ESTIMATION OF MECHANICAL AXIS FROM TIBIOFEMORAL

ALIGNMENT MEASUREMENTS ON SHORT RADIOGRAPHS

FOR TOTAL KNEE ARTHROPLASTY

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAI‘I AT MĀNOA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

EDUCATION

MAY 2011

By

Jennifer J. Wages

Dissertation Committee:

Iris Kimura, Chairperson
Ronald Hetzler
Christopher Stickley
Shuqiang Zhang
Cass Nakasone

ACKNOWLEDGEMENTS

Clint: I dedicate this dissertation to you because none of this would have been possible without you. You kept me going when I felt like I couldn't continue, you celebrated each achievement with me no matter how small, and you made every moment of our time in Hawai'i together special. I love you and here's to our beautiful beginning in Hawai'i!

Mom and Dad: You have not once ever held me back from wanting to do anything nor objected to any aspiration I have had no matter how far it led me from home. But no matter what I always wanted to come home. Thank you for your unconditional love, belief in me, and for giving me a "house that built me."

Meghan and Jill: When I was little I prayed that God would send me little sisters that I could grow up with…all I can say is that the two of you are living proof that dreams do come true.

Terry and Jim: Thank you for everything that you have done for me and for welcoming me into your family from the very beginning when I first met Clint. From road trips to Liberal to the house in Kailua I have had a lot of fun experiences with you and look forward to finally coming home for many more!

Dr. Kimura: Thank you for the opportunity to come here, for believing in me, and for not giving up on me. Thank you for literally sitting next to me when it counted the most, and most of all thank you for expecting nothing less than the very best out of me. I truly feel I will leave here a stronger and better person for all that I have learned from you.

Dr. Hetzler: Thank you for your kindness and your patience. I have really enjoyed writing with you on Friday mornings and as a result now love regression.

Dr. Stickley: I tip my hat to you for the example you set as a PhD student. You are definitely the smartest person I know and if I have lived up to just one of your expectations, I consider this experience a success.

Dr. Zhang: I remember first meeting you at Dr. Stickley's proposal and thinking how awesome it would be if you could be on my committee. I am so honored for so much more than that to have had you be a part of my education and to have known you. Thank you for always pushing me to go beyond the requirement to try to be extraordinary.

Dr. Cleary: You were there in the beginning when my learning curve was the steepest, and I know you have always been there if I ever needed anything the rest of the way through. Thank you for your support.

Dr. Nakasone: You are the most caring, generous, and professional mentor I have ever had. I am so lucky and so grateful to have had the opportunity to work with you over the past four years. You make everything seem so effortless and that anything is possible. Thank you for everything!

Mary and Pam: I cherish this experience and Hawai'i because of the two of you. Thank you for taking care of me and letting me into your lives. You are my family here and I love you both.

Kate: Thank you for always being there. You have been my voice of reason, allowed me to confide in you, and never hesitated to help me when I was stuck. I cherish our friendship and miss you already.

Rachele, Kaori, and Rachel: I am so grateful for our comradary that grew over the years. One of my favorite things about this program was going through some of our greatest challenges of comps and proposals. I learned a lot from each of you about what it takes to make it through this program. Thank you.

Mel, Dax, Brett, and Yukiya: If I can do this, than you all can definitely do this. I have enjoyed getting to know you and really admire each of you.

All of the students in the Post-Professional Athletic Training Masters Program: All of you have helped me more than you know during this process. Thank you for all of your help, hard work and many laughs.

ABSTRACT

Background: The purpose of this study was to develop predictive models to estimate post-operative mechanical axis as measured on long radiographs using anatomic and component alignment measured on short radiographs.

Methods: We retrospectively studied 653 participants (788 knees) who elected to undergo total knee arthroplasty (TKA) between September 2005 and December 2010. Multiple linear regression was conducted to predict post-operative mechanical axis (POSTMA) from pre-operative tibiofemoral angle (PRETFA), post-operative tibiofemoral angle (POSTTFA), and component alignment angles. Multinomial logistic regression was used to predict the risk of lower extremity alignment deformity from POSTTFA and component alignment angles.

Results: The predictive accuracy of the linear regression models to estimate POSTMA from PRETFA and POSTTFA was 4% and 22%, respectively. Nearly 100% of the knees with actual neutral POSTMA of 0º ± 3º were accurately predicted to have a POSTMA of 0º ± 3º. There were zero knees with actual varus or valgus alignment over 3º that were accurately predicted to have a POSTMA over 3º of varus or valgus. Logistic regression analyses revealed the risk of having POSTMA deformity was significantly effected ($p < 0.0001$) by POSTTFA. The model indicated that for every 1º increase in valgus POSTTFA, the odds of predicting any degree of varus POSTMA decreased by 0.29 times, and the odds of predicting any degree of valgus POSTMA increased by 1.36 times. The model indicated that for every 1º increase in valgus POSTTFA, the odds of predicting a varus POSTMA > 3º decreased by 0.41 times and the odds of predicting a valgus POSTMA > 3º increased by 1.63 times. The percentages of knees correctly predicted into deformity category was high for neutral POSTMA but not for predicting the risk of varus or valgus deformity.

Conclusions: The linear and logistic regression models were not adequate to estimate POSTMA using either PRETFA or POSTTFA. We do not recommend the use of short radiographs as a substitute for long radiographs when evaluating lower extremity alignment to determine component position before TKA and for assessment of post-operative alignment outcomes following TKA.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PART I

INTRODUCTION

Osteoarthritis (OA) is a degenerative disease involving progressive deterioration of the joint structures, initially marked by swelling of the articular cartilage and sclerosis of the underlying bone[1]. As OA progresses, an array of changes occurs including the development of osteophytes[2], bone attrition, ligament damage, meniscal degeneration[3], and a reduction in articular cartilage volume over time[4]. At the end-stages of OA, erosions of the articular cartilage extend to subchondral bone leaving the joint surfaces unprotected resulting in severe pain, stiffness and disability[1].

The prevalence of OA is the highest among all forms of arthritis[1,5] affecting approximately 27 million adults in the United States[6], and most commonly occurs in the knee joint[7]. While the cause of OA in the knee is unclear, malalignment of the lower extremity has been identified as a risk factor for the development and progression of the disease[8,9]. Greater varus or valgus alignment has been associated with osteoarthritic structural changes in the medial or lateral compartments of the knee respectively[2-4,10]. Varus malalignment has been identified as the single most influential factor for increased pain and functional decline in advanced OA of the knee[11]. Malalignment has been associated with an increased contact area between degraded femoral and tibial joint surfaces augmenting the severity of symptoms[12]. A primary objective of surgical interventions for OA are to realign the knee with the hip and ankle joints to alleviate symptoms and restore function[12].

Total knee arthroplasty (TKA) is a common surgical option for treatment of end-stage OA in the knee joint through resurfacing degenerated bone with implanted femoral and tibial components. A seven fold increase in the rate of TKA surgeries has been observed since the inception of the procedure in the early 1970's[13]. The estimated annual number of TKA procedures has increased from 143,000 in 1986[14] to 662,700 in 2007[13]. The annual prevalence of TKA is projected to rise to 3.48 million procedures accompanied by a concomitant increase in revision surgeries due to TKA failure by the year 2030[15].

Total knee arthroplasty failure imposes devastating consequences for patients including severe disability[16], pain and emotional distress[17]. Post-operative lower extremity malalignment has been significantly associated with TKA failure[18-20] along with poorer clinical outcomes including greater knee pain and decreased functional ability[21-24]. Polyethylene wear has been identified as the most common indication for revision TKA, followed by aseptic loosening of the components[17]. Varus malalignment of the lower extremity has been significantly associated with loss of polyethylene thickness in the medial compartment of TKA[25]. Post-operative malalignment of the knee was significantly related to subsequent component loosening[26]. Therefore, an important goal of TKA has been to correct lower extremity malalignment through accurate component placement[21,27-29].

Lower extremity alignment and post-operative component position are routinely assessed from radiographs in the anteroposterior (AP) view[30]. The gold standard measurement of lower extremity alignment is considered to be the angle between the mechanical axes of the femur and tibia[31-35]. Theoretically, alignment of the center of the knee with the centers of the hip and ankle joints produces an overall mechanical axis of 0° passing through the center of the knee[36]. Neutral alignment of the knee has been defined as an overall mechanical axis of 0°[37], while a more widely accepted mechanical axis guideline is that the axis pass through the central third of the knee[26].

Assessment of mechanical axis from long radiographs has been recommended to achieve accurate alignment measurements with the ability to view lower extremity deformities[26]. However, the efficacy of this method for post-operative evaluation following TKA is controversial. Long radiographs are not standard care or available in many clinics while short radiographs provide an inexpensive tool to quickly assess TKA[35] alignment. The use of long radiographs for measurement of lower extremity alignment has been criticized for increased administration of radiation to the patient and increased technical difficulty in acquiring accurate images due to the soft tissue differences at the hip and ankle[34]. Due to the potential increased health risks to patients, limited availability and cumbersome method of obtaining long radiographs, alternative methods for the assessment of lower extremity alignment have been developed[34,35,38].

Tibiofemoral angle has commonly been used as an alternative to the mechanical axis for measurement of lower extremity alignment and has widely been reported to be associated with TKA failure when malaligned in varus or valgus deformity[20,21,39,40]. Tibiofemoral angle has been measured as the angle between the midline (anatomic) axes of the femur and tibia[21,22,39,41,42]. The femoral and tibial anatomic axes calculations do not require hip or ankle joint center locations. Therefore, tibiofemoral angle can be obtained from both long and short radiographs. A mean difference ranging from 1.4° to 1.9° was reported in earlier investigations between the mean post-operative tibiofemoral angle measured on short and long radiographs following TKA[41,43,44]. Tibiofemoral angle obtained from short radiographs has recently been reported be reliable with high intra- (r

= 0.92) and inter-observer (r = 0.81) correlation coefficients[45].

Linear regression models have been developed to estimate overall mechanical axis from tibiofemoral angle with a wide range of predictive accuracy (R^2 = 0.21 – 0.78)[34,35,38,46]. Tibiofemoral angle measured on long radiographs of osteoarthritic knees has been reported to account for approximately 42%[34] and 77%[35] of the variance in mechanical axis. Chang et al.[38] conducted the only investigation to estimate mechanical axis from tibiofemoral angle measured on short radiographs in a sample of participants with TKA. Results of their investigation indicated increasing the distance on the femoral and tibial bone shafts to locate the distal points of the anatomic axes improved estimates of mechanical axis as much as 18%[38]. Tibiofemoral angle was the only predictor variable considered in the development of these regression models[34,35,38]. Post-operative lower extremity alignment following TKA has been widely reported to be dependent on femoral and tibial component position[27]. However, estimation of post-operative lower extremity alignment from femoral and tibial component position, using post-operative mechanical axis as a criterion measure, has not been investigated in a sample of TKA participants.

To our knowledge only three linear regression models[35,38,46] are available for use with short radiographs. Regression models with greater predictive accuracy would provide clinicians with a practical and efficacious alternative to determine mechanical axis, without sacrificing the ability to detect risk factors for post-operative TKA failure. Therefore, the purpose of this study was to develop predictive models to estimate post-operative mechanical axis as measured on long radiographs using anatomic and component alignment measured on short radiographs.

Research Hypotheses:

1. Pre-operative tibiofemoral alignment measured from separate short radiographs will be significantly associated with post-operative mechanical axis in participants with TKA.
2. Post-operative tibiofemoral alignment measured from separate short radiographs will be significantly associated with post-operative mechanical axis in participants with TKA.
3. Femoral and tibial component alignment measured from separate short radiographs will be significantly associated with post-operative mechanical axis in participants with TKA.
4. Post-operative tibiofemoral alignment measured from separate short radiographs will be significantly associated with the risk of any degree of post-operative varus or valgus deformity relative to neutral in participants with TKA.
5. Post-operative tibiofemoral alignment measured from separate short radiographs will be significantly associated with the risk of varus or valgus post-operative deformity greater than 3º relative to neutral in participants with TKA.

METHOD

Research Design

A retrospective radiographic review was conducted to determine if a greater proportion of the variability in estimated mechanical axis could be accounted for with the inclusion of component alignment angles. The dependent variable was mechanical axis measured as a continuous variable on long radiographs. Mechanical axis was also converted into alignment ranges (varus, neutral, and valgus) to assess the risk of post-operative malalignment due to TKA approach and component position. The independent variables included surgical group (standard and minimally invasive approaches: midvastus, and subvastus) along with tibiofemoral, femoral component, and tibial component angles measured as continuous variables on short radiographs.

Participants

This study included a total of 788 surgeries in 653 participants (372 females and 281 males) who elected to undergo TKA through either the standard or minimally invasive surgical (MIS) approaches between September 2005 and December 2010. The same Board Certified orthopedic surgeon who was fellowship trained in MIS TKA surgeries performed all procedures. Standard TKA was performed through a medial parapatellar approach and MIS TKA was performed through either the midvastus or subvastus approaches. Inclusionary criteria for all participants were: 1) diagnosis of OA, 2) no history of previous lower extremity fracture, osteotomy, or joint replacement[38] 3) no knee flexion contracture greater than 15^{o}[47], and 4) records of pre- and post-operative radiographs permitting visualization of all structures necessary for alignment measurements[38]. This study was approved by the Institutional Review Board's

Committee for Human Studies.

Instruments

Computed Radiography (CR). Digital imaging of the lower extremities on radiographs was conducted using a CR system (FCR XG5000, CR-IR 362, Fujifilm Medical Systems U.S.A., Inc., Stamford, CT). Digital radiographs including the hip and ankle joints were recorded in the AP view using a 35.4 × 124.5 cm cassette (Type LC) loaded with three 35.56 × 43.18 cm photostimulable storage phosphor image plates (Type ST-VI). Each image plate contained barium fluorohalide (BaFX) phosphors in a high-density a matrix of 3520 × 4280 pixels with a spatial resolution of 10 pixels·mm^{-1}. Short digital radiographs of the knee in the AP view were obtained using the same CR system with one 35.56 × 43.18 cm image plate. All images were obtained at source to image distance of 90 cm to standardize magnification with a setting of ~80-100 mA·sec^{-1} and 80 kV[9,48], and with an optimum sensitivity parameter of 200 – 600 nm[49]. Participants were instructed to stand, evenly distributing weight bilaterally with both knees fully extended[26,36,37,50] and both feet slightly adducted to ensure forward placement of all anatomic landmarks. All digital radiographs were processed and archived using Picture Archiving and Communication Systems (PACS) software (Synapse® v. 3.1.1., Fujifilm Medical Systems U.S.A., Inc., Stamford, CT). The minimum detectable change in alignment angles was 1º. All lower extremity alignment and TKA component angles were measured digitally using a multimodality workstation (Intel® Pentium® 4, Santa Clara, CA) equipped with a 38.1 cm flat panel monitor with a resolution of 1024 × 768 pixels (Compaq 5017, Houston, TX). All alignment measurement data were collected by the same National Athletic Trainers' Association Board of Certification Certified Athletic Trainer with high average intraobserver reliability (ICC = 0.95) (table 1).

Intraobserver Reliability. Intraclass correlation coefficients ($ICC_{2,1}$)[51] and the standard error of the mean (SEM)[52] were calculated to examine the intraobserver reliability of all alignment angles measured twice, separated by two weeks, by the aforementioned independent observer on a sub-sample of 30 randomly selected radiographs (table 1).

Table 1. Reliability ($ICC_{2,1}$) for Alignment Angles on Long and Short Radiographs

Alignment Angle	**Long Radiographs**		**Short Radiographs**	
	ICC Time 1-Time 2	SEM Time 1-Time 2	ICC Time 1-Time 2	SEM Time 1-Time 2
Mechanical Axis (º)	0.987	0.256	~	~
Tibiofemoral (º)	0.983	0.344	0.958	0.477
Femoral Component (º)	0.949	0.426	0.950	0.527
Tibial Component (º)	0.925	0.356	0.921	0.354

Procedures

Medical Record Review. Demographic characteristics, anthropometric measurements, and intraoperative variables were obtained via review of electronic and paper-based medical records. An electronic medical record review was conducted to obtain the following clinical outcome data: history of TKA surgery and other lower extremity surgeries; age, height, body mass, and body mass index at the date of TKA surgery; pre-operative diagnosis; hospital length of stay; discharge disposition; anesthesia physical status and analgesic medications used prior to and following surgery; arthrotomy type; component characteristics; tourniquet time; anesthesia type; radiographic lower extremity alignment; pre- and post-operative Knee Society Scores[53] (Appendix A); predischarge blood transfusions, hematocrit and hemoglobin levels; perioperative physical therapy outcomes; and the incidence(s) of any post-operative complications.

All pre-operative radiographs were obtained within two weeks prior to TKA surgery and post-operative radiographs were obtained at the participant's regularly scheduled six week follow-up appointment. The following lower extremity and component alignment angles were measured using PACS software.

Long Mechanical Axis. Digital measurement of mechanical axis was performed using the technique described by Sailer et al.[54]. The mechanical axis was measured on long radiographs in the AP view between the mechanical axes of the femur and tibia[9,31,36,38]. The mechanical axis of the femur was measured as a line between the centers of the femoral head and intercondylar notch[36]. The mechanical axis of the tibia was measured from the center of the tips of the tibial spines to the center of the talus[36]. The center of the femoral head was identified by locating the center of a close-fit circle generated at the edge of the femoral head using the elliptical function of the PACS software[32,55]. A mechanical axis greater than 0° was defined as valgus and expressed as a positive value. A mechanical axis less than 0° was defined as varus and expressed as a negative value.

Tibiofemoral Angle. Digital measurement of tibiofemoral angle was performed using the same anatomical landmarks as Peterson and Engh[43]. Tibiofemoral angle was defined as the angle between the anatomic axes of the femur and tibia[22]. The femoral anatomic axis on long radiographs was defined as a line extending through the middle cortex of the femur from a point at the height of the lesser trochanter to a point approximately 10 cm above the intercondyar notch[43]. Falling in line with the mechanical axis, the tibial anatomic axis on long radiographs was defined as a line extending from the tips of the tibial spines to the center of the talus[32]. Femoral and tibial anatomic axes on short radiographs were located between the same proximal points from the knee joint line to far distal points as allowed on the radiographs in the middle cortex of the femur and tibia respectively[43]. A post-operative tibiofemoral angle of 6º, ranging from 3º to 9º valgus was considered to be acceptable for this investigation. Ranges of 2° to 12°[39], 4° to 10°[27], 5° to 7°[45], and 3° to 7° valgus[21] for the tibiofemoral angle have also been considered acceptable to restore limb alignment through TKA.

Component Alignment. Alignment of the femoral component was measured in the AP view as the medial angle between the anatomic axis of the femur and a horizontal axis tangent to the femoral condyles[27]. The femoral component angle was recorded as a deviation from 90º, with a position of 6º, ranging from 3º to 9º of valgus considered to be acceptable for this investigation. A range of 4º to 7º valgus for femoral component position has been previously recommended[21,56]. Alignment of the tibial component was measured in the AP view as the medial angle between the anatomic axis of the tibia and horizontal axis tangent to the tibial tray[27]. The tibial component angle was recorded as a deviation from 90º, and a perpendicular position to the anatomic axis of the tibia was considered to be acceptable for this investigation[21,39,41]. A tibial component angle greater than 0º was defined as valgus and expressed as a positive value. A tibial component angle less than 0º was defined as varus and expressed as a negative value.

Statistical Analyses

Descriptive statistics including means, standard deviations, and 95% confidence intervals were generated for all demographic characteristics and variables of interest.

