evert and dislocate the patella. The bone cuts were carried out as per recommendation of the manufacturer. Patellar tracking was checked before closure by flexing the knee and extending it, with no external support for the patella (no thumb technique). All components were cemented in full extension. Physiotherapy was initiated after removing the drain 1 day postoperatively and after reducing the dressing. No continuous passive motion machines were used. Physiotherapy involved aggressive passive and active knee flexion.

Equipment and Data Collection

Kinematic data were collected using a 6-degree-of-freedom electromagnetic motion tracking system (Fastrak; Polhemus, Colchester, Vt) with 4 receivers: the first 3 attached to the subject's right foot, shank, and thigh (with the exception of 1 left TKA patient whose left leg was instrumented), and the fourth attached to the subject's sacrum. The subject's instrumented foot was on a nonconductive force platform (BP400600NC; Advanced Mechanical Technology, Inc., Watertown, Mass) embedded in the wooden platform on which the subject stood. The platform contained no metal parts and was built approximately 50 cm tall to minimize electromagnetic distortion from the steel-reinforced concrete floors. A study by Lionberger et al [10] found that cobalt-chromium, titanium, and stainless steels did not significantly interfere with an electromagnetic surgical navigation system when they were placed within 1 cm of the measuring device. This result was sufficient to alleviate concerns about the TKA in the system.

Anthropometric measurement and kinematic and kinetic data collection were consistent with the protocol presented by Hemmerich et al [2]. Subjects performed multiple trials of the following 4 activities: squatting, kneeling, praying, and sitting cross-legged. Subjects only performed the activities that they were accustomed to