Multiple linear regression using a hierarchical approach was conducted to predict post-operative mechanical axis from tibiofemoral and component alignment angles. Pearson product moment correlation coefficients were used to determine the relationship of selected alignment variables with post-operative mechanical axis. Constant error (CE) was calculated as: actual – predicted post-operative mechanical axis. Standard error of estimate (SEE) was calculated as:

$$\text{SEE} = \sqrt{\sum (predicted - actual)^2 / N}$$

The Kolmogorov-Smirnov test was used to test homogeneity of the residuals obtained using the regression model. Multinomial logistic regression was used to predict the alignment range (varus, neutral, and valgus) from tibiofemoral, femoral component, and tibial component angle, along with surgical group (standard, midvastus, and subvastus). A categorical variable for surgical group was created using dummy coding assigning participants with the standard TKA approach to the control group. All statistical analyses were conducted using Statistical Analysis Software (SAS) v9.1 (SAS Institute Inc., Cary, NC) with an alpha level of $p < 0.05$.

RESULTS

Descriptive data for the participants is presented in table 2. Pre- and post-operative alignment data by gender are presented in tables 3 and 4, respectively. The mean pre-operative mechanical axes were -6.2º ± 7.4º and -4.5º ± 7.9º for males and females, respectively. The mean post-operative mechanical axes were -0.1º ± 2.3º and 0.0º ± 2.3º for males and females, respectively.

Table 2. Means and standard deviations for descriptive data for all TKA participants

	Females			**Males**		
N	372			281		
Age (years)	70.3	±	9.4	69.0	±	9.2
Height (cm)	157.0	±	8.1	173.0	±	8.8
Body Mass (kg)	73.5	±	17.2	90.8	±	18.4
BMI	29.7	±	6.0	30.2	±	5.3
Length of Stay*	3.1	±	1.4	2.6	±	1.3

*Length of stay: calculated for 365 females and 277 males; participants excluded for extended hospital stays unrelated to TKA

Multiple Linear Regression

The best fitting prediction equations to estimate post-operative mechanical axis (POSTMA) using alignment angles measured on short radiographs are presented in table 5. Multiple linear regression using a hierarchical approach for all participants indicated POSTMA was significantly [$F_{(1,786)} = 34.86$, $p < 0.0001$] effected by pre-operative tibiofemoral angle measured on short radiographs (PRETFA). Equation 1 predicted POSTMA using PRETFA with an $R^2 = 0.04$ ($p < 0.001$) and was found to have a small correlation ($r = 0.21$) with the measured POSTMA.

Table 3. Means, standard deviations, and 95% confidence intervals (CI) by gender for pre-operative mechanical axis, tibiofemoral angle, femoral angle, and tibial angle

	Female						Male					
N	446 knees						342 knees					
	Mean	**±**	**SD**	**95% CI**			**Mean**	**±**	**SD**	**95% CI**		
Pre-operative												
Mechanical Axis (º)	-4.5	±	7.9	-5.3	-	-3.8	-6.2	±	7.4	-7.0	-	-5.5
Tibiofemoral Angle Long (º)	1.7	±	7.9	0.9	-	2.4	0.2	±	7.2	-0.5	-	1.0
Tibiofemoral Angle Short (º)	1.6	±	6.8	1.0	-	2.3	0.3	±	6.5	-0.4	-	1.0
Femoral Angle (º)	9.2	±	2.7	8.9	-	9.4	8.1	±	2.6	7.8	-	8.4
Tibial Angle (º)	-3.8	±	2.6	-4.0	-	-3.5	-4.1	±	2.4	-4.4	-	-3.9

Table 4. Means, standard deviations, and 95% confidence intervals (CI) by gender for post-operative mechanical axis, tibiofemoral angle, femoral component angle, and tibial component angle measured on long and short radiographs

	Female						Male					
N	446 knees						342 knees					
	Long			**Short**			**Long**			**Short**		
Mechanical Axis (º)	0.0	±	2.3		~		-0.1	±	2.3		~	
95% CI	(-0.2	-	0.3)				(-0.4	-	0.1)			
Tibiofemoral (º)	6.3	±	2.3	6.2	±	2.1	6.2	±	2.4	5.9	±	2.0
95% CI	(6.1	-	6.5)	(6.0	-	6.4)	(5.9	-	6.4)	(5.6	-	6.1)
Femoral Component (º)	6.1	±	1.8	6.4	±	1.9	6.0	±	2.0	6.1	±	1.8
95% CI	(5.9	-	6.3)	(6.2	-	6.5)	(5.8	-	6.2)	(5.9	-	6.3)
Tibial Component (º)	0.4	±	1.5	0.0	±	1.2	0.4	±	1.3	-0.1	±	1.1
95% CI	(0.2	-	0.5)	(-0.2	-	0.1)	(0.2	-	0.5)	(-0.2	-	0.1)

Considering post-operative alignment measured on short radiographs, POSTMA was significantly [$F_{(4,783)} = 63.08$, $p < 0.0001$] effected by gender, height (cm), femoral component angle (POSTFCA), and tibiofemoral angle (POSTTFA). Approximately 24% of the variance in POSTMA was attributed to the predictor variables. Pearson correlation coefficients were used to investigate the relationships between individual predictor variables and POSTMA (table 6).

Table 5. Equations and coefficients of determination (R^2) to estimate post-operative mechanical axis for all participants and by gender

	Equation	R^2
All Participants (N = 788 knees)		
Equation 1	-0.11 + 0.07 PRETFA (º)	0.04*
Equation 2	-3.15 + 0.51 POSTTFA (º)	0.22*
Females (N = 446 knees)		
Equation 3	-0.05 + 0.05 PRETFA (º)	0.03†
Equation 4	-3.07 + 0.50 POSTTFA (º)	0.22*
Males (N = 342 knees)		
Equation 5	-0.17 + 0.09 PRETFA (º)	0.07*
Equation 6	-3.27 + 0.53 POSTTFA (º)	0.22*

PRETFA: pre-operative tibiofemoral angle measured from short radiographs, POSTTFA: post-operative tibiofemoral angle measured from short radiographs

*p < 0.0001, †p < 0.0005

Table 6. Zero-order correlations between all predictor variables and post-operative mechanical axis (N = 788 knees)

Variable	POSTMA	Gender	Height	PRETFA	POSTFCA	POSTTFA
POSTMA	1.00	-0.04	0.02	0.21*	0.28*	0.47*
Gender		1.00	0.69*	-0.10†	-0.07†	-0.09†
Height			1.00	-0.01	-0.11†	-0.16*
PRETFA				1.00	0.07	0.07
POSTFCA					1.00	0.73*
POSTTFA						1.00

POSTMA: post-operative mechanical axis, PRETFA: pre-operative tibiofemoral angle measured from short radiographs, POSTFCA: post-operative femoral component angle measured from short radiographs, POSTTFA: post-operative tibiofemoral angle measured from short radiographs

*p < 0.0001, †p < 0.05

The high correlation between gender and height ($r = 0.69$, $p < 0.001$), and between POSTFCA and POSTTFA ($r = 0.73$, $p < 0.0001$) indicated the presence of multicollinearity in the full regression model. The unique effects of height and POSTFCA accounted for approximately 1.7% and 1% of the variance, respectively in POSTMA. Approximately 16% of the variance in POSTMA was attributed to the unique effect of POSTTFA. Therefore, height and POSTFCA were removed from the model. The reduced model indicated POSTMA was significantly [$F_{(1,786)} = 217.39$, $p < 0.0001$] effected by POSTTFA.

Equation 2 predicted POSTMA using POSTTFA with an $R^2 = 0.22$ ($p < 0.001$) and was found to have a moderate correlation ($r = 0.46$) with the measured POSTMA. Separate regression models were generated for females (Equations 3 and 4) and males (Equations 5 and 6). The gender specific analyses produced similar equations and coefficients of determination to the equations generated for all participants.

Table 7 presents the mean and standard deviation values for the predicted POSTMA, constant error, absolute error, standard error of estimate, and correlation coefficients for each of the prediction equations. Results of the Kolmogorov-Smirnov test indicated that the residuals obtained using Equation 1 ($D = 0.12$, $p < 0.01$) and 2 ($D = 0.10$, $p < 0.01$) for all participants were not normally distributed. The Kolmogorov-Smirnov test also indicated that the residuals obtained using the separate equations for males and females were not normally distributed (D ranging from 0.10 - 0.15, $p < 0.01$).

Table 7. Means and standard deviations for the predicted post-operative mechanical axis, constant error, standard error of the estimate (SEE), and correlation coefficients

	Predicted Mean	**Constant Error**	**Absolute Error**	**SEE**	***r***
All Participants (N = 788 knees)					
Equation 1	-0.04 ± 0.47	0.00 ± 2.23	1.58 ± 1.57	2.23	0.21
Equation 2	-0.04 ± 1.06	0.00 ± 2.02	1.48 ± 1.37	2.02	0.46
Females (N = 446 knees)					
Equation 3	0.04 ± 0.36	0.00 ± 2.25	1.59 ± 1.59	2.25	0.16
Equation 4	0.04 ± 1.06	0.00 ± 2.02	1.50 ± 1.35	2.02	0.46
Males (N = 342 knees)					
Equation 5	-0.14 ± 0.61	0.00 ± 2.19	1.57 ± 1.53	2.20	0.27
Equation 6	-0.14 ± 1.06	0.00 ± 2.01	1.45 ± 1.40	2.02	0.47

Multinomial Logistic Regression

Multinomial logistic regression analyses produced four separate models that each included one variable. The regression coefficients for each significant logistic model are presented in table 8. In models one and two, the outcome variable of POSTMA contained three categories based on the mechanical axis as any degree of varus (n = 252), any degree of valgus (n = 215), or neutral (0º) (n = 321). Reduced models with the single main effect of POSTTFA were found to explain POSTMA as adequately as a full model which included interactions between surgical approach (midvastus, subvastus, or standard) and POSTTFA (χ^2 difference = 2.48, df = 4).

The probability of having post-operative varus, valgus, or neutral mechanical axes was significantly effected ($\chi^2 = 154.11$, df = 2, $p < 0.0001$) by POSTTFA. The regression coefficients, odds ratios, and 95% Wald confidence limits for each model are presented in table 9. In model one, the regression coefficient for POSTTFA was negative, indicating a decreased POSTTFA angle was associated with greater probability of having a predicted varus POSTMA. The model indicated that for every 1º increase in valgus POSTTFA, the odds of predicting any degree of varus POSTMA decreased by 0.29 times. In model two, the regression coefficient for POSTTFA was positive, indicating an increased POSTTFA angle was associated with greater probability of having a valgus POSTMA. The model indicated that for every 1º increase in valgus POSTTFA, the odds of predicting any degree of valgus POSTMA increased by 1.36 times.

When POSTMA was categorized as > 3º varus (n = 53), > 3º valgus (n = 58), or neutral (3º varus to 3º valgus) (n = 677), the probability of having post-operative varus, valgus, or neutral mechanical axis was significantly effected ($\chi^2 = 104.07$, df = 2, p <

0.0001) by POSTTFA. Reduced models with the single main effect of POSTTFA were found to explain POSTMA as adequately as a full model which included interactions between surgical approach (midvastus, subvastus, or standard) and POSTTFA (χ^2 difference = 6.44, df = 4). In model three, the regression coefficient for POSTTFA was also negative, indicating a decreased POSTTFA angle was associated with greater probability of having a POSTMA greater than 3º varus. The model indicated that for every 1º increase in valgus POSTTFA, the odds of predicting a varus POSTMA > 3º decreased by 0.41 times. In model four, the regression coefficient for POSTTFA was also positive, indicating an increased POSTTFA angle was associated with greater probability of having a POSTMA of greater than 3º valgus. The model indicated that for every 1º increase in valgus POSTTFA, the odds of predicting a valgus POSTMA > 3º increased by 1.63 times.

Table 8. Logistic regression data for predicting post-operative mechanical axis by alignment category* (varus, neutral, or valgus) and deformity† (> 3º varus or valgus) in all knees with TKA (N = 788 knees)

***Post-operative mechanical axis categorized as any degree of varus, neutral (0º), or any degree of valgus**

	Parameter Estimate	**Wald Chi-square**	**Pr>Chi Sq**
Model 1:			
Varus vs. Neutral			
Intercept	1.68	33.42	< 0.0001
POSTTFA (º)	-0.35	46.96	< 0.0001
Model 2:			
Valgus vs. Neutral			
Intercept	-2.45	50.42	< 0.0001
POSTTFA (º)	0.31	38.72	< 0.0001

†Post-operative mechanical axis categorized as > 3º varus, neutral (3º varus to 3º valgus), or as > 3º valgus

	Parameter Estimate	**Wald Chi-square**	**Pr>Chi Sq**
Model 3			
Varus vs. Neutral			
Intercept	0.17	0.18	0.67
POSTTFA (º)	-0.53	38.98	< 0.0001
Model 4			
Valgus vs. Neutral			
Intercept	-5.88	109.94	< 0.0001
POSTTFA (º)	0.49	48.25	< 0.0001

POSTTFA: post-operative tibiofemoral angle measured from short radiographs

Table 9. Regression coefficients, odds ratios, and 95% Wald confidence limits for predicting post-operative mechanical axis (varus, neutral, or valgus) using each of the four models in all knees with TKA (N = 788 knees)

	Parameter Estimate	Odds Ratio	95% Wald Confidence Limits
Model 1:			
POSTTFA (º)	-0.35	0.71*	0.64 – 0.78
Model 2:			
POSTTFA (º)	0.31	1.36*	1.24 – 1.50
Model 3:			
POSTTFA (º)	-0.53	0.59*	0.50 – 0.69
Model 4:			
POSTTFA (º)	0.49	1.63*	1.42 – 1.87

POSTTFA: post-operative tibiofemoral angle measured from short radiographs

*$e^{\text{parameter}(1^{\circ})}$

Sensitivity and Specificity for Logistic Regression Models. The frequencies, percentages of knees predicted for each category, and cumulative percentages for models 1 and 2 are presented in table 10. Models 1 and 2 provided correct estimates of the risk of post-operative deformity for 53% of the knees. The cumulative percentages for knees correctly predicted into their respective categories indicated the sensitivity of the models. The sensitivity of models 1 and 2 was approximately 72% for accurately predicting neutral POSTMA for knees with actual neutral POSTMA. Sensitivities for models 1 (39%) and 2 (43%) were lower for correctly predicting varus or valgus POSTMA values for knees with actual varus and valgus POSTMA.

The percentages of knees with actual post-operative valgus alignment incorrectly estimated to have post-operative neutral or varus alignment were 49% and 8%, respectively. Similarly, the percentages of knees with actual post-operative varus alignment incorrectly estimated to have post-operative neutral or valgus alignment were 52% and 10%, respectively. The specificity of models 1 and 2 was approximately 50% for detecting the absence of neutral POSTMA. The specificities for models 1 and 2 were approximately 89% and 87%, respectively for detecting the absence of varus or valgus POSTMA.

Table 10. Frequency, predicted percent, and cumulative percent deformity prediction for models 1 and 2

Frequency % predicted Cumu. %	**Actual Neutral**	**Actual Valgus**	**Actual Varus**	**Total**
Predicted Neutral	232 29.44 72.27	105 13.32 48.84	129 16.37 51.19	466 9.14
Predicted Valgus	49 6.22 15.26	93 11.80 43.26	24 3.05 9.52	166 21.07
Predicted Varus	40 5.08 12.46	17 2.16 7.91	99 12.56 39.29	156 19.80
Total	321 40.74	215 27.28	252 31.98	788 100.00

The frequencies, percentages of knees predicted for each category, and cumulative percentages for models 3 and 4 are presented in table 11. Models 3 and 4 provided correct estimates of the risk of post-operative deformity for 86% of the knees. The sensitivity of models 3 and 4 was approximately 99% for accurately predicting neutral POSTMA for knees with actual neutral POSTMA. The sensitivities for models 3 and 4 were only 0% and 2%, respectively for correctly predicting varus or valgus POSTMA values for knees with actual varus and valgus POSTMA. The percentage of knees with actual post-operative valgus deformity greater than 3° incorrectly estimated to have post-operative neutral was 98%. There were zero knees with actual post-operative varus deformity greater than 3º varus that were correctly predicted into the varus category. All knees with actual post-operative varus deformity were incorrectly predicted to have a post-operative neutral alignment using model 3. The specificity of models 3 and 4 was only 1% for detecting the absence of neutral POSTMA. The specificities for models 3 and 4 were approximately 100% and 99%, respectively for detecting the absence of varus or valgus POSTMA greater than 3º.

Table 11. Frequency, predicted percent, and cumulative percent deformity prediction for models 3 and 4

Frequency **% predicted** **Cumul. %**	**Actual Neutral**	**Actual Valgus**	**Actual Varus**	**Total**
Predicted Neutral	675 85.66 99.70	57 7.23 98.28	53 6.73 100.00	785 99.62
Predicted Valgus	2 0.25 0.30	1 0.13 1.72	0 0.00 0.00	3 0.38
Total	677 85.91	58 1.72	53 6.73	788 100.00

DISCUSSION

The most important findings of the present study were that tibiofemoral angles measured from short standing radiographs provided poor estimates of post-operative mechanical axis (POSTMA) in individuals with TKA. The accuracy of equation 1 to estimate POSTMA using pre-operative tibiofemoral angle (PRETFA) was only 4%. The accuracy of equation 2 to estimate POSTMA using the post-operative tibiofemoral angle (POSTTFA) was 22%. The inclusion of pre-operative femoral and tibial angles did not increase the accuracy of equation 1 above that of PRETFA. Similarly, post-operative femoral and tibial component angles did not increase the accuracy of equation 2 above that of POSTTFA. Measurements of POSTMA, PRETFA, and POSTTFA as obtained from the digital radiographs are presented in figure 1.

Linear Regression Models to Estimate Mechanical Axis

Estimation of Mechanical Axis in Patients with Mild to Moderate OA. Linear regression analysis resulted in selection of the same predictor variable (tibiofemoral angle) as models reported in previous investigations for estimation of mechanical axis[34,35,38,46]. Hinman et al.[35] reported a strong relationship ($r = 0.88$, $p < 0.001$) between mechanical axis and tibiofemoral angle measured on 40 knees in 40 participants with medial compartment OA with 77% predictive accuracy[35]. Kraus et al.[34] reported a moderately high relationship ($r = 0.75$, $p < 0.0001$) between mechanical axis and tibiofemoral angle measured on 114 knees with symptomatic and radiographic OA in 57 participants with 56% predictive accuracy[34]. Similarly, McDaniel et al.[46] also reported a moderately high relationship between mechanical axis and tibiofemoral angle measured on 104 knees in 52 participants with 55% predictive accuracy.

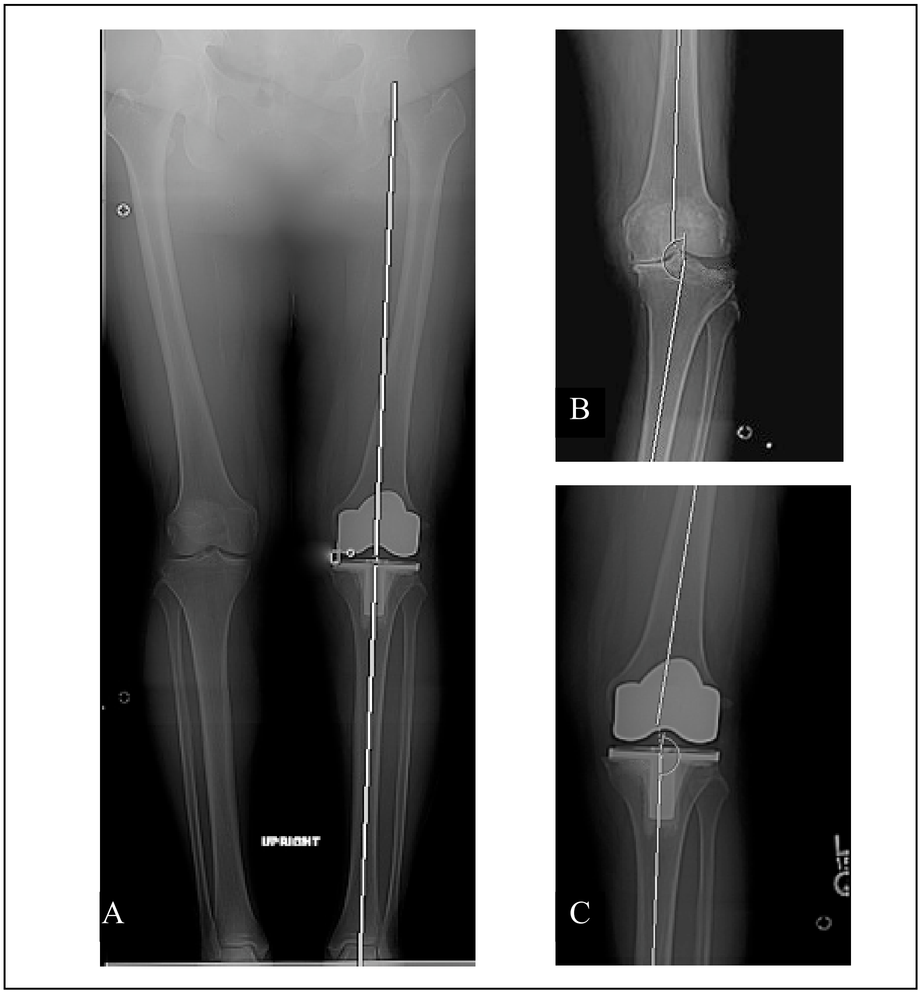

Figure 1. Radiograph measurements of the outcome variable: A) post-operative mechanical axis (POSTMA) and predictor variables: B) pre-operative tibiofemoral angle (PRETFA), C) post-operative tibiofemoral angle (POSTTFA)

Compared to measurements obtained from long radiographs, the aforementioned authors agreed that tibiofemoral angle measured from short radiographs was a valid and more accessible method for the clinic setting to evaluate alignment in participants with OA[34,35,46]. Conversely, the findings of the present study indicated a considerably lower relationship between mechanical axis and tibiofemoral angle obtained from short radiographs with extremely low predictive accuracy for participants with TKA. Interpretation of our results in comparison to the findings of the previous investigations may be further explained by methodological differences in obtaining tibiofemoral alignment and sample selection[34,35,46].

Radiographic Methodological Considerations. Examination of the methods used to assess alignment angles in previous investigations[34,35,46] may explain the contradictory findings of the relationship between tibiofemoral angle and mechanical axis compared to the results of the present study. Variability in alignment measurements between radiographs due to magnification, rotation, and knee position has widely been recognized as a limitation in previous investigations[36,37,40,43,45,57]. The strong relationship between tibiofemoral angle and mechanical axis reported by Hinman et al.[35] is to be expected as both angles were obtained from the same radiograph, as opposed measurement techniques drawn from separate short radiographs by Kraus et al.[34], McDaniel et al.[46], and the present study. Consequently, Hinman et al.[35] reported the highest predictive accuracy of all previous investigations and this interpretation may be exaggerated. Their method did not permit assessment of alignment measurements obtained from separate short radiographs as a valid substitute for long radiographs.

The moderately high relationships between tibiofemoral angle and mechanical axis reported by Kraus et al.[34] and McDaniel et al.[46] are surprising as separate short radiographs with the knee flexed to 30º were used to measure tibiofemoral angle in the posteroanterior view. Yamanaka et al.[58] investigated the effect of the degree of knee flexion (15º, 30º, and 45º) on tibiofemoral angle measured from 113 knees in 95 participants with medial tibiofemoral OA. Differences in tibiofemoral angles measured with the knee extended and flexed at 15º were significantly ($p < 0.0007$) less than the differences between measurements with the knee extended and flexed at 30º[58]. Therefore, the authors recommended knees be positioned in no more than 15º of flexion for tibiofemoral alignment on short radiographs. Both the long and separate short radiographs in the present study were obtained with the participant in the exact same position with both knees in full extension. Therefore, it is unlikely the error in predicting POSTMA using the linear regression models in the present study was due to methodological errors associated with knee position.

Estimation of Mechanical Axis in Patients with TKA. Whereas the samples in the previous investigations[34,35,46] consisted of individuals with a wide range of mild to severe OA, all participants in the present study had severe end-stage OA prior to TKA. Chang et al.[38] also evaluated a sample of 102 patients with advanced OA prior to TKA surgery (OA group) and following TKA (TKA group). The R^2 values (males: 0.66, females: 0.78) for the best performing equations to estimate mechanical axis from tibiofemoral angle for the OA group were similar to the values reported in previous investigations[34,35,46]. Similar to the present study, the R^2 values (males: 0.33, females: 0.21) reported by Chang et al.[38] were considerably lower for the TKA group compared to the OA group. The low predictive accuracy for the linear regression models in the present study are in agreement with Chang et al.[38] for the TKA group that nearly 80% of the variance in POSTMA was attributed to unknown factors and error. Examination of the error between the actual and predicted measurements of POSTMA using the equations generated in the present study may provide further insight on factors attributing to the prediction error.

Prediction Error in Estimating Mechanical Axis.

The residuals resulting from both equations 1 and 2 were not found to be normally distributed. The residuals between the predicted and actual POSTMA were plotted against the actual POSTMA using Bland-Altman plots[59] for both equations (figures 2 and 3). Greater error was associated with predicting POSTMA for participants as the magnitude of the actual POSTMA increased in either the varus or valgus position providing an indication of the error for each individual alignment measurement.

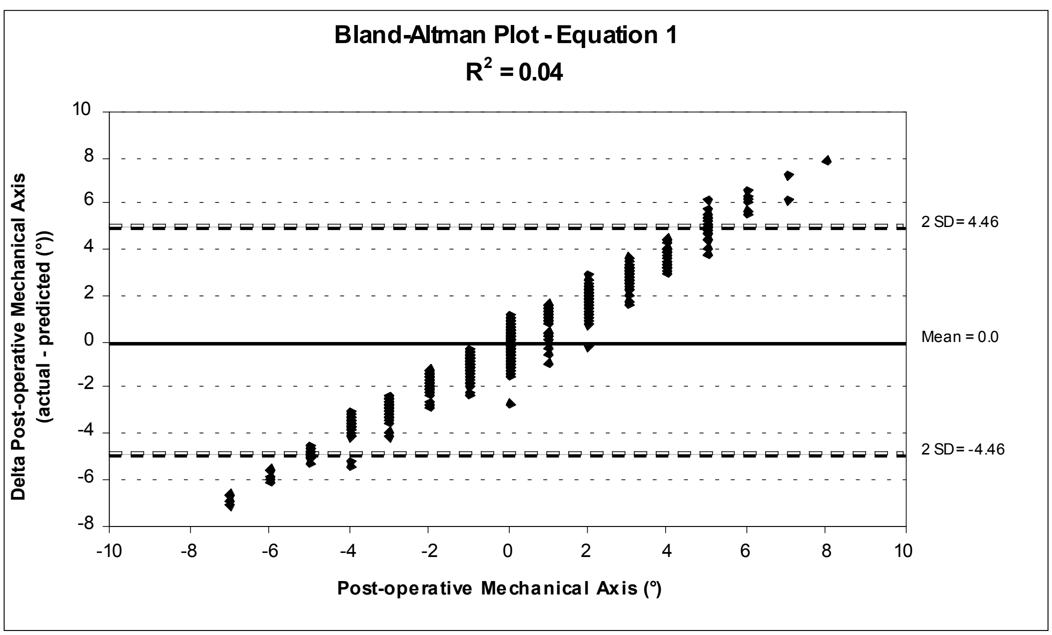

Figure 2. Bland-Altman Plot for equation 1

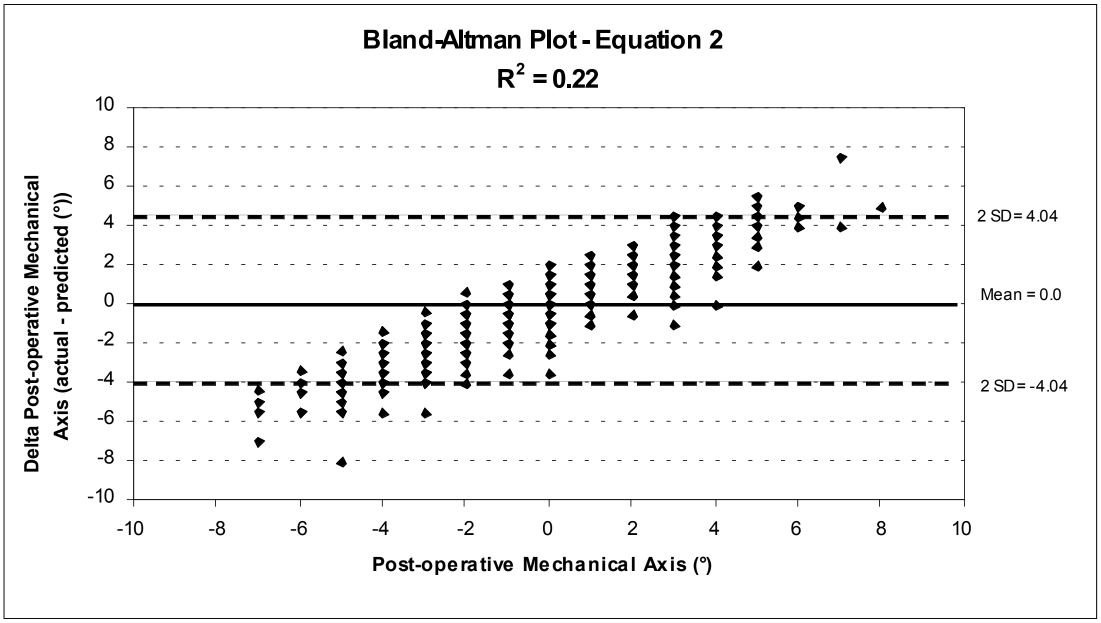

Figure 3. Bland-Altman Plot for equation 2

Considering only the mean differences between the actual and predicted POSTMA measurements may be misleading. The mean differences between the actual and predicted POSTMA measurements were 0.00º ± 2.23º and 0.00º ± 2.02º for equations 1 and 2, respectively. The mean absolute differences between the actual and predicted POSTMA measurements were 1.58º ± 1.57º and 1.48º ± 1.37º for equations 1 and 2, respectively. Therefore, 95.44% (± 2 standard deviations of the mean absolute error) of any individual predicted POSTMA values may vary from the actual measurement using equation 1 by a minimum of -1.56º to at most 4.72º. Similarly, approximately 95.44% of any individual predicted POSTMA values may vary from the actual measurement using equation 2 by a minimum of -1.26º to at most 4.22º.

The highest level of precision is required when using alignment measurements from radiographs as a factor leading to surgical decisions such as in the application of equation 1 when a pre-operative measurement is used for the surgical plan. Many surgeons continue to rely on measurements obtained from short rather than long radiographs prior to TKA to determine the appropriate component position for correcting lower extremity malalignment. Increased incidences of TKA failure have previously been associated with POSTMA greater than 3º of varus or valgus alignment[18,19,26,29]. Therefore, a POSTMA of 0º ± 3º has been widely used as a post-operative goal for correcting lower extremity alignment through TKA[26,37]. There were 53 and 58 knees in the present study with an actual POSTMA greater than 3º of varus or valgus alignment respectively. There were 677 knees with actual neutral POSTMA of 0º ± 3º. All 677 knees with actual neutral alignment were accurately predicted to have a POSTMA of 0º ± 3º using equation 1. In contrast, zero knees with actual varus or valgus alignment over 3º were accurately predicted to have a POSTMA over 3º of varus or valgus using equation 1. All knees with actual varus or valgus POSTMA were inaccurately predicted to have a neutral alignment when using PRETFA to estimate post-operative mechanical axis.

A high level of precision is also required when using alignment measurements from radiographs to assess post-operative alignment following TKA such as in the application of equation 2. There were 675 knees with an actual POSTMA of 0º ± 3º that were accurately predicted to have a neutral POSTMA using equation 2. There were zero knees with an actual POSTMA over 3º varus that were accurately predicted to have a POSTMA over 3º varus using equation 2. Only one knee with an actual POSTMA over 3º valgus was accurately predicted to have a POSTMA over 3º valgus.

These findings suggest that the ability to estimate mechanical axis from tibiofemoral angle may be influenced by the magnitude of the actual mechanical axis. Sheehy et al.[60] recently investigated the effect of the magnitude of knee deformity on the relationship between mechanical axis and tibiofemoral angle measured from 120 knees stratified into four equal groups based on deformity of severe varus (≤ -5.0º), mild varus (0.0º to -4.9º), mild valgus (0.1º to 4.9º), and severe valgus (≥ 5.0º). Results indicated the offset (difference between mechanical axis and tibiofemoral angle) was greater for the severe varus and valgus groups than knees in the milder ranges[60]. Therefore, the greater error in predicting POSTMA for individuals with severe varus or valgus deformity in the present study may be influenced by the varying relationship between mechanical axis and tibiofemoral angle across the range of knee deformity.

The relationship between continuous measurements of alignment previously reported may not be consistent when evaluated as a categorical variable (varus, valgus, and neutral)[61]. When using linear modeling, assessment of the error in agreement between the actual and predicted measurements indicated that estimates of POSTMA as a categorical variable may result in misclassification of the severity of deformity. The results of logistic regression analysis in the present study supported this assessment. When post-operative deformity was categorized as any degree of valgus, neutral alignment of 0º, and any degree of varus based on POSTMA, nearly half of the knees with actual varus or valgus malalignment were incorrectly classified as neutral. This finding indicated use of tibiofemoral angle from a short radiograph to evaluate post-operative alignment would potentially lead to an inaccurate assumption of a neutral mechanical axis when a true varus or valgus deformity is present. When post-operative deformity was categorized as greater than 3º of varus or valgus deformity, all knees with actual malalignment were incorrectly classified as neutral. These findings indicated more detrimental consequences of using tibiofemoral angle from short radiographs, which resulted in 100% misclassification of post-operative alignment as neutral for patients with deformity in the extreme ranges of varus or valgus malalignment.

Logistic Regression Models to Estimate Mechanical Axis

The regression coefficients for POSTTFA were negative in both models 1 and 3, while the regression coefficients for POSTTFA were positive in both models 2 and 4 for predicting post-operative deformity (table 8). The regression coefficient for the comparison of varus to neutral was similar in magnitude but opposite in sign to the regression coefficient for the comparison of valgus to neutral alignment. Therefore, a less valgus POSTTFA was associated with a greater probability of predicting a varus POSTMA while a more valgus POSTTFA was associated with a greater probability of predicting a valgus POSTMA.

A concomitant effect of POSTTFA on the odds ratios (ORs) was revealed for the models comparing varus to neutral alignment (model 1: OR = 0.707 per degree, model 3: OR = 0.587), and the models comparing valgus to neutral alignment (model 2: OR = 1.36 per degree, model 4: OR = 1.63 per degree) (table 9). Models 2 and 4 produced slightly higher risks of predicting a valgus POSTMA compared to the risks when using models 1 and 3 for predicting a varus POSTMA based on POSTTFA. The percent increase in the odds of predicting a valgus POSTMA over neutral with greater valgus POSTTFA was approximately 36% and 63% for models 2 and 4, respectively. Similarly, the percent increase in the odds of predicting a varus POSTMA over neutral with decreased valgus POSTTFA was approximately 29% and 41% for models 2 and 4, respectively.

The probabilities of predicting POSTMA as varus, valgus, or neutral over the range of POSTTFA measurements using the two sets of models are presented in figures 4 and 5, respectively. The mean (± SD) POSTTFA for all knees in the present study was 6.06º ± 2.07º with a range of 1º to 14º valgus. The highest probabilities of predicting a neutral POSTMA were found to be within one standard deviation of the mean POSTTFA for both sets of models. The probabilities of predicting a neutral POSTMA for knees within the neutral POSTTFA range were from 43% to 45% using models 1 and 2, respectively. The probabilities of predicting a neutral POSTMA for knees within the neutral POSTTFA range were from 87% to 91% using models 3 and 4, respectively.

Categories for post-operative malalignment based on POSTTFA have previously been reported to be varus (< 4.0º valgus), neutral (5.0º to 8.0º valgus), and valgus (> 9.0º valgus)[29]. Survival rates for TKA have been found to be significantly lower ($p < 0.05$) for knees with POSTTFA varus malalignment compared to neutral and valgus groups with no significant difference in survival rate between neutral and valgus groups[29]. Being within one standard deviation of the mean POSTTFA resulted in placement of knees in the present study into similar categories as varus (-1 SD: < 4.0º valgus), neutral (4.0º to 8.0º valgus), and valgus (+ 1 SD: > 9.0º valgus). An inverse relationship was observed between the probabilities of predicting POSTMA as varus or valgus relative to neutral over the range of POSTTFAs (figures 4 and 5). The probabilities of predicting a varus POSTMA were the highest for knees with varus POSTTFA between 50% and 77% using model 1. Similarly, the probabilities of predicting a valgus POSTMA were the highest for knees with valgus POSTTFA between 53% and 86% using model 2. However, both models 1 and 2 resulted in prediction of a neutral POSTMA for knees with varus or valgus POSTTFA up to 38%. Both models 3 and 4 resulted in a greater prediction of a neutral POSTMA than varus or valgus for knees with varus or valgus POSTTFA.