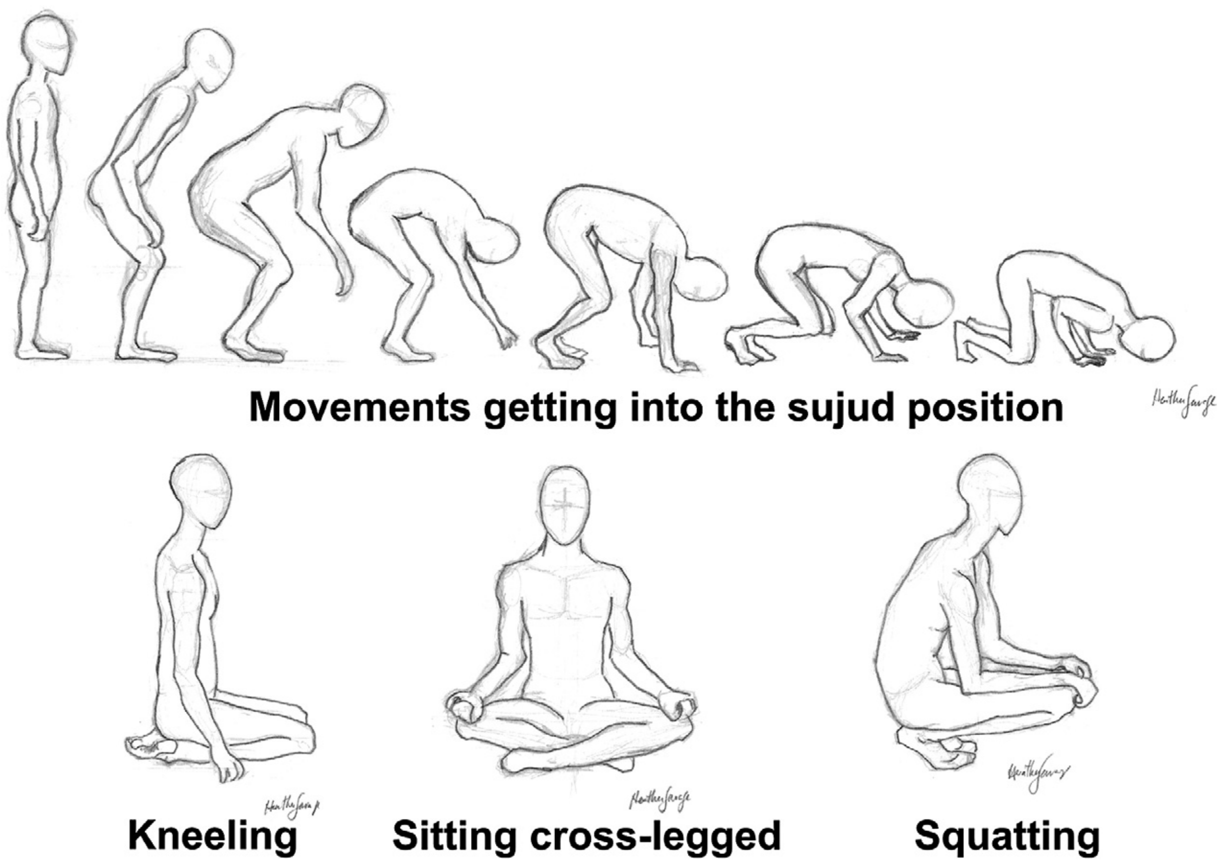

Fig. 1. The 4 activities that subjects were asked to perform: (top row) prayer, (bottom row) kneeling, sitting cross-legged, and squatting. Only the movements that comprise the first phase of the prayer activity are shown. The subject started and ended all activities in standing position.

doing. The 4 activities are depicted in Fig. 1. The squatting activity was performed with either the heels resting flat on the floor or with the heels raised off the floor, and the subject's weight balanced over the balls of the feet. The kneeling activity was performed in the manner in which the subject normally kneels during a Muslim *khutbah* (sermon). This posture was also used by some subjects for eating meals at low dining tables or for relaxing and lounging at home. The prayer activity was representative of a portion of the Muslim *rak'ah*, a repeated series of movements involved in prayer. From standing, the subject first bowed the torso forward and bent the knees, lowering the body into the *sujud* position, where the knees, hands, and forehead rested on the floor (platform), as shown in Fig. 1. The torso was then flexed back toward upright while flexing the knees back to almost a full kneeling position. The subject then returned to a standing position. The sitting cross-legged activity involved sitting with the buttocks on the platform and the feet resting under the knees. Subjects indicated that they often sat cross-legged during meal times or leisure time.

The subject was asked to lower the body into position with the aid of gravity and then pause to ensure that all segments had fully come to rest. After staying in this rest position for a few seconds, the subject was then asked to rise up out of the position against gravity.

Segment-Fixed Coordinate Systems and Kinematics Analysis

Segment-fixed coordinate systems were defined for the foot, shank, and thigh to define floating axis angles [11]. Only the femur-fixed and tibia-fixed coordinate systems are described here because only these axes were used to calculate the 3-dimensional knee angles. The origin of the femur-fixed coordinate system was the midpoint between the medial and lateral femoral epicondyles. The direction of the z-axis was defined from this origin to the hip joint center, which was positioned 2 cm distal from the midpoint between the symphysis pubis and the anterior superior iliac spine [12]. The z-axis and the transepicondylar line were used to define the frontal plane, and the y-axis was defined as a normal to the frontal plane, with the x-axis defined as the cross product between the y-axis and the z-axis. The origin of the tibia-fixed coordinate system was positioned at the midpoint between the lateral and medial malleoli. The z-axis was directed from this origin to the midpoint between the lateral and medial tibial condyles. The y-axis was defined as