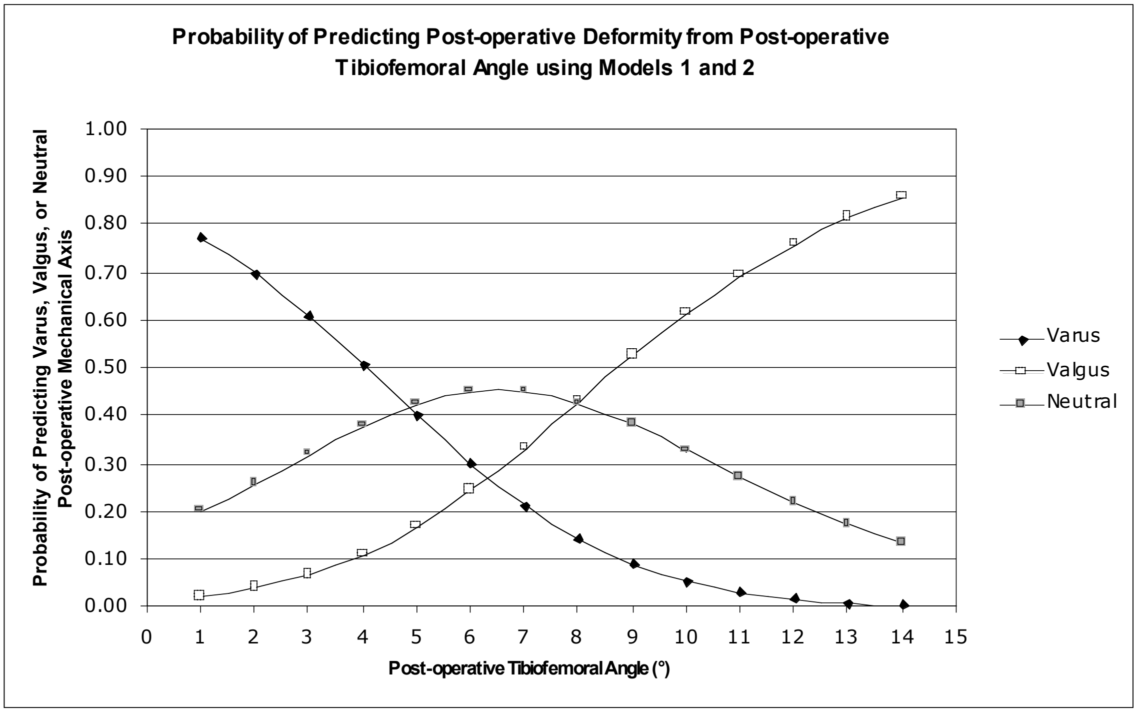

Figure 4. Probability of predicting post-operative deformity from POSTTFA using models 1 and 2

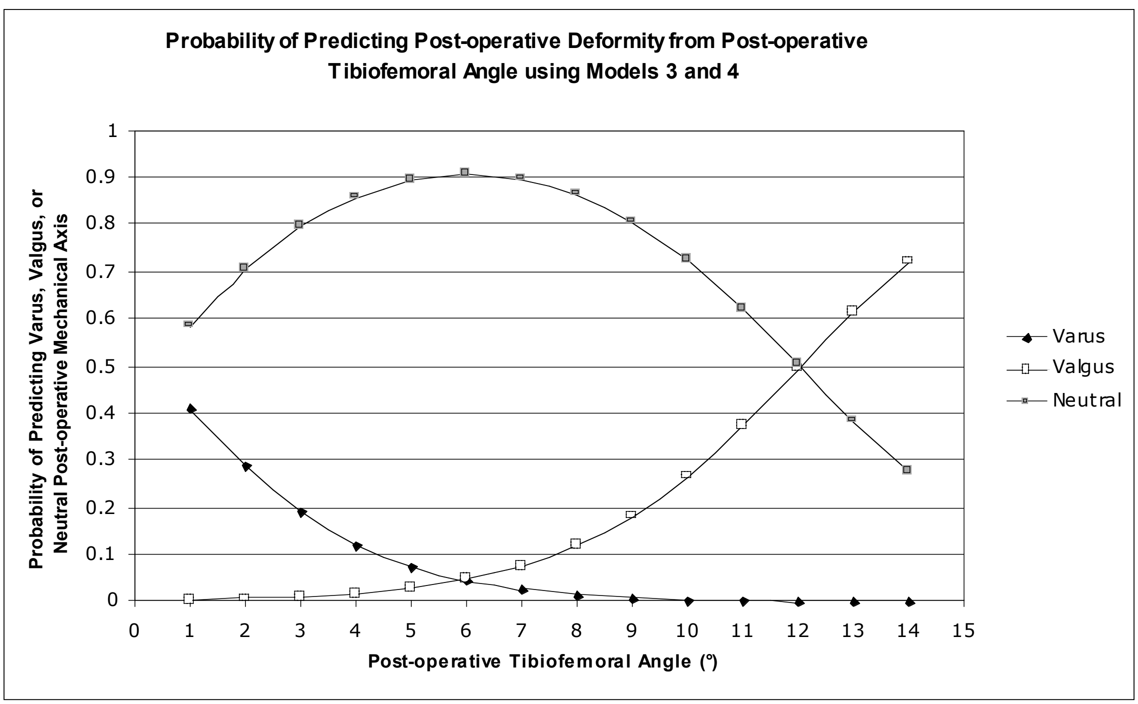

Figure 5. Probability of predicting post-operative deformity from POSTTFA using models 3 and 4

Sensitivity and Specificity of the Logistic Regression Models. Examination of the percentages of knees correctly predicted into their respective actual categories provided an indication of the predictive power of the models (tables 10 and 11). Overall, approximately 53% of all knees were correctly predicted into their respective categories indicating the ability to estimate post-operative deformity can be detected with moderate predictive power half of the time using models 1 and 2. Comparisons of the sensitivities and specificities for predicting neutral, varus, or valgus POSTMA provides a clearer indication of the precision of the models for each category. The sensitivity of models 1 and 2 was high for detecting neutral POSTMA (72%) but not for predicting the risk of varus (39%) or valgus (43%) deformity. The specificity of models 1 and 2 was low (50%) with respect to predicting the absence of neutral alignment and high for predicting the absence of varus (89%) or valgus (87%) POSTMA. Although sensitivity was high for predicting neutral POSTMA, models 1 and 2 lacked specificity for the neutral alignment category. Conversely, while sensitivity was low for predicting varus and valgus POSTMA, models 1 and 2 provided high specificity for the deformity categories.

Overall, approximately 86% of all knees were correctly predicted into their respective categories using models 3 and 4 indicating a high predictive power for the models. However, considering the overall predictive power for models 3 and 4 is misleading for the precision of the models in detecting varus or valgus deformity. Indices of sensitivity and specificity were difficult to discern for the models. Models 3 and 4 demonstrated very high sensitivity for predicting neutral POSTMA with no specificity. Conversely, models 3 and 4 were not sensitive enough to predict varus or valgus deformity but the models were specific at least to detect the absence of varus or valgus deformity for each respective category.

In summary, as hypothesized, tibiofemoral angles measured from short standing radiographs before (PRETFA) and after (POSTTFA) TKA were statistically associated with POSTMA but not clinically able to detect varus or valgus deformity. In contrast to the research hypothesis, tibial component alignment was not significantly associated with POSTMA. The femoral component angle was statistically associated with POSTMA, however this variable did not improve the predictive accuracy of equation 2 above that of POSTTFA. Although PRETFA and POSTTFA were found to be related to POSTMA, the majority of the variance in POSTMA was unaccounted for by the linear regression models and was attributed to unknown factors or error. Due to advancements in radiographic technology and methods employed in the present study for obtaining digital alignment measurements, it was unlikely prediction of POSTMA in the models was inhibited by methodological error. With no improvement in the relationship between POSTMA and tibiofemoral alignment by adding femoral and tibial component measurements, data from the present study demonstrated alignment measurements obtained from short radiographs were not adequate to estimate POSTMA.

The research hypothesis was confirmed that POSTTFA was associated with the probability of any degree of varus or valgus POSTMA deformity relative to neutral alignment. Similarly, as hypothesized, POSTTFA was associated with the probability of varus or valgus POSTMA deformity greater than 3º relative to neutral alignment. However, none of the logistic models demonstrated both high sensitivity and specificity for estimating the risk of POSTMA deformity. Both sets of logistic models demonstrated high percentages of misclassification of POSTMA as neutral for patients with actual varus or valgus deformity. All models were found to be only sensitive enough to detect neutral POSTMA but not specific enough to detect the absence of neutral POSTMA. The models were less effective for predicting varus or valgus deformity and at best could only detect the absence of deformity in either direction but not specifically varus or valgus malalignment.

Within the limitations of the present study, the linear and logistic models were not adequate to estimate POSTMA using either PRETFA or POSTTFA. Use of short pre-operative radiographs for determining component position to correct lower extremity malalignment indicated that neutral alignment was inaccurately suggested even when extreme varus and valgus deformities were present. Use of short radiographs on post-operative TKA patients indicated that neutral alignment was inaccurately suggested even when extreme varus and valgus deformities were present. Consequently, we do not recommend the use of short radiographs as a substitute for long radiographs when evaluating lower extremity alignment to determine component position before TKA and for assessment of post-operative alignment outcomes following TKA.

PART II

REVIEW OF LITERATURE

The orientation of the hip, knee, and ankle joints accounts for a large majority of lower extremity alignment. Theoretically, alignment of the center of the knee with the centers of the hip and ankle joints produces a neutral axis of the lower extremity. Deviations from neutral position have been shown to be associated with musculoskeletal injury, degeneration, and even structural failure of the affected joint. Alignment measurements are valuable for identifying factors contributing to musculoskeletal conditions, determining the severity of joint damage, and assessing outcomes following clinical and surgical treatments. Assessment of lower extremity alignment is a key component of the clinical examination for the population of individuals affected by degenerative arthritis of the knee that eventually require joint replacement surgery.

Radiographs are the optimum modality used to obtain an image of the lower extremity for assessment of alignment. The methods used to measure alignment have changed considerably as technology has evolved leading to little consensus regarding a standard protocol for clinical practice. Therefore, the purpose of this literature review is to discuss the application of radiography for detecting osteoarthritis and measuring lower extremity alignment before and after knee replacement surgeries along with how radiography has evolved over time. The first sections of this review are to provide a brief overview of osteoarthritis and a description of knee replacement surgeries relative to lower extremity alignment. The remaining sections focus on a description of radiographic imaging modalities and how the methods of obtaining alignment measures vary across investigations of clinical outcomes following knee replacement.

Prevalence and Incidence of Osteoarthritis

Osteoarthritis (OA) is a degenerative disease involving progressive deterioration of the joint structures[1]. The prevalence of OA is the highest among all forms of arthritis[1,5] affecting approximately 27 million adults in the United States[6] and most commonly occurs in the knee joint[7]. Increasing in prevalence with increasing age, OA affects females more than males[7,62]. Prevalence and incidence rates will vary according to the definitions of OA in the knee along with stratification by age and gender. Previous investigations have reported these rates according to radiographic and symptomatic definitions of OA.

Radiographs are a widely employed diagnostic tool to evaluate structural changes associated with OA including joint space narrowing, osteophytes, sclerosis and cysts[7,63]. The Kellgren and Lawrence[63] grading system is considered one of the main reference standards for defining radiographic OA. Inter- and intra-observer differences in this grading system was previously determined from 510 radiographs of the hand, cervical spine, lumbar spine, hips, knees and feet in 85 participants. Radiographic evidence of OA in the knee included the presence of 1) osteophytes on the tibial spines, 2) periarticular ossicles, 3) cartilage narrowing, and 4) pseudocystic areas with sclerosis. The severity of OA in the joint was graded as 0) none, 1) doubtful, 2) minimal, 3) moderate, and 4) severe. Correlation coefficients of r = 0.83 both between two observers and within the same observer indicated low inter- and intra-observer error for grading OA using this system. The authors concluded that radiographs should preferably be read by two observers or the same observer for grading OA[63].

Felson et al.[7] were among the first to establish prevalence and incidence rates of OA in the large population-based Framingham OA Study. Radiographic and symptomatic OA of the knee were evaluated in 1,420 participants stratified into age groups (<70, 70-79, ≥80 years). Radiographic OA was defined according to the Kellgren and Lawrence grading system[63] and symptomatic OA was defined as the presence of pain in or around the knee joint. The prevalence of radiographic OA was found to be 33% in all participants and significantly increased ($p<0.001$) with age at 27.4% (age <70 years), 34.1% (ages 70-79 years), and 43.7% (age ≥80 years). Radiographic OA was detected in more females (34.4%) than males (30.9%) with increasing prevalence with age in females but not males. The prevalence of symptomatic OA was 9.5% in all participants and significantly increased ($p<0.05$) with age at 9.5% (age <70 years), 11.0% (ages 70-79 years), and 11.2% (age ≥80 years). Symptomatic OA was reported by more females (11.4%) than males (6.8%) with increasing prevalence with age in females but not males. The prevalence of symptomatic OA also increased with radiographic severity from 7.6% in participants with a normal grade to 40% at the highest severity. The authors concluded the age-related increase in OA may lead to further lower extremity dysfunction and decreased mobility[7].

Felson et al.[62] followed-up with 869 participants at 8.1 ± 0.3 years following their previous study to determine the incidence rates of knee OA. Radiographic and symptomatic OA were determined using similar methods as the original Framingham OA Study. The authors modified the Kellgren and Lawrence scale[63] used in this study to include joint space narrowing along with the presence of osteophytes as an indicator of OA. The incidence of radiographic OA was higher in females (18.1%) than males

(11.1%). Similarly, the development of symptomatic OA was higher in females (8.1%) versus males (4.3%). The incidence rates for both males and females did not increase with increases in age. Overall, the annual rate of progression for radiographic OA was between 3% and 4% for both genders. Although the findings from the present study indicated a slow development in the disease over time, the authors concluded that new cases continue to occur during this age of life augmenting the prevalence of OA[62].

Oliveria et al.[64] found similar incidence rates of OA of the knee to that of Felson et al.[62] among members of a local health maintenance organization plan in Massachusetts. Potential incident cases included continuous members (ages 20 to 89 years) of the plan between 1988 and 1991 or between 1989 and 1992 with an index radiograph of the hand, hip, or knee at 1991 or 1992 respectively. An incident case was defined as the presence of radiographic OA at the index radiograph with symptomatic OA concurrently or within one year prior to the radiograph in the respective joint. Radiographic OA was defined according to the Kellgren and Lawrence grading system[63] and symptomatic OA was defined as the presence of pain, stiffness, soreness, swelling, aching, discomfort and tenderness. The overall age- and sex-standardized incident rate of OA was highest in the knee (240 per 100,000 person-years) compared to rates of OA in the hip (88 per 100,000 person-years), and OA in the hand (100 per 100,000 person-years). Among 1,155 members with an index knee radiograph obtained from 1991 and 1992, 461 participants demonstrated incident OA. When stratified by age groups, the highest incidence rates of knee OA in females was ~0.66% per year (60-69 years), ~1.08% per year (70-79 years) and ~1.05% per year (80-89 years). The highest incidence rates of knee OA in males was ~0.49% per year (60-69 years), ~0.84% per year (70-79 years) and ~0.62% per year (80-

89 years). The authors concluded the incidence of OA increases with the age up to age 80 and is higher in females than males after age 50[64].

Lower Extremity Alignment and Osteoarthritis

Although the specific cause of OA is unknown, lower extremity malalignment has been associated with structural changes in the knee[3] and the progression of the disease[4,8,11]. Brouwer et al.[8] investigated the effect of lower extremity malalignment on the development and progression of OA in 1,501 participants (892 female, 609 male; mean age 66.4 ± 6.7 years; BMI 26.3 ± 3.6 kg/m^2). Lower extremity alignment and OA severity were measured on 36.0 × 43.0 cm radiographs in the AP view obtained with a setting of 70 kV at baseline and a follow-up period (6.6 years). All participants were positioned 120 cm from the x-ray tube, weight bearing fully extending both knees. The Kellgren and Lawrence grading system[63] was used to define the presence (grade ≥ 2) and severity of radiographic OA. Lower extremity alignment was measured as the medial angle between the midline axes of the femur and tibia from which participants were stratified into three alignment groups as normal (182º to 184º), varus (< 182º), and valgus (>184º). Logistic regression analyses indicated participants with varus alignment had a significantly higher risk of developing OA (OR = 2.06, 95% CI = 1.28 – 3.32, p = 0.003) and for the progression of OA (OR = 2.90, 95% CI = 1.07 – 7.88, p = 0.037) compared to participants with normal alignment. Considering BMI as another independent variable, varus alignment and BMI significantly increased the risk for the development of OA in participants with a BMI between 25 and 30 kg/m^2 (OR = 2.02, 95% CI = 1.07 – 3.84, p = 0.031) and with a BMI ≥ 30 kg/m^2 (OR = 5.06, 95% CI = 1.71 – 14.94, p = 0.003). There was no significant effect of valgus alignment on the risk of OA development or progression, however, there was a trend towards an increased risk in OA development (OR = 1.54, 95% CI = 0.97 – 2.44, p = 0.065) in all participants. When stratified according to BMI, participants with valgus alignment and a BMI ≥ 30 kg/m^2 were at a significantly increased risk for the development of OA (OR = 3.25, 95% CI = 1.14 – 9.27, p = 0.028). The authors concluded that malalignment of the lower extremity at baseline was associated with the risk of the development and progression of knee OA with an increased risk in overweight individuals[8].

Similarly, Sharma et al.[9] investigated the influence of lower extremity alignment on the progression of OA and function. A total of 230 participants (173 female, 57 male; mean age 64.0 ± 11.1 years; BMI 30.3 ± 5.8 kg/m^2) were stratified into a bilateral valgus alignment group (n = 126; < 5º varus), unilateral varus alignment group (n = 52; > 5º varus), and bilateral varus alignment group (n = 37; > 5º varus) based on baseline mechanical axis. The remaining 15 participants were not included in this portion of the analysis as they could not complete the functional assessment. Radiographs were obtained for all participants using a 36 × 130 cm graduated grid cassette in the AP view including the hip and ankle joints. Mechanical axis was defined as the angle between the mechanical axes of the femur and tibia. Function was assessed at baseline and 18 months later for all participants from chair stand performance measured as the rate of sit to stand transfers from a chair per minute. Logistic regression indicated participants with more than 5º of varus alignment in both knees demonstrated a significant decline in functional performance across time compared to participants with less than 5º of varus bilateral alignment. To assess the effect of alignment on the progression of OA, participants were classified according to baseline mechanical axis in varus alignment (n = 117; > 0º), valgus alignment (n = 97; < 0º), and neutral (n = 16; 0º). Logistic regression indicated patients with varus malalignment at baseline demonstrated a 4-fold increase in the odds for OA progression in the medial compartment compared to non-varus aligned patients. Patients with varus malalignment at baseline also demonstrated increased joint space narrowing and pain across time compared to patients with non-varus alignment[9].

Cicuttini et al.[4] assessed the influence of alignment on change in the volume of knee articular cartilage over two years in 117 participants (mean 68 female, 49 male; age 67.0 ± 10.6; BMI 28.7 ± 5.1 kg/m^2) with moderate OA. Baseline radiographs were obtained from all participants in the AP view to measure tibiofemoral angle. Magnetic resonance imaging (MRI) scans were obtained from all participants at baseline and at a two-year follow-up period to measure cartilage volume. The rate of change in cartilage volume was determined by subtracting the baseline measurement from the follow-up measurement and then dividing this value by the time between the MRI scans. Increased malalignment in the varus or valgus direction at baseline was associated with decreased cartilage volume in the respective joint compartment. Multiple linear regression analysis indicated an increase in baseline varus alignment of 1º was significantly (p = 0.04) associated with an annual loss (17.7 μl) in medial femoral cartilage volume. A similar trend was observed between increased baseline varus alignment of 1º and medial tibial cartilage volume loss (2.6 μl loss), however, this finding was not significant. An increase in baseline valgus alignment of 1º was significantly (p = 0.02) associated with a loss (8.0 μl) in lateral tibial cartilage volume per year. There was no significant association between valgus alignment and lateral femoral cartilage change. The findings of this investigation supported previously observed relationships between the progression of OA and alignment of the knee. The authors concluded there was an association between lower extremity alignment and annual cartilage loss across all grades of radiographic OA[4].

In addition to articular cartilage volume, Hunter et al.[3] conducted a cross-sectional analysis to investigate the influence of other structural joint changes on lower extremity malalignment in 132 participants (58 female, 74 male; mean age 66.5 ± 9.7; BMI 30.2 ± 4.4 kg/m^2). Magnetic resonance imaging (MRI) scans were obtained from all participants at a baseline and two follow-up examinations (15 and 30 months) to assess the following structural changes in the knee joint: anterior and posterior cruciate ligament integrity, medal and lateral collateral ligament integrity, cartilage morphology, bone attrition, osteophytes, and meniscal degeneration. Long radiographs including the hip and ankle joints in the AP view were obtained using a 130.0 × 36.0 cm graduated cassette and mechanical axis was measured according to the parameters described by Moreland et al.[36]. Partial correlation coefficients for univariate regression analysis indicated medial bone attrition ($R^2 = 0.51$), meniscal degeneration ($R^2 = 0.36$), meniscus subluxation ($R^2 = 0.35$), cartilage morphology ($R^2 = 0.34$), and osteophytes ($R^2 = 0.31$) contributed to the variance in varus malalignment. Multiple regression analysis with stepwise backward elimination indicated varus malalignment was significantly ($p < 0.0001$) affected by cartilage morphology, and bone attrition adjusted for age, sex, and BMI. Approximately 50% of the variance in varus malalignment was attributed to these structural factors with a relative proportion of the variance explained by bone attrition ($R^2 = 0.50$) and cartilage morphology ($R^2 = 0.51$). The authors concluded multiple structural factors along with cartilage loss contribute to malalignment in individuals with OA. As this was a cross-sectional design, the authors recommended longitudinal investigations of contributing factors to malalignment should be conducted to clarify a cause and effect relationship between these variables[3].

Chang et al.[11] investigated the prevalence of radiographic structural changes associated with advanced OA with varus malalignment and predictors of symptom severity. A review of a prospectively collected database and radiographs was conducted for 341 knees in 217 participants (208 female, 9 male; mean age 68.7 ± 5.9; height 151.6 ± 5.9 cm, weight 60.5 ± 9.2 kg) that underwent TKA between November 2003 and February 2005 for severe OA in the medial compartment of the knee. Long radiographs including the hip and ankle joints in the AP view were obtained using a 130.0 × 36.0 cm graduated cassette and mechanical axis was measured according to the parameters described by Moreland et al.[36] in digital format. All participants were positioned using a reference template with a standard foot angle to control rotation of the knee on radiographs. The severity of symptoms was determined using the pre-operative pain and function scores from the Western Ontario McMaster Universities OA Index (WOMAC)[65]. Univariate linear regression analysis indicated the degree of varus alignment along with subluxation and radiographic OA scores of the tibiofemoral joint were significantly ($p < 0.05$) associated with decreased WOMAC function scores. Varus alignment was the only variable that was significantly ($p < 0.05$) associated with increased pain. Multivariate linear regression analysis indicated the degree of varus alignment was the only variable significantly associated with poorer WOMAC function ($p = 0.003$) and pain scores ($p = 0.017$). The authors concluded the severity of symptoms in patients with advanced OA was better explained by overall radiographic severity of the knee. Individual radiographic characteristics were not sensitive enough to detect symptom severity while the degree of varus malalignment was the primary predictor of increased pain and functional impairment[11].

While the exact causes of OA in the knee continues to remain unknown, the recent investigations[8,9] identified lower extremity malalignment as a risk factor for the development and progression of the disease. Greater varus alignment was reported to be associated with structural changes in the medial compartment of the knee including bone attrition, ligament damage, meniscal degeneration[3], increased osteophytes[2] and a reduction in articular cartilage volume over time[4]. Greater valgus alignment was associated with a similar pattern of degenerative changes in lateral compartment of the knee[2-4,10]. Most recently, Chang et al.[11] identified varus malalignment as the most influential factor for increased pain and functional decline in advanced OA of the knee. When conservative treatments have failed to manage this irreversible disease and alleviating side effects outweighs the need to preserve the natural joint structures, many individuals elect to undergo total knee arthroplasty (TKA) surgery.

Total Knee Arthroplasty

Introduced in the early 1970's[66], TKA has been reported as the most effective surgical option for treatment of end-stage arthritis in the knee joint[67,68]. The rate of TKA procedures between the periods of 1971 to 1976 was reported to be 31.2 per 100,000 person years and increased to 220.9 per 100,000 person years for the period of 2005 to 2008[13]. The estimated annual amount of TKA procedures has increased from 143,000 in 1986[14] to 662,700 in 2007[13]. Nationwide hospital discharge records indicated the prevalence of TKA each year is projected to rise to 3.48 million by 2030[15]. The rise in

TKA procedures has been accompanied by a projected increase in revision TKA from 38,300 in 2005 to 268,200 by 2030[15]. The most common surgical technique of TKA is the standard medial parapatellar approach[69].

Standard Surgical Technique. The standard TKA approach begins with an anterior midline skin incision approximately 15-25 cm in length[68,70,71]. The incision begins five to ten cm[68] proximal to the superior pole of the patella, extending over the medial aspect of the patella through the patellar tendon to approximately one cm medial to the tibial tuberosity[70]. A capsular incision (arthrotomy) is then made splitting the medial one third of the quadriceps tendon[72,73] and medial patellar retinaculum[69] continuing parallel with the patellar tendon, ending five to ten mm medial to the tibial tuberosity[70]. The patella is everted laterally and the medial portion of the quadriceps tendon is retracted medially over the femoral condyle with the knee flexed to gain access the knee joint[73]. The anterior cruciate ligament along with the anterior portions of the medial and lateral menisci are cut and a portion of the infrapatellar fat pad is removed. Once access to the knee joint is achieved with adequate exposure, the sequence of bone resections will vary according to surgeon preferences, however, the femoral cuts are commonly performed first[70].

With the knee flexed to 90º, access to the intramedullary canal of the femur is obtained using a drill with an entry hole approximately one cm to the origin of the posterior cruciate ligament[70]. An intramedullary rod is passed through the center of the canal and a distal femoral cutting guide is positioned at the end of the rod and pinned into place on the distal femur. A distal femoral cut ranging from 4º to 7º valgus (depending on the degree of preoperative varus or valgus deformity) relative to the femoral canal is made[70]. The contents of the intercondylar notch including the posterior cruciate ligament are removed. An AP femoral axis (Whiteside's line) extending from the deepest aspect of the trochlear groove to the center of the intercondylar notch[74,75] is identified and marked on the distal surface of the femur. A referencing guide is pinned into place on the distal femur to determine the appropriate femoral component size. A distal femoral cutting jig is then pinned into place to visually determine appropriate external rotation of the femoral component relative to Whiteside's line. The remaining cuts along the posterior aspects of the femoral condyles and intercondylar notch are made to complete contouring of the distal femur.

An extramedullary guide is pinned into place on the proximal tibia in alignment with the tibial tuberosity, center of the tibial plateau, long axis of the tibia, and center of the ankle[70]. A proximal tibial cutting jig is then pinned into place and the proximal tibial cut is made perpendicular to the mechanical axis of the tibia. The menisci are then removed along with any posterior femoral osteophytes. Soft tissue releases are used as necessary to balance the femoral and tibial joint surfaces of the knee. Balance of flexion and extension of the knee is determined using spacer blocks. A sizing guide is pinned into place on the proximal tibia to determine the appropriate tibial component size. The sizing guide is positioned in alignment with tibial tubercle and the proximal tibia is prepared to accept the tibial trial component. Femoral and tibial trial components are then placed and the knee is examined through full range of motion to confirm stability and balance. Once the knee is felt to be mechanically ideal, the trial components are removed, and the final components are cemented into place along with the polyethylene insert. The femoral component has commonly been positioned in 4º to 7º valgus[70,76] relative to the femoral anatomic axis with 3º of external rotation relative to Whiteside's line[47]. The tibial component is positioned perpendicular to the mechanical axis of the tibia in the coronal plane with approximately a 3º to 5º posterior slope in the sagittal plane[70].

Minimally Invasive Surgical Techniques. Minimally invasive (MIS) is a broad term encompassing a variety of surgical approaches to TKA that emerged in the late 1990's[77] and were designed to involve less trauma to the knee joint structures than the standard approach[66]. The definition of MIS TKA has been stated to include a skin incision less than 15 cm along with the use of specific MIS instrumentation[68,78]. More accurate descriptions of MIS TKA specify the degree and location of trauma to the knee joint and surrounding structures. Thus, various MIS TKA techniques are used including the midvastus, and subvastus approaches.

The midvastus approach begins with an anterior skin incision approximately 6-13 cm in length beginning one to two cm proximal to the superior pole of the patella, extending along the medial aspect of the patella to approximately one cm medial to the tibial tuberosity[66,68,79,80]. A medial capsular arthrotomy is made incising the medial parapatellar retinaculum and continuing along the medial aspect of the patellar tendon to the tibial tubercle[68]. An oblique incision extending one to three cm proximal from the superomedial pole of the patella is made splitting the vastus medialis obliquus (VMO) muscle[66,68,81,82].

The subvastus approach begins with an anterior midline skin incision similar in length to the midvastus approach extending from the superior pole of the patella over the medial aspect of the patella, and extending through the patellar tendon to the tibial tuberosity[73]. A medial capsular arthrotomy is made along the medial border of the patella and patellar tendon to the tibial tubercle leaving the quadriceps tendon intact[73]. The arthrotomy is then extended using blunt dissection from the medial border of the patella approximately 10 cm along the inferior edge of the VMO muscle to the adductor tubercle[69,83]. The patella and distal portion of the extensor mechanism are retracted laterally to gain access the anterior compartment of the knee joint[84].

Clinical Outcomes Following MIS TKA. The popularity of MIS TKA has increased due to potential benefits of the surgical features including decreased blood loss, reduced post-operative pain, and earlier return of range of motion[80]. Comparisons of clinical outcomes between standard and MIS TKA have previously been conducted to ensure the safety and efficacy of the procedure has not been compromised. Boerger et al.[80] compared short-term clinical and radiographic outcomes between MIS and standard TKA. Comparisons were made between equal groups of patients selected to undergo MIS TKA through the mini-subvastus approach (45 female, 15 male; mean age 69 ± 6 years; BMI 28 ± 4 kg/m^2) and standard TKA through the medial parapatellar approach (46 female, 14 male; mean age 68 ± 5 years; BMI 29 ± 4 kg/m^2) matched for age, gender, BMI, knee range of motion, and lower extremity deformity. Pre-operatively, patients with less than 90º of knee flexion, a flexion contracture greater than 15º, loss of tissue mobility due to severe scarring, or previous knee surgery were excluded from the MIS TKA group. The authors claimed pre-operative knee ROM as the only predictive variable of poor post-operative ROM. Immediate outcomes evaluated within the initial 24 hour post-operative period included overall operation time, tourniquet time, blood loss, and pain as assessed by the visual analog scale. Radiographs were obtained 2 weeks post-operatively in the lateral, AP, and long views including the hip and ankle to determine overall lower extremity alignment along with femoral and tibial component position. Independent t-tests indicated significantly greater ($p < 0.001$) operation time, tourniquet time, and total blood loss for the MIS TKA versus the standard TKA group. Participants in the MIS TKA group demonstrated significantly earlier ($p < 0.001$) return of knee flexion, ability to perform straight leg raising, and significantly ($p < 0.001$) less pain than the standard TKA group. The MIS TKA group also demonstrated significantly greater ($p < 0.02$) knee flexion at 30, 60, and 90 days post-operatively than the standard TKA group. Neutral overall alignment and component alignment was achieved in all participants except one patient in the MIS TKA group with a tibial component in 3º of varus position. Complications occurred in two patients in the MIS TKA group including one fracture of the lateral femoral condyle and one rupture of the patellar ligament. The authors concluded the immediate advantages that were observed following MIS TKA diminished with time and the approach resulted in longer operation times and more complications[80].

Karpman and Smith[79] conducted a prospective randomized clinical trial to evaluate post-operative clinical and radiographic outcomes following TKA through three different surgical approaches all performed by a single surgeon. Comparisons were made between three groups of patients randomly assigned to undergo TKA through the standard medial parapatellar approach (n = 19; mean age 73 ± 5.1 years; BMI 29 ± 4.6 kg/m^2), quad sparing approach (n = 20; mean age 73 ± 7.4 years; BMI 28 ± 4.4 kg/m^2) or mini midvastus approach (n = 20; mean age 74 ± 7.7 years; BMI 30 ± 7.3 kg/m^2). All patients completed the SF-36 and WOMAC questionnaires along with a return to function form weekly for the first 6 weeks and again at the 3 and 6 month post-operative periods. The return to function form involved an assessment of distance walked, the use of assistive devices, and return to work. Additional clinical outcomes included, the Knee Society Score[53] and rehabilitation assessment conducted at the same post-operative time periods. The rehabilitation assessment involved pain scores (visual analog scale), range of motion, and quadriceps strength. Tibiofemoral alignment and tibial slope were assessed for all participants at 6 weeks post-operatively. Although all radiograph measurements were performed by the same independent reviewer blinded to the TKA approach, the methods utilized to obtain alignment angles were not described. Independent t-tests indicated no significant differences in post-operative tibiofemoral alignment or tibial slope between groups. Participants in the quad-sparing group demonstrated significantly greater ($p < 0.05$) distance walked and significantly less pain ($p \leq 0.01$) than both the mini midvastus and standard TKA groups. Participants in the mini midvastus group demonstrated significantly less ($p < 0.05$) dependence on walking assistive devices than the standard TKA group. Participants in the quad sparing group demonstrated improved KSS pain scores, flexion, quadriceps strength and were also less dependent on walking assistive devices than the standard TKA group, however these finding were not statistically significant. The authors concluded that TKA surgery performed through the quad sparing approach produced significantly improved clinical outcomes at 2 weeks post-operatively compared to the mini midvastus and standard medial parapatellar approaches. The authors attributed nonstatistical trends to a small sample size and possible influence of additional medical comorbitities[79].

Subsequently, Chin et al.[85] conducted a prospective randomized controlled trial to evaluate post-operative radiographic outcomes following TKA through the same three surgical approaches. A control group of patients undergoing TKA through the medial parapatellar approach (n = 30; 63.4 years; BMI 29 kg/m^2) was compared to two experimental groups randomized to undergo TKA through the mini midvastus approach (n = 30; mean age 67.4 years; BMI 28 kg/m^2) or quad sparing approach (n = 30; mean age 69.0 years; BMI 30 ± 28 kg/m^2). All TKA procedures were performed by two different surgeons familiarized with MIS TKA techniques (cadaveric workshops). Overall mechanical axis, AP femoral and tibial components angles, lateral femoral component flexion angle, and tibial slope were assessed for all participants. Alignment measurements were performed by three independent researchers on three separate occasions on long hip to ankle radiographs. Pearson's chi square analysis indicated the control and mini midvastus group had a higher proportion of patients with optimal femoral and tibial component alignment compared to the quad-sparing group. This analysis also indicated a significantly higher proportion of patients with an optimal angle between the mechanical axes of the femur and tibia in the control group (83.8%; mean angle 1.03° varus, -6.0° to 6.0°) and mini midvastus group (83.3%; mean angle 0.87° varus, -4.0° to 7.0°) compared to the quad sparing group (56.7%; mean angle 0.37° varus, -8.0° to 8.0°). There were no significant differences among groups for lateral femoral component flexion angle and tibial slope. The authors concluded the mini midvastus approach produces comparable radiographic outcomes to the standard medial parapatellar approach while greater variability was demonstrated in the quad sparing group[85].

Kolisek et al.[86] evaluated post-operative clinical and radiographic outcomes following MIS TKA compared to standard TKA performed by six different surgeons. Comparisons were made between two groups of patients randomly assigned to undergo TKA through the midvastus approach (n = 40; mean age 67 years; BMI 32 kg/m^2) or standard medial parapatellar approach (n = 40; mean age 70 years; BMI 30 kg/m^2). Knee Society Scores[53], quadriceps strength, range of motion, walking, and chair rise ability were assessed for all participants at 2, 6, and 12 weeks following TKA. Post-operative femoral and tibial component angles were measured from short radiographs in the AP and lateral views. Due to the small sample size, descriptive statistics were computed for all variables indicating similar results for function, clinical and radiographic outcomes across time. The mean KSS was slightly higher in the MIS group (81) compared to the standard group (77) at 3 months following surgery. At this time, the mean function KSS was also similar between the MIS (74) and standard group (73). The mean AP femoral component ranged from 93-99° for all participants. The mean AP tibial component angle was similar between the MIS (89°) and standard groups (90°). The lateral femoral component angles were in a small degree of extension between the MIS (2°) and standard groups (0.5°). The mean lateral tibial component angles ranged from 83° to 89° for all participants. The authors concluded the short term clinical and radiographic outcomes were comparable between the MIS and standard groups[86].

Expanding upon comparisons of clinical and radiographic outcomes between MIS and standard TKA groups, Tashiro et al.[56] sought to determine whether additional functional changes were evident along with these clinical outcomes. Comparisons were made between two groups of patients randomly selected to undergo TKA through the medial parapatellar approach (n = 21; mean age 73.9 years; height 151.4 cm; weight 59.5 kg) or a minimally invasive approach (n = 20; mean age 76.1 years; height 147.7 cm; weight 55.0 kg). In the MIS group, the quadriceps mechanism was not disrupted in four patients while the VMO was snipped (midvastus approach) in 16 patients. Lower extremity radiograph alignment, pain (VAS), and KSS outcomes were assessed for all participants 3 weeks following surgery and at additional 3 month intervals for 1 year. Tibiofemoral, femoral component, and tibial components angles were measured for all participants. Assessment of functional outcomes for all participants included ability to perform straight leg raising, knee flexion, and pre-/post-operative isometric extensor torque ratios. Independent t-tests indicated the MIS group demonstrated significantly higher extensor torque ratios ($p < 0.05$) than the standard TKA group. The MIS TKA group also demonstrated significantly less pain ($p < 0.05$), earlier return of knee flexion ($p < 0.001$), ability to perform straight leg raising, and T-cane gait ($p < 0.005$). The MIS TKA group demonstrated significantly higher KSS function scores ($p < 0.05$) compared to the standard TKA group at 3 months post-operatively but not at 6 months following TKA surgery. There were no significant differences in any radiograph alignment angles between the MIS and standard TKA groups. The authors concluded the MIS TKA group demonstrated higher quadriceps strength compared to the standard TKA group. The authors attributed this finding to decreased pain with little to no disruption of the extensor mechanism leading to a faster rehabilitation[56].

Although prospective randomized clinical trials[79,85,86] have recently emerged comparing clinical outcomes between standard and MIS TKA, these investigations are limited by multiple surgeons, multiple institutions, and small sample sizes. It is important to obtain results controlling for variations in surgical technique, and protocol differences for pain management, and post-operative rehabilitation. Both Karpman and Smith[79], and Kolisek et al.[86] reported the small sample sizes in their investigations limited the statistical analyses and resulted in nonstatistical trends that could possibly have been significant findings with more participants.

Another limitation of the previous investigations was the methods used to assess lower extremity alignment and component position. Alignment has been considered an important variable that should be routinely evaluated before and after TKA[26,36,44] as malalignment has been identified as a significant mechanism of TKA failure[18-21]. Additionally, a major criticism of MIS TKA approaches has been the potential for compromising component position and post-operative lower extremity alignment due to decrease visualization of the knee joint during surgery through a smaller exposure[87]. Due to improvements in radiographic imaging modalities and the variety of methods reported to obtain alignment measurements[22,42,43,54,88], a thorough understanding of factors influencing the accuracy of different protocols is necessary.

Conventional Radiography

Radiography consists of the generation, processing, archiving, and visual display of an image obtained from the projection of x-ray beams through the human body[89-91]. Images are generated using a detector that absorbs exposed x-rays emitted by a standard tube[89]. In conventional radiography, screen-film loaded in a cassette is used as the image detector and is placed behind the participant during image generation[90]. When x-ray beams pass through the body, photons are both absorbed and scattered (attenuated) at varying degrees depending on the densities of anatomic structures[91]. A pattern of x-rays are absorbed by the film as an imprint of the attenuated beams emanating from the body onto the detector[91]. The film is then removed from the cassette and processed to convert the latent image absorbed by the film into a developed transparent radiograph for visual display in a view box[91]. As light passes through the radiograph, an image of the anatomic structures is produced with a range of brightness from white to black referred to as the dynamic range[91]. Bony structures of higher density cause greater attenuation of photons as x-rays pass through the body producing a whiter appearance on radiographs compared to soft tissues[57]. Among the many imaging modalities, film radiographs are reported to have the best spatial resolution ranging from 0.05 to 0.1 mm resulting in the ability to detect small details of high density structures[57,90]. Therefore, radiographs are considered the primary diagnostic imaging modality to detect musculoskeletal conditions[57].