Table 2. Mean Values for the 2 Subject Groups

	Normal (9 Subjects)		TKA (6 Subjects)	
Prayer	Mean	SD	Mean	SD
Flexion maximum	140.4	11.5	132.8	11.7
Flexion minimum*	−1.0	6.7	5.7	5.3
Abduction maximum	18.6	5.9	19.5	14.9
Abduction minimum	−7.3	3.0	−8.1	8.0
External rotation maximum	5.0	10.0	4.7	6.0
External rotation minimum	−22.0	9.0	−32.3	12.2
	Normal (8 Subjects)		TKA (5 Subjects)	
Kneeling	Mean	SD	Mean	SD
Flexion maximum	141.6	8.3	140.2	11.2
Flexion minimum	0.3	3.9	5.7	6.0
Abduction maximum	18.3	5.8	25.7	11.7
Abduction minimum	−7.1	3.7	−4.7	6.3
External rotation maximum	1.7	5.6	6.6	10.8
External rotation minimum	−26.0	11.3	−33.8	13.1
	Normal (7 Subjects)		TKA (7 Subjects)	
Sitting Cross-Legged	Mean	SD	Mean	SD
Flexion maximum	131.5	8.3	136.3	17.6
Flexion minimum*	−1.2	4.2	5.8	4.1
Abduction maximum	15.8	7.6	20.7	20.8
Abduction minimum	−11.8	3.4	−14.6	15.9
External rotation maximum	4.6	6.6	7.4	13.5
External rotation minimum	−30.5	19.8	−44.3	10.5
	Normal (8 Subjects)		TKA (5 Subjects)	
Squatting	Mean	SD	Mean	SD
Flexion maximum	125.6	25.9	133.4	12.4
Flexion minimum*	0.4	2.7	7.6	6.4
Abduction maximum	19.0	4.8	19.5	17.1
Abduction minimum	−6.4	3.3	−6.8	11.0
External rotation maximum	0.7	8.0	7.7	14.7
External rotation minimum	−20.8	11.6	−27.0	14.0

Positive values indicate flexion, abduction, and external rotation, whereas negative values indicate extension, adduction, and tibial internal rotation.

*Significant difference between the normal and TKA subject groups ($P < .05$).

the cross product between the z-axis and the line joining the tibial condyles. The x-axis was again defined as the cross product between the y-axis and the z-axis. Three-dimensional knee joint angles were calculated from these segment-fixed axes as described by Hemmerich et al [2], following the joint coordinate system convention [11]. Care was taken to palpate points accurately because of the potential for kinematic cross-talk effects when defining anatomic coordinate systems via palpation of bony landmarks. Previous work that investigated the effect of kinematic cross talk has advised this as the best precaution against cross-talk error [13]. However, as with all marker systems, including those that overcome the skin movement concern, there is no way to completely eliminate the potential for this cross talk.

Mean Kinematics Curves

The data were split into 2 phases, moving into and out of the rest position with and against gravity, with the rest position data removed. The phases were normalized to a 100% phase, where the end (100%) of the first phase occurred when the subject reached the rest position after moving with the aid of gravity, and the start (0%) of the second phase occurred when the subject started to move against gravity from the rest position to return to the standing position. After determining normalized kinematic data for each trial of a given activity for a given subject, a mean curve for that subject and activity was created. One mean curve per subject was then used to create a mean curve for the whole subject group.

Comparison Between Normal and Postoperative TKA Kinematics

The maximum and minimum angles in each of the 3 anatomic planes were identified for each individual trial. The result was a 6-value summary of each trial (3 maximum values and 3 minimum values). These values were averaged to determine 6 mean values for each subject and activity. An overall set of 6 average values (and 6 corresponding SDs) for each activity was then determined. Small independent sample inference tests (*t* tests) on equivalence of means with unequal variances were used to detect differences in these values between the 2 groups [14]. A P value less than .05 was considered significant. Positive angles corresponded to flexion, abduction, and external rotation, whereas negative angles corresponded to extension, adduction, and internal rotation. Thus, a negative value representing minimum flexion also corresponded to maximum extension.

Results

The maximum angles and ranges of motion were not significantly different between the normal and TKA postoperative groups (Table 2). This finding shows that these TKA patients had the same mobility as the normal subjects, with the exception of a statistically significant difference that was found for the minimum flexion ($P < .05$) for all activities except kneeling. Therefore, based on the coordinate systems defined previously, some of the TKA patients may have had limited extension.

The mean kinematics in the 2 groups were relatively similar in both range and pattern (Figs. 2–5). During the kneeling activity, there was a phase shift between initial flexion peaks (Fig. 3). This indicates that, on average, when kneeling, the TKA patients flexed the knees later

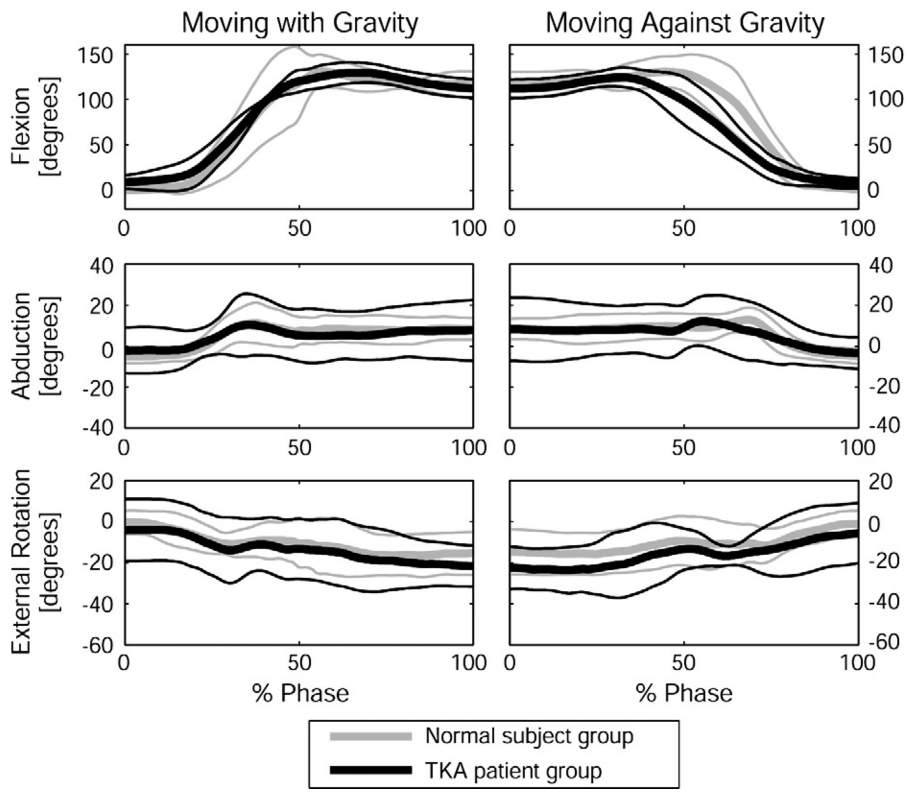

Fig. 2. Mean (±1 SD) kinematics curves for the prayer activity. Positive values represent flexion, abduction, and external rotation. The gray curve was based on 9 normal subjects, and the black curve was based on 6 TKA patients.