Lower Extremity Alignment and TKA. Radiographic examination of the knee is an important component of standard clinical care for patients with TKA. Routine radiographs are obtained in the AP and lateral views[30] to measure lower extremity alignment and post-operative component position. To obtain a radiograph in the AP view, a patient is positioned standing in front of the image detector, fully extending both knees with the patellae facing anteriorly, and the x-ray beam projected at a perpendicular angle to the cassette[26,30,36,43,44]. Standard measurements commonly obtained from this view includes tibiofemoral, femoral component, and tibial component angle. Traditionally, these angles have been measured manually using a goniometer from lines drawn directly on short (36 × 43 cm) radiographic film[21,22,39,41]. In earlier investigations of post-operative alignment, tibiofemoral angle was measured manually from lines representing the midline axes of the femur and tibia[21,39,41]. In both the AP and lateral views, femoral component alignment was measured as the angle between the midline axis of the femur and a line tangent to the medial and lateral condyles. Similarly, tibial component angle was measured as the angle between the midline axis of the tibia and a line tangent to the tibial plateau[21,39,41]. Both the distal femoral and proximal tibial component angles were recorded as the deviation from 90º (perpendicular position to the respective axes) with positive values indicating valgus alignment.

Using this methodology, Lotke and Ecker[21] conducted one of the earliest attempts to evaluate the outcome of TKA using radiographs to measure lower extremity and component alignment. Their investigation involved examination of the relationship between clinical outcomes and component position. Between May 1972 and June 1974, a total of 76 TKA surgeries were performed in 66 patients diagnosed with OA (n = 48), rheumatoid arthritis (n = 27), and ankylosing spondylitis (n = 1). Clinical outcomes were assessed pre-operatively and between one to three years post-operatively using a Knee Evaluation Index developed by the authors from information gathered during the clinical evaluation. This index allocated points (perfect score = 100) for pain, function, and neutral alignment with deductions for flexion contracture, stability, and deformity (varus or valgus). Lower extremity alignment and component position were assessed at an initial post-operative period using a Roentgenogram Index that allocated points (perfect score = 100) for tibiofemoral angle, tibial component placement in the AP and lateral views, and femoral component placement in the AP view. Based on this index, criteria for optimal component positioning included a tibiofemoral angle of 3º to 7º valgus, an AP femoral component angle of 4º to 6º valgus along with both an AP and lateral tibial component angle of 0º. The mean clinical outcome scores improved from 50 points pre-operatively to 82 points post-operatively with a mean post-operative roentgenogram score of 78.2 points in OA patients. Correlation coefficients and paired t-tests indicated a significant ($p < 0.05$) correlation between clinical outcomes and roentgenogram scores. The authors concluded that component positioning influenced clinical outcomes following TKA and suggested that malalignment may lead to deterioration of the joint components. As less than 10% of all patients had a perfect roentgenogram score, the authors also concluded that accurate position of the components is difficult to achieve[21].

Subsequently, Hood et al.[39] investigated the success rate of TKA using radiographs in a series of 225 consecutive TKA surgeries performed in 181 patients diagnosed with OA (84%) and rheumatoid arthritis (16%) between November 1978 and March 1980. In this series, 43 patients underwent revision TKA and 182 patients underwent primary TKA surgery. Radiographs were obtained pre- and post-operatively for all patients using the same method as that reported by Lotke and Ecker[21]. The authors reported long radiographs including the hip and ankle joints were evaluated, however could not be used due to logistic and technical issues. The ideal range for tibiofemoral angle was defined as 2º to 12º valgus and was achieved in 89% of the patients post-operatively. Neutral placement of the tibial component was achieved in 42% of the patients in the AP view and within 2.0º in 72% of the patients in the lateral view. The highest amount of patients ($n = 39$) demonstrated AP femoral component placement in 7º valgus with 67% between 4º and 8º valgus. The authors concluded their results provided a valid representation of post-operative alignment and component position following TKA surgery[39].

With earlier investigations of TKA outcomes reporting acceptable ranges for post-operative alignment, Tew and Waugh[20] hypothesized TKA would be most successful with post-operative tibiofemoral alignment between 4.0º to 10.0º valgus. A retrospective review of 428 records of TKA was conducted to assess tibiofemoral alignment recorded initially between 6 and 14 months post-operatively and again from 6 months to 9 years following the first measurement. Clinical measurement of tibiofemoral angle (Q-angle) was obtained using a short-armed goniometer during the initial years when TKA surgery was performed. To improve the accuracy of this method, tibiofemoral angle was later measured using a goniometer with longer arms extending to the hip and ankle joints with the patients in the supine position. The authors stated due to a lack of consistency and reliability with radiographs, clinical measurements of tibiofemoral angle were the preferred method. The knees reviewed were stratified into subgroups based on tibiofemoral alignment for analysis as 1) > 2.0º varus, 2) between 2.0º varus to 2.0º valgus, 3) 3.0º to 7.0º valgus, 4) 8.0º to 12.0º valgus, and 5) > 12.0º valgus. Results indicated failure rates were significantly higher ($p < 0.001$) in knees with > 2.0º varus and > 12.0º valgus alignment compared to the intermediate alignment groups. Drift into deformity over time was indicated by the increased amount of knees in the groups with > 2.0º varus (31 to 57) and > 12.0º (22 to 41) valgus from the first to last review period. In knees initially aligned between 2.0º varus and 12.0º valgus, the rate of failure was significantly higher ($p < 0.001$) in knees that drifted out of this range (32 of 53; 60.4%) compared to knees that retained initial post-operative alignment (65 of 322; 20.2%). Out of the total failures ($n = 122$), 65 knees retained initial post-operative alignment between 2.0º varus and 12.0º valgus. Knees aligned between 3.0º to 7.0º valgus demonstrated significantly less ($p < 0.001$) drift into deformity compared to the other alignment groups and accounted for 23 of the total 122 knee failures (18.9%). The authors concluded that knees realigned between 2.0º varus and 12.0º valgus demonstrated the lowest risk of failure and a post-operative tibiofemoral angle of 5.0º valgus was optimal to retain this alignment range[20].

Although reference guides for measurement of post-operative lower extremity alignment and component positioning were provided in the preceding investigations, the reliability of these measurements had yet to be reported. Ilahi et al.[40] investigated the inter- and intra-observer variability of tibiofemoral angle measured on radiographs obtained from 36 patients (20 males and 16 females; age range = 19 to 64 years). Short radiographs (35 × 43 cm) in the AP view were obtained at a source to image distance of 1.1 m from all participants in a standing position (knees together). Tibiofemoral angle was measured twice, bilaterally for all participants by four different physicians separated by one month using conventional methods as previously described[21,39,41]. Tibiofemoral angle was also measured clinically as the angle between the palpable shafts of the femur and tibia using a standard goniometer with the knee fully extended. The mean clinical and radiographic tibiofemoral angles were 5.6º and 4.0º of valgus respectively. Intra-observer variation of radiographic tibiofemoral angle was assessed with comparisons of the two measurements performed by the same physician. Inter-observer variation was assessed with comparisons of the measurements performed by each physician to each measurement of the other three physicians. The intra-observer variation was estimated with 95% and 98% confidence to be within 3.1º and 4.0º respectively. The inter-observer variation was estimated with 95% confidence to be within 3.7º among measurements of the four physicians. A one-way ANOVA indicated significant differences ($p<0.05$) among measurements of the four physicians. The authors concluded the variability in tibiofemoral angle measured from short radiographs should be considered during the pre-operative planning process and the post-operative evaluation of alignment[40].

While short radiographs were an established tool to quickly assess TKA, the accuracy of measurements obtained from this modality continued to be criticized due to the limited distances provided above and below the knee joint line for locating the femoral and tibial anatomic axes[40,43]. Along with high variability[40], the use of short radiographs have previously been reported to magnify the center of the intramedullary canal at the intersection of the femoral and tibial axes[40], and underestimate tibiofemoral alignment[43]. Whereas the routine use of longer radiographs was not yet feasible[39], and lacked reliability[20], subsequent investigations established protocols for obtaining radiographs including the hip and ankle joints. In these investigations, measurement of tibiofemoral angle was based on protocols involving more defined anatomic landmarks to locate the femoral and tibial anatomic axes[43,44,50].

Previous attempts had been made to assess alignment using long radiographs, however, due to logistical and technical problems no method had been established for routine use in clinical practice[39]. Moreland et al.[36] developed a method to measure mechanical axis of the lower extremity on long radiographs obtained from 25 asymptomatic males. A 35.6 × 129.5 cm cassette loaded with three 35.6 × 43.2 cm conventional screen-films was used to obtain radiographs including the hip and ankle joints. To obtain radiographs in the AP view, all participants were positioned 2.4 m from the x-ray tube that projected beams at a setting of 50 $mA \cdot s^{-1}$ and 70 kV. The center of the femoral head was located using a template of concentric circles developed by Mose[92]. The center of the knee was visually selected as the midpoint of five points including the centers of the 1) femoral intercondylar notch, 2) femoral condyles at the level of the top of the intercondylar notch, 3) tibia, 4) tips of the tibial spines, and 5) soft tissue at the level of the cartilaginous space. The center of the ankle was located in a similar manner by visual selection of the midpoint of the following three points including the centers of the 1) talus, 2) external surface of the malleoli, and 3) soft tissue proximal to the level of cartilaginous space. The mechanical axis of the femur was measured by drawing a line from the center of the femoral head to the center of the knee. The mechanical axis of the tibia was defined as a line drawn from the center of the knee to the center of the ankle. The overall mechanical axis of the lower extremity was defined as a line drawn from the center of the femoral head to the center of the ankle. The mean angle of intersection between the mechanical axes of the femur and tibia was 178.5º ± 2.0º for the right knee and 178.9º ± 2.1º for the left knees. The authors concluded varus alignment with high variation was to be expected in the normal knee[36].

With normative values now established for mechanical axis, Peterson and Engh[43] investigated lower extremity alignment from long radiographs obtained from patients following TKA. Radiographs in the AP view on 14 × 17 inch short films and 14 × 51 inch long films were obtained for 50 knees with TKA in 43 patients (35 female, 15 male; mean age 68.7 years). The authors also expanded upon the findings of Moreland et al.[36] with the addition of methods to measure tibiofemoral angle on long and short radiographs using defined anatomic landmarks. Tibiofemoral alignment of the knee was defined as the angle between the anatomic axes of the femur and tibia[43,44] with an acceptable range of 4° to 10° valgus. On the long radiographs, the femoral anatomic axis was defined as a line extending from the isthmus to a point 10 cm above the knee joint line in the middle cortex of the femur. The full-length tibial anatomic axis was defined as a line extending from a point 10 cm below the knee joint line to the center of the talus. Femoral and tibial anatomic axes on short radiographs were located between the same 10 cm points from the knee joint line to far proximal points as allowed on the radiographs in the middle cortex of the femur and tibia respectively. The mechanical axis was measured as described by Moreland et al.[36]. A significant difference ($p < 0.001$) was reported between the mean tibiofemoral angle measured on short films (5.8º ± 3.1º) and long films (7.2º ± 3.9º). The authors further examined the radiographs in nine cases with alignment differences greater than 3º attributing measurement variances to femoral and tibial bowing along with difficulty locating the anatomic axes on short films. The authors stated short radiographs were inaccurate due to the limited distances provided above and below the knee joint line for locating the femoral and tibial anatomic axes. Another limitation of the short radiographs were indices with the radiographic plate not centered on the joint resulting in further limited distances to located the anatomic axes. The authors concluded that due to the significant amount of knees outside of the acceptable alignment range, surgeons should critically analyze the results when evaluating TKA in terms of alignment. The authors did not make any final recommendations regarding the preferred use of either short or long radiographs[43].

Patel et al.[44] found similar results to the previous investigation[43] in their comparison of tibiofemoral alignment measured from short and long films in a series of 50 knees with TKA in 34 participants (24 female, 10 male; mean age 69.7). Tibiofemoral alignment was measured as previously described[43] from AP radiographs on 14 × 16 inch short films and 14 × 38 inch long films. A mean difference of 1.6º was reported between the mean tibiofemoral angle measured on short films (5.3º ± 2.6º) and long films (6.9º ± 3.0º). No significant differences were reported between the groups of short and long film measurements. A Mann-Whitney U two-tailed test indicated there were significant differences ($p < 0.0013$) between the pairs of measurements obtained from both films. The authors concluded that although short radiographs underestimated tibiofemoral alignment, this method was adequate for routine TKA follow-up appointments in the clinic setting. Long radiographs were recommended for research and scientific documentation[44].

Due to the inconsistency in lower extremity alignment reported in previous investigations[36,43,50], Jenny et al.[37] proposed this variability may be attributed to the small sample size (n = 25) used to established the normative data for mechanical axis in the investigation by Moreland et al.[36]. Therefore, variability in various alignment angles of the lower extremity in a larger sample (n = 100; 69 males and 31 females; age range = 17 to 62 years) was further investigated[37]. Long radiographs in the AP view were obtained with a source to image distance of 2.5 m for one randomly selected lower limb. All participants were instructed to stand, fully weight bearing on the selected leg with the knee in full extension. The mechanical femoral axis was defined as a line from the center of the femoral head to the highest point of the femoral intercondylar notch. Mose circles[92] were used to locate the center of the femoral head. A bicondylar femoral axis was defined as a line between the lowest points on the medial and lateral femoral condyles. The anatomic tibial axis was defined as a line between the center of the tibial spines and the lowest point of the tibial plafond. The bicondylar tibial axis was defined as a line between lowest points of the medial and lateral tibial condyles. A goniometer was used to manually measure 1) femoro-tibial angle, 2) distal femoral angle, and 3) proximal tibial angle. Similar to the mechanical axis, the femoral-tibial angle was measured between the mechanical femoral and anatomic tibial axis. The distal femoral angle was measured between the mechanical and bicondylar femoral axes. The proximal tibial angle was measured between the anatomic and bicondylar axes of the tibia. Both the distal femoral and proximal tibial angles recorded after subtracting 90º with a positive value for varus alignment. Criteria for neutral alignment included a femoro-tibial angle of 0º, a distal femoral angle of -3º, and a proximal tibial angle of 3º. The mean femoro-tibial angle (1.4º ± 2.8º) was estimated with 95% confidence to be between -3.5º and 8.5º. The mean distal femoral angle (-1.5º ± 2.2º) was estimated with 95% confidence to be between -6.5º and 3.0º. The mean proximal tibial angle (1.9º ± 2.3º) was estimated with 95% confidence to be between -2.5º and 6.5º. No participant demonstrated the three angles to meet "normal criteria. Regression analyses indicated none of the alignment angles measured in this study were significantly affected by age. Student's t-tests indicated no significant differences between males and females for all alignment angles. Similar to the findings of Moreland[36], the authors concluded there was high variability in all lower extremity alignment angles that were not significantly influenced by age and gender[37].

The most recent investigations[33,45] comparing alignment between short and long radiographs have lead to conflicting results to that of previous reports[41,43,44]. Skyttä et al.[45] expanded upon these previous investigations with the addition of comparisons between component alignment angles on short and long radiographs along with tibiofemoral angle and mechanical axis. Inter- and intra-observer variability of all alignment angles were also investigated from measurements conducted by two radiologists on a sub-sample of radiographs. The mean post-operative mechanical axis was 179.2º ± 3.9º with high intra- (r = 0.92) and inter-observer (r = 0.907) correlation coefficients. On long radiographs, the mean tibiofemoral angle was 175.5º ± 3.8º with high intra- (r = 0.958), and inter-observer (r = 0.911) correlation coefficients. On short radiographs the mean tibiofemoral angle was 175.4º ± 3.6º with slightly lower intra- (r = 0.917) and inter-observer (r = 0.807) correlation coefficients. On long radiographs, the mean femoral component angle was 95.2º ± 2.8º with moderately high intra- (r = 0.775) and inter-observer (r = 0.840) correlation coefficients. On short radiographs the mean femoral component angle was 95.8º ± 2.6º with moderately high intra- (r = 0.879) and inter-observer (r = 0.880) correlation coefficients. The tibial component angle was nearly identical between long (89.0º ± 2.0º) and short (89.0º ± 2.1º) radiographs. The intra-observer variation was moderately high for the tibial component angle on long (r = 0.716) and short radiographs (r = 0.813). The inter-observer reliability of the tibial component angle was moderately low between the long (r = 0.596) and short (r = 0.512) radiographs. The authors concluded that tibiofemoral angle and component position can be reliably and accurately measured from both short and long radiographs [45].

The high test-retest reliabilities of the mechanical axis and tibiofemoral measurements in the previous investigation[45] were attributed to a standardized technique of patient positioning and obtaining the radiographs. While radiographs have generally been obtained with patients standing, foot position has been emphasized in many investigations in an attempt to minimize rotation of the knee on the radiographs which has been reported to distort alignment of the lower extremity[37,40,45]. External and internal rotation of the knee have been reported to exaggerate the degree of varus and valgus alignment respectively[36]. Another factor that can distort alignment on knee radiographs is magnification. The projected image on the detector becomes enlarged due to the diverging x-ray beams emanating from the tube[57]. To minimize magnification, it is recommended that a standard object be placed next to the patient when the radiograph is taken to calibrate measurements of length[57]. Peterson and Engh[43] identified radiographic magnification as a source of error in their investigation. Inconsistent source to image distance (distance from the x-ray tube to the patient) can also contribute to magnification error. Previous investigations reported radiographs were obtained at a source to image distance ranging from 1.1 to 2.5 m[36,37,45].

Along with the technical sources of error associated with obtaining radiographs, conventional screen-film systems are limited by a fixed non-linear gray scale response and contrast[90,93]. Linear gray scale response refers to the capacity of the detector to accurately display exposure levels as differences in various tissue densities[48]. As long radiographs have become incorporated into routine clinical evaluations for TKA, increased technical difficulty in acquiring an accurate image has been reported due to the differences in soft tissue densities at the hip and ankle[34]. These variations in tissue thickness can result in overexposure around the hip and underexposure around the ankle on radiographs[94]. Although conventional screen-film has multiple functions as the image detector, storage, and display medium, loss of permanent information is a risk in the event radiographs become lost or misplaced[94]. Other limitations of conventional radiography includes the cost of film, the inability to view the same image simultaneously in more then one location, and the capacity to produce only one copy of an original radiograph at a time[90,94]. Advancements in technologies have lead to the production of radiographs using digital imaging techniques with the capacity for image reprocessing, permanent storage of information, electronic distribution of images to multiple locations, and the potential to reduce radiation to patients through greater detector efficiency[93-95].

Digital Radiography

Digital imaging consists of four separate steps of image generation, processing, archival, and display[89]. Images are generated using a digital detector that absorbs exposed x-rays emitted by a standard tube. Image processing is completed using post-processing software that organizes the raw data into a clinically meaningful image. The final images are then sent to a digitized storage medium by an image acquisition device for archiving and digital presentation on a computer workstation[89]. As many radiology departments have transitioned into digital format, conventional radiographs have been transformed into digital images using film digitizers[32,96]. The four steps of digital imaging are commonly obtained using computed radiography.