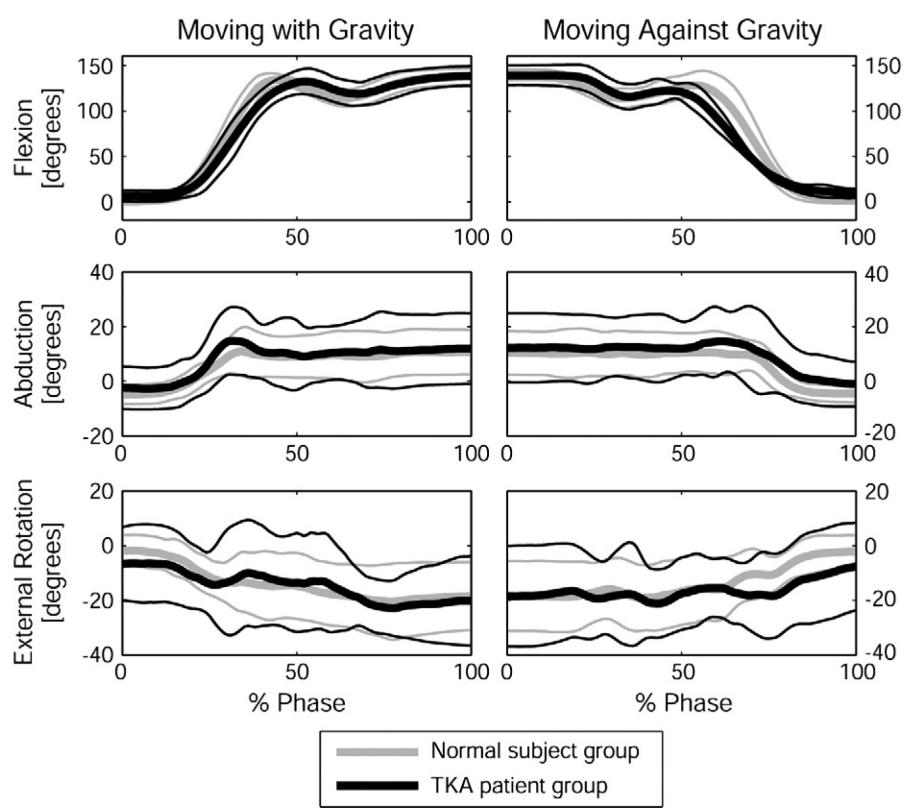

Fig. 3. Mean kinematics (±1 SD) curves for the kneeling activity. Positive values represent flexion, abduction, and external rotation. The gray curve was based on 8 normal subjects, and the black curve was based on 5 TKA patients.

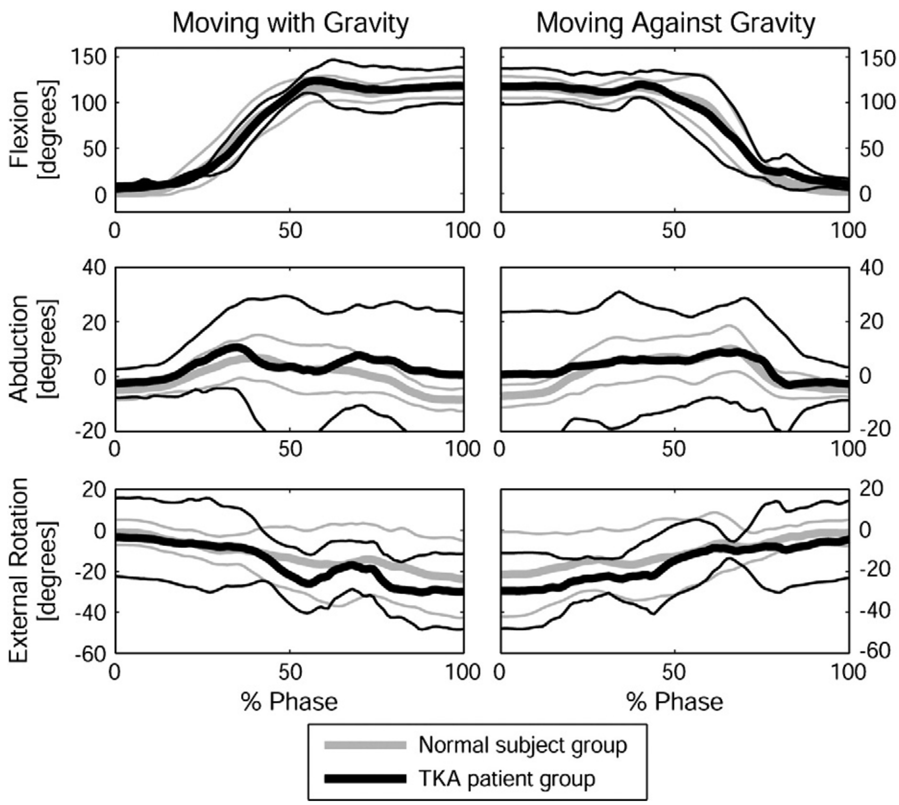

Fig. 4. Mean (±1 SD) kinematics curves for the sitting cross-legged activity. Positive values represent flexion, abduction, and external rotation. The gray and black curves were based on 7 normal subjects and 7 TKA patients, respectively.

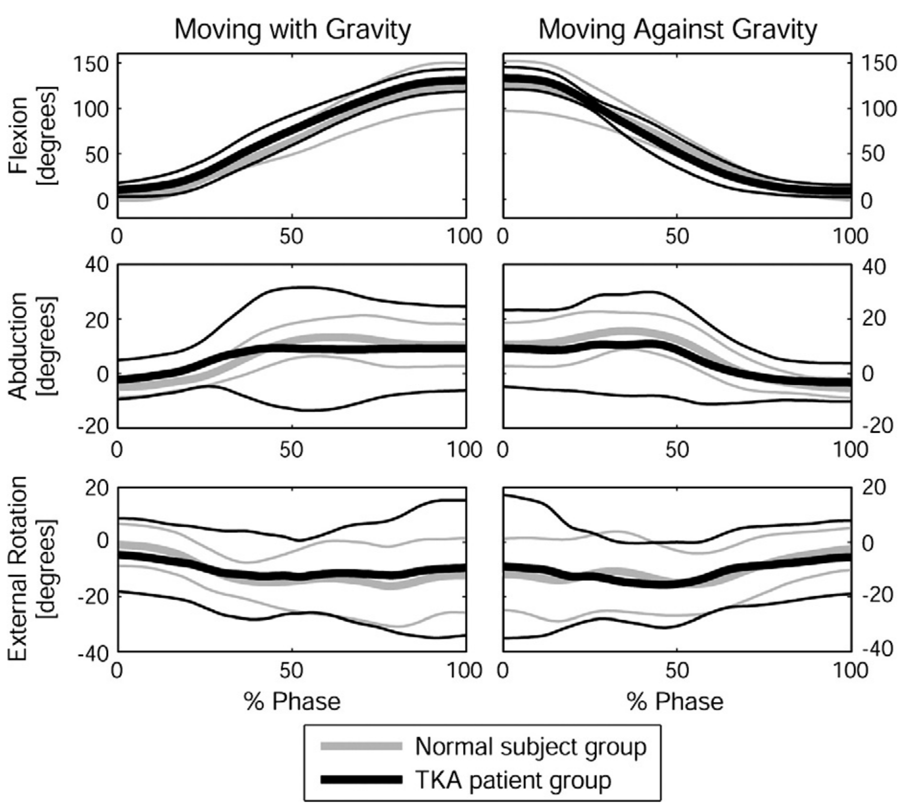

Fig. 5. Mean (±1 SD) kinematics curves for the squatting activity. Positive values represent flexion, abduction, and external rotation. The gray curve was based on 8 normal subjects, and the black curve was based on 5 TKA patients.

in the phase than the normal subjects but were able to reach similar mean maximum flexion angles. During both the prayer and kneeling activities, the TKA patients extended the knee earlier in the second phase than did the normal subjects (Figs. 2 and 3). On average, internal rotation increased slightly more for the TKA group than for the normal group at high flexion during these activities (Figs. 2 and 4). On average, the flexion angles at the start and end of all activities (represented by the minimum flexion values in Table 2) were 6.6° greater for the TKA patients than for the normal subjects, which corroborates the possibility of somewhat limited TKA extension. There were no other consistent differences between the 2 groups across all activities.

It should be noted that the maximum and minimum values in Table 2 differ from the maximum and minimum values of the mean curves in Figs. 2 through 5. This is because of the way in which the mean curves were created from individual curves. The phase percentage that corresponded to the extreme values of the individual curves varied from curve to curve. An extreme value on the mean curve is the mean of all the subject curves at that given phase percentage, which may or may not have corresponded to the individual subject extreme values. The values in Table 2 are the means of the extreme values of each individual subject curve, which did not necessarily correspond to the same phase percentage on each curve.