Computed Radiography (CR). Introduced in 1980, cassette-based storage-phosphor image plates were first used to generate digital images from x-rays[89,97]. In contrast to conventional radiography, storage-phosphor image plates are used instead of film in the cassette serving as the digital detector in current CR systems[48,89,95,97]. Most widely used for digital imaging[94,98], storage-phosphor image plates contain a detective layer of photostimulable phosphor crystals scattered unstructurally into resin material (termed unstructured scintillators)[48,89,97]. Image generation in CR involves two steps. First, the image plate is exposed to x-rays exciting the phosphor crystals for absorption and temporary storage of energy in the detective layer[48,89,97]. The quality of the image obtained with CR systems depends upon several properties of the digital detector including spatial resolution, dynamic range, and contrast resolution[89,94]. Defining the shape of characteristics within an image, spatial resolution refers to the spacing of pixels in reference to the original image size producing separation between high-contrast objects[89,94]. After the x-ray beam passes through the patient, the energy in the phosphor crystals is stored as picture elements (pixels) collected two-dimensionally into a matrix producing a digital image[89,94]. Thus, a larger the matrix or smaller pixel size maximizes spatial resolution. The amount of x-ray exposure in each pixel is measured as a gray level (expressed as bits). Therefore, the dynamic range of the image refers to the range of gray levels in each pixel representing the range of x-ray exposure that a meaningful image can be generated. Lastly, contrast resolution refers to the distribution of various gray level values contained in the dynamic range of the image[94].

Following x-ray exposure is the readout process in which the image plate is scanned pixel by pixel with a laser beam and stored energy is converted into electrical charges. Defined as photostimulable luminescence, during scanning of the image plate, radiation from the laser stimulates the phosphor crystals to released stored energy as emitted light (luminescence radiation)[48,94,95]. The light is collected into an array of photomultiplier tubes and converted to electrical charges with an analog-to-digital converter[48,89,95,97]. Following image generation, software is used to process the raw image data for digital presentation.

Picture Archiving and Communications Systems (PACS). Developed in response to the increased demand for radiographic images with digital modalities, PACS are commonly used in the busy outpatient clinic setting[99]. The components of PACS include an image acquisition device, data management system, data storage device, transmission network, and digital image display stations[99]. An analog-to-digital converter serves as the image acquisition device inputting the digital image from the CR system into PACS for image processing, archival, and presentation[99]. Interface between PACS and the physician occurs at computer workstations where digital images are displayed for assessment using compatible PACS software[99]. Algorithms within the software alter processing of digital images with noise reduction, artifact removal, edge and contrast enhancement[89]. Among the technical properties of detectors previously discussed, spatial resolution cannot be changed once the digital image is generated[89]. However, PACS can be used to further enhance image quality during image processing through alteration of dynamic range and contrast resolution. The window level function in PACS software can be used transform the gray scale levels of pixels within a specific range to be displayed over the full dynamic range enhancing the contrast of the image[93,94]. Additional software functions including pan, zoom, and gray scale inversion can be used to manipulate digital images to further improve the visibility of anatomic structures on digital radiographs[89,98].

The same standard alignment measurements that have been established for radiographic examination of TKA can be conducted using CR systems. In recent investigations, digital alignment measurements have involved selection of the same anatomic landmarks by mouse-click on a PACS workstation for automatic angle calculation using custom measurement software[22,42,54,88]. As previously defined in earlier investigations that used conventional radiographs[43,44], digital measurement of tibiofemoral alignment follows the same definition as the angle between the anatomic axes of the femur and tibia. The middle cortex of the femur and tibia involved selection of two points on the cortical margins at the distal and proximal levels on the femur and tibia. Following selection of these points, the axes of the femur and tibia along with the tibiofemoral angle were automatically displayed on the workstation[22]. Other investigations have involved the use of measurement software with icons to draw the relevant axes on the digital image following location of anatomic landmarks[38]. Mechanical axis has been measured digitally as the angle between the mechanical axes of the femur and tibia as previously described[36]. The center of the femoral head was located center as the of a close-fit circle inserted around the edge of the femoral head[32,55]. The center of the knee and ankle were located as the midpoint of a line between the lateral and medial margins of the tibial plateau and plafond, respectively[32,55].

Digital Lower Extremity Alignment Measurements. Digital measurements obtained using CR systems have been shown to be valid and reliable for assessment of lower extremity alignment [22,42,54,88]. Sanfridsson et al.[42] established intra- and inter-observer reliability for a digital method of measuring lower limb alignment in ten healthy asymptomatic participants (1 female, 9 males; age range 35-55 years). All participants were positioned in a frame and digital radiographs were obtained using a CR system (Fuji AC-2) with three 35 × 43 cm photostimulable phosphor storage plates (Fuji ST-V). All digital radiographs were archived, processed and displayed at a workstation using PACS software. Bony landmarks were manually selected by mouse-click for calculation of nine different alignment angles and ten distances of the lower limb. The capito-midcondylar axis was calculated from selections of the centers of the femoral head and intercondylar notch. The capito-midmalleolar axis was calculated from selections of the centers of the femoral head and mid-point between the medial and lateral malleoli. The transcondylar axis was defined as a line tangent to the medial and lateral femoral condyles. The nine angles were calculated between the 1) capito-midcondylar axis and tibial shaft, 2) femoral and tibial shafts, 3) capito-midcondylar axis and femoral shaft, 4) capito-midcondylar and capito-midmalleolar axes, 5) femoral neck and femoral shaft, 6) femoral shaft and transcondylar axis, 7) capito-midcondylar and transcondylar axis, 8) tibial plateau and tibial shaft, and 9) flexion. All lower limb alignment angles were measured twice, bilaterally for all participants by two different radiologists separated by 1 to 7 days for a total of 80 measurements. Intra-observer variation was assessed with comparisons of all measurements performed between the two radiologists. All measurements were also performed once by an orthopaedic surgeon. Inter-observer variation was assessed with comparisons of the first measurements performed by one radiologist and measurements of the same exposure performed by the orthopedic surgeon. Mean differences with 95% confidence limits indicated both intra- and inter observer variation was low for lower limb alignment measurements except for the angle between the femoral neck and shaft. The intra-observer variation for the angle between the capito-midcondylar axis and tibial shaft (mechanical axis) was ±0.40º in both the flexed and extended position. The inter-observer variation for this angle was ±0.46º and ±0.48º in the flexed and extended positions, respectively. The intra-observer variation for the angle between the femoral and tibial shafts (anatomic axis) was ±0.36º and ±0.40º in the flexed and extended positions, respectively. The inter-observer variation for this angle was ±0.48º and ±0.50º in the flexed and extended positions, respectively. The authors concluded the QPR method reduced variability in measurements of lower limb alignment and was reliable for radiographic assessment of the weight-bearing knee[42].

Similarly, Takahashi et al.[22] investigated the validity and reliability of a digital method for measuring tibiofemoral alignment on radiographs of 73 knees in 52 participants (42 females, 10 males; age range 43-92 years) diagnosed with OA. Using the Kellgren and Lawrence[63] classification system, the severity of OA among the knees measured was found to be grade 2 (n = 30), grade 3 (n = 31), and grade 4 (n = 12). Short radiographs on film (30 × 40 cm) recorded by phosphor storage plates were obtained using a computer radiography system and archived in a multimodality workstation. Measurement of the tibiofemoral angle was performed twice by three orthopaedic surgeons using the digital method, and once using the manual method. Similar to Peterson and Engh[43], the tibiofemoral angle was defined the angle between the anatomic axes of the femur and tibia. The anatomic axis of the femur was defined as the line between a point 10 cm above the knee joint line to another point as far proximal as allowed over 15 cm above the joint in the middle cortex of the femur. The tibial anatomic axis was defined as the line between a point 10 cm below the knee joint line to another point as far distal as allowed over 15 cm below the joint in the middle cortex of the tibia. Manual measurement was conducted using a goniometer. Digital measurements consisted of manual selection by mouse-click of the two points on the cortical margins at the distal and proximal levels of the femur and tibia. Following selection of these points, the axes of the femur and tibia along with the tibiofemoral angle were automatically displayed on the workstation. Intra-class correlation (ICC) coefficients indicated approximately 97% of measurements among each of the three observers and between the two measurements of all observers, were within 1.125º and 1.12º, respectively. Variability between the manual and digital measurements was also low (ICC range 0.915 to 0.932). Based on these findings, the authors concluded their computer-assisted method provided accurate digital measurements of tibiofemoral alignment[22].

Similarly, Sailer et al.[54] compared full-length lower extremity alignment between conventional and digital radiographs obtained from 24 participants (16 female, 8 male; mean age 68.6 ± 10.2 years). Original sized radiographs were obtained using a conventional film screen system (20 × 96 cm or 30 × 120 cm) with a measurement grid. Digital radiographs were obtained using a full-length cassette holder (ADC, AGFA Diagnostic center) with three overlapping 35 × 43 cm phosphor storage plates (ADCC/MD, AGFA Diagnostic Center Cassette). Lower extremity alignment was quantified as the axial deviation of the mechanical axis. Measurements of mechanical axes of the femur and tibia were performed on conventional and digital radiographs by three board-certified radiologists. Conventional measurements were performed using a goniometer. Digital radiograph measurements consisted of manual selection of the same anatomic landmarks by mouse-click on a PACS workstation using custom measurement software (IMPAX, AGFA-GEVART, Belgium). The mechanical axes were automatically drawn with the angle displayed by the software. Dependent t-tests indicated no significant differences in the mean axis deviation on conventional (6.71 ± 3.84º) and digital radiographs (6.08 ± 3.67º). Spearman's correlation coefficient indicated higher interobserver reliability for digital radiographs (ρ = 0.91) compared to the conventional method (ρ = 0.74). Additionally, the mean time requirement for each measurement was significantly lower using the computer-assisted method (1.08 min/patient) compared to conventional radiographs (4.9 min/patient). The authors concluded computer-assisted measurement on digital radiographs was a valid method to determine lower extremity axial alignment angle[54].

Whereas Sailer et al.[54] compared conventional and digital measurements of lower limb alignment in healthy participants, Rozzanigo et al.[88] conducted a similar investigation in 40 participants (19 females, 21 males; age range 12-82 years) with a congenital or acquired alignment deformity. All participants were positioned standing with a radiopaque graduated marker between both limbs for digital calibration of all measurements. All digital radiographs were obtained using a remote-controlled device (Omnidiagnost, Philips Medical Systems, Eindoven - Netherlands) then archived, processed, and displayed at a workstation (Easy Vision, Philips Medical Systems, Eindoven - Netherlands). All digital radiographs were printed in 35 × 43 cm format and an orthopaedic surgeon conventionally measured all alignment angles on transparent paper placed over the image. All digital measurements were performed by a radiologist and alignment angles were automatically calculated by the software program following manual selection of 9 anatomic landmarks. Comparisons were made between conventional and digital measurements angles between 1) the femoral mechanical axis and line tangent to the femoral condyles (medial distal femoral angle), 2) the tibial anatomic axis and line tangent to the tibial plateau (medial proximal tibial angle), and 3) femoral mechanical and tibial anatomic axes (femoral-tibial angle; mechanical axis).

Dependent t-tests indicated no significant differences in all three alignment angles measured between conventional and digital radiographs. In addition to the analyses of differences between the two methods, conventional and digital measurements of the same alignment angles were conducted from a sub-sample of 20 lower limbs by five different orthopaedic surgeons to assess inter-observer variability. Fisher's F-test indicated no significant differences in conventional and digital measurements in 78% of the cases for inter-observer variability. Alignment was found to be less variable when measured digitally compared to conventional measurements in the remaining cases at 5% and 17%, respectively. Similar to the findings of Sanfridsson et al.[42] and Sailer et al.[54] the authors concluded computer-assisted measurements of lower limb alignment on digital radiographs was comparable in accuracy and reliability to conventional radiography[88].

Although methods were emerging for digital measurement of the knee alignment, Goker and Block[55] reported a need for further simplified methods with higher sensitivity in assessing the lower limb with radiographs. The authors sought to validate quantification of knee alignment angles through a new method that used standard full-limb radiographs and software freely available to the public for access. A total of 14 patients (10 females, 4 males; mean age = 60.1 ± 8.3 years, BMI = 29.2 ± 4.5 kg/m^2) with symptomatic OA were included in this study. Mechanical axis was measured conventionally according to Moreland et al.[36] and on digital radiographs twice, bilaterally for all participants by the same observer separated by one to two days. All digital measurements were obtained using PACS software (Image J, National Institutes of Health, Bethesda, MD) that is freely available to the public (http://rsb.info.nih.gov/ij/). The mechanical axis was measured using the software macro "measure angle and length" after the mechanical axes of the femur and tibia were drawn digitally. The mechanical axis of the femur was generated as a line extending from the center of the femoral head to the center of the intercondylar notch. The center of the femoral head was located as the center of a close-fit circle inserted around the edge of the femoral head. The tibial axis was generated as a line extending from the proximal and distal tibial midpoints. The proximal and distal tibial midpoints were located as the midpoint of a line between the lateral and medial margins of the tibial plateau and plafond respectively. Linear regression indicated approximately 96% (R^2 = 0.96) of the variance in the digital measurement of mechanical axis (1.52º ± 3.41º varus) was attributed to conventional measurements (1.75º ± 3.49º varus). Bland-Altman plots indicated the minimum detectable change in measurements between both days was lower when obtained digitally (0.4º) compared to the conventional method (1.6º). The authors concluded precision and reproducibility in measuring mechanical axis of the lower limb on long radiographs is improved when using digital compared to conventional radiography methods[55].

Previous researchers reported the validity and reliability of various digital methods to assess lower limb alignment, however, these investigations involved participants with a wide spectrum of joint conditions ranging from asymptomatic to severe knee pathology. Although Sailer et al.[54] included participants with TKA, their investigation compared mechanical axis between conventional and digital radiographs in participants who also had THA along with varus or valgus deformity with no joint replacement. Similar to Takahashi et al.[22], Prakash et al.[100] compared manual and digital methods of tibiofemoral alignment, however, their investigation involved measurements of 65 knees with TKA. Tibiofemoral alignment was measured manually twice by two orthopaedic surgeons and two clerical observers as described by Peterson and Engh[43] from AP radiographs on 30 × 40 cm short films. Conventional radiographs were digitized using a flatbed scanner (JX-610, Japan) and converted to a grey scale by a computer algorithm that automatically identifies edges of the femur and tibia. The digitized image was then subtracted leaving a plot of the grey scale values. The anatomic axes of the femur and tibia with same locations used for the manual measurements were determined by another algorithm for calculation of the tibiofemoral angle. A mean difference of 1.6º was reported between the mean tibiofemoral angle measured on short films (5.3 ± 2.6º) and long films (6.9 ± 3.0º). Paired t-tests indicated there were no significant differences in the pairs of measurements, between observers and both methods. Pearson's correlation coefficients indicated moderately high reliability between the two measurements conducted by the same observer (ranging from 0.792 to 0.873) and among observers (ranging from 0.712 to 0.810). There was a moderate to high association between conventional and digital measurements obtained by each observer (ranging from 0.553 to 0.809). The authors concluded their computer assisted method reduced the errors in tibiofemoral alignment by eliminating manual selection of reference points by the operator[100].

Alternative Assessment of Lower Extremity Alignment

The use of long radiographs for measurement of lower extremity alignment has been criticized for increased administration of radiation to the patient and increased technical difficulty in acquiring an accurate image due to the soft tissue differences at the hip and ankle. Due to the potential increased health risks to patients and cumbersome method of obtaining long radiographs, investigations of alternative methods for the assessment of lower extremity alignment have recently emerged[34,35,38].

Kraus et al.[34] investigated the relationship between three alternative methods to assess lower extremity alignment. Participants included 40 females (mean age 65.7 ± 11.9; BMI 31.7 ± 6.7 kg/m^2), and 17 males (mean age 68.8 ± 8.1; BMI 29.6 ± 18.3 kg/m^2) with symptomatic and radiographic OA. Lower extremity alignment was assessed for both knees in all participants using the mechanical axis measured on full-length radiographs in the AP view. Alternative assessments of lower extremity alignment were also conducted for both knees including measurements of anatomic axis from 1) fixed-flexion radiographs in the posteroanterior view, 2) full-length radiographs in the AP view, and 3) physical examination using a goniometer. To obtain a fixed-flexion radiographs, participants were positioned in a frame for placement of the feet in 10º of external rotation and with the knees in contact with the anterior portion of the frame. The anatomic axis was defined as the angle between lines extending from the center of the tibial spine tips to a point 10 cm distally bisecting the femur and tibia respectively. Bivariate analysis indicated BMI ($r = 0.36$, $p = 0.005$) and the severity of OA ($r = 0.41$, $p = 0.001$) were significantly associated with the degree of malalignment but not age or gender. Multivariate analysis indicated the severity of OA ($p = 0.0005$) was significantly associated with the degree of malalignment but not BMI. Linear regression analysis indicated a significant correlation between mechanical axis and anatomic alignment measured on the fixed-flexion ($r = 0.75$, $p < 0.0001$) and AP long radiographs ($r = 0.65$, $p < 0.0001$). Analysis resulted in the following prediction equation for mechanical axis using anatomic axis measured from the fixed flexion radiograph: mechanical axis = 53.69

+ 0.69(anatomic axis). The prediction equation for mechanical axis using anatomic alignment from the long radiograph in the AP view was: mechanical axis = 55.86 + 0.67(anatomic axis). Additionally, linear regression analysis was used to determine the angle offset for anatomic axis using the alternative methods resulting in a 4.3º valgus offset from mechanical axis. The authors concluded the alternative methods for measuring lower extremity alignment were valid and more accessible for the clinic setting in comparison to measurements obtained from long radiographs[34].

Similarly, Hinman et al.[35] investigated the relationship between mechanical axis and anatomic alignment measured clinically and on radiographs of knees with medial compartment OA in 40 participants (mean age 64.7 ± 9.4; BMI 29.6 ± 4.2 kg/m^2; 24 female; 16 male). Conventional radiographs in the AP view including the hip and ankle joints were obtained with a 35.6 × 91.4 cm or a 35.6 × 129.5 cm (depending on height) cassette with all participants positioned using foot maps 2.4 m from the x-ray tube that projected beams at a setting of 25 mA·s^{-1} and 100 kV. Mechanical axis was measured as previously described by Sharma et al.[9] and anatomic axis was measured as described in the previous investigation by Kraus et al.[34]. Similar to the previous investigation[34], linear regression analysis indicated a significant correlation between mechanical axis and anatomic alignment ($r = 0.88$, $p < 0.001$) with the following prediction equation: mechanical axis = 13.915 + 0.915(anatomic axis). The authors concluded the anatomic axis, inclinometer, and calipers are valid methods for measuring alignment in participants with OA[35].