Discussion

The maximum flexion exhibited by a single subject was 158.9° for the normal subject group and 158.8° for the TKA subject group. Several TKA patients indicated that squatting was part of physiotherapy after TKA surgery, which may explain why 4 of the normal subjects exhibited a flexion range smaller than that of most TKA patients when squatting (Table 2, Fig. 5). Of the 11 TKA patients, 9 (82%) who were invited to participate in this study stated that they were able to perform the activities. No significant difference was found for most maximum and minimum angles between the normal and TKA postoperative groups (Table 2). These similar ranges of motion (maximum or minimum values) could indicate that these patients were performing the activities through similar kinematic mechanisms as the normal subjects.

The preoperative range of motion has been indicated as the single most important factor in determining postoperative range of motion [15]. The results of this study agree with that observation because these patients also had a high range of motion before surgery (average preoperative range of flexion, 135°). The average increase in range of flexion was 13.8°. This increase is most likely because of a combination of surgical technique, implant design, aggressive physiotherapy, and patient commitment to rehabilitation because high flexion is such an essential requirement of daily living. These factors were not individually assessed in this study.

The average passive postoperative range of flexion was 148.8°. The TKA group appeared to have limited postoperative extension, which may indicate a residual flexion contracture, or the quadriceps release procedure may be the cause of this active extension lag. It may also simply be indicative of the short postoperative times for some of the patients, and the extension range of motion may improve over time. It was not expected that all patients had reached a full recovery. This was not intended to be a follow-up study but a study that would characterize the knee kinematics of patients who have returned to performing these required activities relatively quickly after receiving a high-flexion TKA. It is possible that some smaller differences in angles or ranges of motion were not detected because of the small sample size and large SDs.

In this study, the average maximum tibial internal rotation with respect to the femur for normal subjects during kneeling was 26.0° ± 11.3°. Using radiographs during weight-bearing knee flexion up to 120° for 6 normal, healthy Japanese males, Asano et al [16] found that the tibia was externally rotated to 4.2° on average at hyperextension (relative to the femoral position at 0° flexion) and internally rotated to a maximum of 24.9° at 105° flexion. A fluoroscopic analysis of deep knee bends by Dennis et al [8] of 20 healthy, normal knees found that the average range of axial rotation for the 10 subjects from 0° to 120° flexion was 23.67° ± 9.56°. Following the same protocol as was used in this study, the average tibial rotation of 26 healthy, normal Indian subjects during kneeling with ankles plantar-flexed ranged from 12.4° ± 6.0° external rotation to 19.7° ± 15.3° internal rotation [2]. The average range of tibial rotation found in this study agrees well with this previously published data. However, these results do not agree with those presented by Kanekasu et al [7] nor with those presented by Argenson et al [17]. From fluoroscopic analysis, Kanekasu et al reported only 9° of tibial internal rotation on average at 160° flexion, whereas Argenson et al reported an average of only 4.9° internal rotation at an average of 125° flexion. These discrepancies may be attributed to cultural and lifestyle differences between the subject groups, as well as differences in the manner of performing the various activities.

Although the mean curves (Figs. 2-5, thick lines) are within reasonable ranges, the ranges of nonsagittal rotations found in this study were large for some subjects, indicated by the wide SDs (Figs. 2-5, thin lines.) There are several potential contributors to these large ranges of motion, as follows:

1. Actual kinematic mechanisms (lift-off, distraction) that allow for a larger range of motion

2. Patient/surgery factors (implantation angle, some short postoperative times) that increase variation in kinematics for the TKA group
3. Experimental errors (kinematic cross-talk, soft tissue artifact) that result in the range of motion appearing larger than what is actually exhibited

Lift-off between the implant components would be represented in the tracking data as a change in abduction angle and may explain the large ranges of motion in the frontal plane. Uncalibrated fluoroscopic images in a static, high-flexion pose were available for only one of the patients in the study. These images confirm lift-off for 1 of the TKA patients. Although there is no previous literature to provide a fair comparison for abduction angles, the internal rotation values determined for these high-flexion activities agree well with some previous radiographic and fluoroscopic analyses of high-flexion activities [8,16], as discussed previously.

Despite this agreement with some previous literature, the range of internal rotation found for TKA patients was higher than what would be allowed by the implant design because of rotational stops on the tibial tray that limit the range of axial rotation of the tibial insert on the tibial tray. At higher flexion angles, soft tissue is tightly interposed between the thigh and shank segments, which may have caused the joint to distract. This subluxation may allow additional rotation beyond the stops and may contribute to the large range of internal rotation during kneeling: 26.0° ± 11.3° for normal subjects and 33.8° ± 13.1° for TKA patients. Because of the noninvasive nature of the study, it is not possible to confirm joint distraction for these subjects.

The large SDs for TKA patients (Figs. 2-5, black lines) may also reflect the variation on how TKA patients approach the activities and may be because of short postoperative recovery times for some subjects. The large variation may also be partly because of variations in implantation angle, creating an offset in the data for some patients.

As with all approaches that are based on the identification of bony landmarks, there was also potential for kinematic cross talk, which occurs when the defined axes do not align with the true anatomic axes of the joint. The result is that motion about 1 axis is erroneously represented as motion about another axis and could have been a source of erroneous nonsagittal motion. To investigate the contribution of coordinate system misalignment to nonsagittal errors, coordinate systems were perturbed in the frontal plane, with the goal of minimizing the range of motion in abduction for the 4 activities for each subject. This approach was not successful in significantly reducing range of abduction, which rules out a significant cross-talk contribution.

The nonsagittal angles reported in this study could also be affected by skin and soft tissue motion relative to the underlying bones. Although radiographic methods would have overcome the soft tissue artifact concern, they would have also limited the subject's natural movement and range of motion when performing the high-flexion activities in this study. It is not possible to quantify the soft tissue artifact for these subjects. Thigh-calf contact occurs during high flexion, increasing soft tissue distortion, and thus increasing uncertainty in the nonsagittal angles as flexion increases. The onset of thigh-calf contact was not monitored in this study and would depend on the thickness of the subject's limb [18]. In one kneeling study from Nagura et al [18], thigh-calf contact was reported to occur beyond 140° flexion. Because the subjects in the current study were, on average, heavier than the subjects of Nagura et al (mean, 69 kg vs 90.0 kg and 76.7 kg for the 2 subject groups in this study), it is possible that the flexion angle at thigh-calf contact onset was less than 140° for some subjects.

Using an electromagnetic tracking system, the kinematics for high range of motion activities of daily living were characterized for 10 normal, healthy Muslim males and compared with 9 male, Muslim high-flexion TKA patients who were able to perform the following required activities: kneeling, Muslim prayer, sitting cross-legged, and squatting. A comparison of the 2 groups showed that for 3 of the 4 activities, a statistically significant difference was found in the minimum flexion (maximum extension) angle achieved during the activities. This may be because of short postoperative times for the TKA patients, residual flexion contracture, or the quadriceps release procedure during surgery. No statistically significant difference was found in the maximum joint angles between the 2 groups, although for some patients, surgery was as recent as 3 months before the study. Thus, the TKA patients exhibited a normal range of motion for high-flexion activities of daily living. The range of internal rotation found in this study agrees well with studies by Dennis et al [8] and Asano et al [16] using radiography and fluoroscopy.

Acknowledgments

The authors are very grateful for the help of Maria Chouraichy, Administrative Secretary to the Director of Joint Replacement, Center of Excellence, American Hospital Dubai, and for the kind cooperation of all our subjects. The authors would also like to acknowledge Onno Oosten for his design and construction assistance and Kevin Deluzio for sharing his kinematic data collection and processing knowledge.

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