While the previous investigations[34,35] reported estimates of mechanical axis using anatomic alignment in participants with mild to moderate OA, Chang et al.[38] evaluated the influence of gender, advanced OA, and TKA on mechanical axis in addition to tibiofemoral angle. Post-operative lower extremity alignment was evaluated for a control group of 45 females (mean age 44.8 ± 11.7; BMI 24.2 ± 4.9 kg/m^2) and 54 males (mean age 33.5 ± 11.1; BMI 24.1 ± 2.9 kg/m^2) and in a cohort of 52 females (mean age 68.7 ± 6.2; BMI 26.5 ± 3.6 kg/m^2) and 50 males (mean age 70.3 ± 5.4; BMI 26.1 ± 2.9 kg/m^2) with advanced OA prior to TKA surgery (OA group) and following TKA (TKA group). All participants were positioned weight-bearing on a reference template with a set foot angle and with the knee in full extension to obtain short and long radiographs in the AP view. All radiograph images were processed digitally using PACS for measurement of mechanical axis, anatomic alignment, femoral and tibial bowing angles, and tibial plateau shift angle. Mechanical axis was measured as previously described by Moreland et al.[36]. Tibiofemoral angle was measured using two different methods. The first method involved measuring the femoral and tibial anatomic axes using points 10 cm proximal to the knee. The second measurement involved extending these points to 15 cm proximal to the knee. Linear regression analyses indicated the second measurement for tibiofemoral angle accounted for a greater portion of the variability (ranging from an increase of 11% to 18%) in overall mechanical axes than the first measurement. Based on the findings of this study, the authors recommend the use of more distant reference points (15 cm from the knee) for standard measurement of tibiofemoral angle when using short radiographs[38].

Implications of Alignment on TKA Outcomes

An important goal of TKA is to correct lower extremity malalignment through accurate component placement to restore neutral mechanical and anatomical axes[21,27-29]. Post-operative lower extremity malalignment has been reported to be a significant predictor of TKA failure[18-20], and has been associated with poorer clinical outcomes including greater knee pain and decreased functional ability due to excessive uneven stress within the knee joint[21-24]. Therefore, the purpose of realigning the knee with the hip and ankle through component position is to redistribute forces evenly across the knee joint [50].

The consequences of improper component positioning including post-operative lower extremity malalignment, early aseptic loosening, and ultimately TKA failure have been well documented [17-19,26,27,29]. Dorr et al.[41] investigated of factors associated with mechanical loosening of the components in a series of 55 TKA surgeries performed in 43 patients diagnosed with OA (n = 17, knees = 19) and rheumatoid arthritis (n = 26, knees=36). Short radiographs (17 inches in length) were obtained pre- and post-operatively for all participants for measurement of tibiofemoral and component alignment as described by Lotke and Ecker[21]. Alignment measurements were categorized into three groups based on tibiofemoral angle as group 1 (< 3° valgus), group 2 (3 to 9° valgus), and group 3 (> 9° valgus). Density of the tibial condyles obtained from a densitometer (X-Rite model 301) was expressed as a ratio between the medial and lateral condyles. A ratio of 0.89 obtained from density measurements of 27 radiographs of knees with no acute and history of injury was considered normal. Categorized according to tibiofemoral alignment, higher ratios indicated a higher density in the medial plateau (varus). Participants aligned in less than 3.0º valgus demonstrated significantly greater ($p < 0.001$) density in the medial tibial condyle than the normal ratio. There were no significant differences between density ratios for the normal group and knees aligned in 3.0º to 9.0º valgus, however, the mean ratio for eight knees with medial tibial plateau loading (contact of the femoral and tibial condyles on either the medial or lateral side) in this alignment group was 1.14. Based on the postoperative densitometry ratios, the authors stated accurate lower extremity alignment evenly distributes load in the knee joint and results in a lower incidence of TKA failures[41].

Jeffery et al.[26] investigated the association between post-operative mechanical axis and the incidence of component loosening following TKA surgery. A total of 115 TKA surgeries were performed in 102 patients diagnosed with OA ($n = 50$) and rheumatoid arthritis ($n = 52$) between 1976 and 1981. Long radiographs were obtained pre- and post-operatively for all participants for measurement of mechanical axis, tibiofemoral angle, and the distance from the mechanical axis to the center of the tibial plateau. Long radiographs were obtained again for 68 knees in 58 patients available at a minimum of eight years for long-term review. The percentage of knees with a post-operative mechanical axis passing through the central third of the knee improved from 13% pre-operatively to 68% post-operatively with a corresponding tibiofemoral angle between 4° and 10° valgus. This finding was demonstrated in 65% of the knees at the long-term follow-up period. A total of 11 (10%) knees in this series demonstrated clinical and radiographic signs of component loosening or underwent revision TKA surgery. A Fisher's exact test indicated post-operative alignment passing outside of the central third of the knee was significantly ($p = 0.001$) related to subsequent component loosening. A total of 37 knees with post-operative varus or valgus alignment outside of the central third of the knee resulted in 9 incidences (24%) of component loosening. The authors concluded the post-operative mechanical axis should pass through the central third of the knee which corresponds to a tibiofemoral angle of $7.0° \pm 3.0°$ valgus[26].

Due to discrepancies in the literature regarding the location of the post-operative mechanical axis, Ritter et al.[29] investigated the degree of varus or valgus alignment that can be tolerated and still result in successful TKA outcomes. A total of 421 TKA surgeries (113 bilateral; 308 unilateral) were performed between 1975 and 1983 in knees with OA (n = 253), rheumatoid arthritis (n = 60), and osteonecrosis (n = 10). Tibiofemoral alignment was measured from 14 × 17 inch short radiographs in the AP view with the patient in standing position. The patients were initially stratified into six groups based on tibiofemoral angle as 1) > 5.0º varus, 2) 1.0º to 5.0º varus, 3) 0.0º to 4.0º valgus, 4) 5.0º to 8.0º valgus, 5) 9.0º to 10.0º valgus, and 6) > 10.0º valgus. Due to the small amount of participants with extreme varus or valgus alignment, groups one through three were combined to form a varus group (n = 35; < 4.0º valgus), group 4 represented the normal group (n = 234; 5.0º to 8.0º valgus), and groups 5 and 6 represented the valgus group (n = 82; > 9.0º valgus). In this series there were a total of eight failures that underwent revision TKA surgery. The varus and normal groups accounted for five and three failures respectively. Kaplain-Meir curves indicated the survival rates for TKA were significantly different ($p < 0.05$) between the varus and normal groups; and between the varus and valgus groups. There was no significant difference in survival rate between the normal and valgus groups. The authors conducted a subsequent review of 442 revision TKA surgeries performed between 1975 and 1990 at the same institution. In this series 244 knees that underwent revision TKA demonstrated varus alignment, while 140 were in neutral and 58 in valgus. The authors concluded surgeons should strive to achieve post-operative tibiofemoral alignment in neutral or slight valgus with placement of TKA components[29].

Sharkey et al.[17] conducted a retrospective review to investigate the mechanisms of TKA failure. A total of 212 consecutive revision TKA surgeries were performed in 128 females (mean age 68.4 years; height 161.884 cm; weight 87.14 kg) and 75 males (mean age 68.7 years; height 177.8 cm; weight 95.93 kg). Participants requiring revision TKA less than two years following their initial TKA surgery were classified as the early failure group. Participants requiring revision TKA more than two years following their initial TKA surgery were classified as the late failure group. The most common overall mechanism of TKA failure was polyethylene wear (25%), followed by component loosening (24.1%), and instability (21.2%). The most common mechanisms of TKA failure for the early failure group were infection (25.4%), instability (21.2%), component loosening (16.9%), and arthrofibrosis (16.9%). The most common mechanisms of TKA failure for the late failure group were polyethylene wear (44.4%), component loosening (34.4%), and instability (22.2%). Malalignment or malposition of the components accounted for 11.9% and 12.2% of the TKA revisions in the early and late failure groups, respectively. Although this mechanism of TKA failure was lower than other rates, the authors reported it was likely that component malalignment or malposition lead to subsequent loosening and ultimately TKA failure. The authors concluded improvements in instrumentation and technique are vital for optimum component placement and fixation[17].

While previous investigations found polyethylene wear to be the most common mechanism for TKA failure[17], Berend et al.[18] sought to determine the cause of tibial component failure in the absence of this mechanism. Between 1983 and 2000, 3152 TKA surgeries performed in 2125 patients for OA were reviewed at a minimum follow-up period of two years. Radiographs in the AP and lateral views were obtain from 14 × 17 inch cassettes for all participants. Tibiofemoral anatomic axes were measured conventionally using a goniometer to determine overall limb alignment. Additional radiographic assessments included measurement of tibial component alignment, polyethylene wear, and radiolucent lines. Tibial component failure occurred in 41 of the total 3152 (1.3%) TKA surgeries. The most prevalent mechanism of failure was medial tibial collapse accounting for 20 of the 41 knees that failed. Regression tree analysis indicated placement of the tibial component in more than 3º varus alignment significantly ($p < 0.0001$) increased the odds for TKA failure. Varus tibial component malalignment, pre- and post-operative varus tibiofemoral malalignment were significant predictors ($p < 0.0001$) of this mechanism of failure. When varus tibial component alignment was combined with BMI, there was a 168-fold increase ($p < 0.0001$) in TKA failure. The authors reported the findings of this study supported the theory that excessive loading of the medial compartment could be the path of TKA failure as the combination of BMI and varus tibial component alignment along with varus lower extremity malalignment significantly influenced medial tibial collapse[18].

Fang et al.[19] expanded upon the previous investigation of Berend et al.[18] with the addition of TKA patients comprised in the subsequent six years. Their study included a retrospective review of 6070 TKAs in 3992 patients performed between 1983 and 2006. The purpose of this follow-up investigation was to determine the necessity of lower extremity alignment correction in the coronal plane and all mechanical failures. Participants were stratified into a neutral alignment group (n = 4029; 4.8º ± 2.5º valgus tibiofemoral angle), varus alignment group (n = 1222; < 1 SD mean tibiofemoral angle), and valgus alignment group (n = 819; > 1 SD mean tibiofemoral angle). Pre- and post-operative AP tibiofemoral angles were measured from 14 × 17 inch short radiographs for all participants. Kaplan-Meier survivor analysis indicated the revision rate for knees placed in neutral tibiofemoral alignment at 0.5% was significantly lower than that of varus or valgus aligned knees at 1.8% ($p < 0.0017$) and 1.7% ($p < 0.0028$), respectively. Similarly, the fail rate for knees placed in neutral tibiofemoral alignment at 0.5% was significantly lower than that of varus or valgus aligned knees at 1.8% ($p < 0.0004$) and 1.5% ($p < 0.0027$), respectively. Medial tibial collapse accounted for 13 of the 18 varus malaligned knees that failed. The risk for failure due to medial tibial collapse was 6.9 times higher ($p < 0.0001$) for TKAs placed in varus tibiofemoral malalignment compared to neutrally aligned knees. Furthermore, this analysis indicated no significant differences in survivorship based on pre-operative tibiofemoral varus, valgus, or neutral alignment. With a relatively low failure rate for TKAs placed within ±5° of neutral alignment, the authors concluded there was no single degree that can be defined as the optimal post-operative tibiofemoral angle. Based on the survivorship of TKA in this investigation, the authors recommend surgeons strive to correct lower extremity malalignment to between 2.4° and 7.2° valgus for post-operative tibiofemoral alignment[19].

Bankes et al.[27] investigated the effect of pre-operative lower extremity deformity on post-operative clinical outcomes and component alignment. A total of 198 TKA surgeries were performed in 194 patients with varus deformity secondary to OA (n = 159) or valgus deformity secondary to rheumatoid arthritis (n = 39). A subsample of participants were further stratified into a varus group (n = 86) or valgus group based on pre-operative coronal alignment of the knee. Radiographs on 18 × 48 cm short film were obtained for all participants in the AP and lateral views. Coronal alignment of the knee was defined as the angle between the anatomic axes of the femur and tibia. The authors considered 4 to 10º of valgus ideal for post-operative lower extremity alignment. The AP femoral component alignment was defined as the medial angle between the anatomic axis of the femur and horizontal axis tangent to the femoral condyles. The AP tibial component alignment was defined as the medial angle between the anatomic axis of the tibia and horizontal axis tangent to the tibial tray. Sagittal femoral component alignment was defined as the angle between the midline axis of the femur and a line perpendicular to the femoral component. Sagittal tibial component alignment was defined as the posterior angle between the midline axis of the tibia and horizontal axis tangent to the tibial tray. These component alignment angles are similar to the reference guides reported by Lotke and Ecker[21], and Hood, Vanni, and Insall[39]. The mean AP femoral and tibial component angles were 96.04º ± 2.94º and 88.23º ± 1.81º, respectively. The mean sagittal femoral and tibial component angles were 4.05º ± 1.21º and 89.67º ± 1.96º, respectively. The mean tibiofemoral angle was 4.28º ± 3.56º with 64.6% of patients within the ideal range of 4º to 10º of valgus. Factorial ANOVA indicated patients with varus deformity demonstrated significantly higher ($p < 0.001$) varus alignment of the tibial component, KSS, and KSS function scores. Pre-operative coronal alignment had no significant effect on AP femoral component alignment or lateral femoral and tibial component alignment angles. The authors concluded excessive varus placement of the tibial component produced tibiofemoral malalignment[27].

With the association between post-operative malalignment and TKA failure[18] [18,19,25] surgeons are recommended to restore lower extremity alignment within a neutral range. However, the optimum range for neutral alignment continues to be a topic of debate among orthopaedic surgeons. A variety of ranges for post-operative tibiofemoral angle have been reported in the literature including valgus alignment between 2.4° to 7.2°[19], 4° to 10°[26,27,43], 2° to 12°[39], and 3° to 7°[21]. Due a reportedly low failure rate for TKAs placed within $\pm 5^{\circ}$ of neutral tibiofemoral alignment, it has been concluded that there is no single degree that can be defined as the optimal for post-operative tibiofemoral angle[19]. A mechanical axis of 0° has been previously suggested[37], however a general guideline recommending that the mechanical axis pass through the central third of the knee is more widely accepted[26]. While there have been fewer recommendations regarding placement of the femoral component, a neutral range has been previously defined as valgus positioning between 4° to 6°[21]. Neutral placement of the tibial component has been considered to be perpendicular to the long axis of the tibia or within 3° of varus or valgus alignment[21,37,39].

Considering the high variability in post-operative outcomes in previous investigations, it has been acknowledged that "normal" alignment is difficult to achieve as a moderate amount of patients have demonstrated alignment outside ideal ranges[21,26,39,43]. Nevertheless, radiographic examination is still recommended during pre-operative planning and post-operative evaluation of TKA[36,44] with careful consideration of this variability[40,43]. Digital radiography has been shown to reduce variability in alignment measurements[42,54,88] through the reprocessing and image enhancement capabilities of CR systems[93,94]. Regardless of imaging technique, it is important to understand how to interpret radiographic parameters when evaluating lower extremity and component alignment. Understanding the overall variability of post-operative alignment outcomes in practice and recognizing component malalignment as a mechanism of TKA failure provides information to improve implant longevity.

APPENDIX A

KNEE SOCIETY SCORE

ID _______________ Surgery Date: ___________________ Today's Date: ___________________

Follow-up Period:

Pre-op 6 weeks 3 mo 6 mo 1 yr 2 yr 3 yr

Patient Category:

A1. Bilateral, opposite normal knee
A2. Unilateral, opposite normal knee
B. Unilateral, other knee symptomatic
C. Multiple arthritis or medial infirmity

Objective Scoring

Pain	**Points**
None	50
Mild or occasional	45
Stairs only	40
Walking & stairs	30
Moderate	
Occasional	20
Continuous	10
Severe	0

Range of Motion

(5º = 1 point)	25

Stability

AP	
<5 mm	10
5-10 mm	5
10 mm	0
Mediolateral	
<5º	15
6º - 9º	10
10º - 14º	5
15º	0
Subtotal:	

Deductions ____________________

Flexion Contracture	
5º - 10º	2
10º - 15º	5
16º - 20º	10
>20º	15
Extension Lag	
<10º	5
10º - 20º	10
>20º	15
Alignment	
5º - 10º	0
0º - 4º	3 points each degree
11º - 15º	3 points each degree

Total deductions: ____________________

Knee score: ____________________

Functional Scoring

Walking	**Points**
Unlimited	50
>10 blocks	40
5-10 blocks	30
<5 blocks	20
Housebound	10
Unable	0

Stairs	
Normal up & down	50
Normal up, down with rail	40
Up & down with rail	30
Up with rail; unable down	15
Unable	0

Subtotal: ________________

Functional Deductions

Cane	5
Two Canes	10
Crutches or walker	20

Total deductions: ________________

Function Score: ________________

Bibliography

1. Felson DT. An update on the pathogenesis and epidemiology of osteoarthritis. Radiol Clin North Am. 2004;42:1-9, v.
2. Teichtahl AJ, Cicuttini FM, Janakiramanan N, Davis SR, Wluka AE. Static knee alignment and its association with radiographic knee osteoarthritis. Osteoarthritis Cartilage. 2006;14:958-62.
3. Hunter DJ et al. Structural factors associated with malalignment in knee osteoarthritis: the Boston osteoarthritis knee study. J Rheumatol. 2005;32:2192-9.
4. Cicuttini F, Wluka A, Hankin J, Wang Y. Longitudinal study of the relationship between knee angle and tibiofemoral cartilage volume in subjects with knee osteoarthritis. Rheumatology (Oxford). 2004;43:321-4.
5. Helmick CG et al. Estimates of the prevalence of arthritis and other rheumatic conditions in the United States. Part I. Arthritis Rheum. 2008;58:15-25.
6. Lawrence RC et al. Estimates of the prevalence of arthritis and other rheumatic conditions in the United States. Part II. Arthritis Rheum. 2008;58:26-35.
7. Felson DT, Naimark A, Anderson J, Kazis L, Castelli W, Meenan RF. The prevalence of knee osteoarthritis in the elderly. The Framingham Osteoarthritis Study. Arthritis Rheum. 1987;30:914-8.
8. Brouwer GM, van Tol AW, Bergink AP, Belo JN, Bernsen RM, Reijman M, Pols HA, Bierma-Zeinstra SM. Association between valgus and varus alignment and the development and progression of radiographic osteoarthritis of the knee. Arthritis Rheum. 2007;56:1204-11.
9. Sharma L, Song J, Felson DT, Cahue S, Shamiyeh E, Dunlop DD. The role of knee alignment in disease progression and functional decline in knee osteoarthritis. Jama. 2001;286:188-95.
10. Issa SN et al. Full-limb and knee radiography assessments of varus-valgus alignment and their relationship to osteoarthritis disease features by magnetic resonance imaging. Arthritis Rheum. 2007;57:398-406.
11. Chang CB, Koh IJ, Seo ES, Kang YG, Seong SC, Kim TK. The radiographic predictors of symptom severity in advanced knee osteoarthritis with varus deformity. Knee. 2010 Sep 15 [Epub ahead of print].
12. Maquet PGT. Biomechanics of the Knee: With Application to the Pathogenesis and the Surgical Treatment of Osteoarthritis. Berlin: Springer-Verlag: 1976. 230 p.
13. Singh JA, Vessely MB, Harmsen WS, Schleck CD, Melton LJ, Kurland RL, Berry DJ. A Population-Based Study of Trends in the Use of Total Hip and Total Knee Arthroplasty, 1969-2008. Mayo Clin Proc. 2010.
14. Quam JP, Michet CJ, Jr., Wilson MG, Rand JA, Ilstrup DM, Melton LJ, 3rd, Wallrichs SL. Total knee arthroplasty: a population-based study. Mayo Clin Proc. 1991;66:589-95.
15. Kurtz S, Ong K, Lau E, Mowat F, Halpern M. Projections of primary and revision hip and knee arthroplasty in the United States from 2005 to 2030. J Bone Joint Surg Am. 2007;89:780-5.

16. Saleh KJ, Santos ER, Ghomrawi HM, Parvizi J, Mulhall KJ. Socioeconomic issues and demographics of total knee arthroplasty revision. Clin Orthop Relat Res. 2006;446:15-21.
17. Sharkey PF, Hozack WJ, Rothman RH, Shastri S, Jacoby SM. Why are total knee arthroplasties failing today? Clin Orthop Relat Res. 2002:7-13.
18. Berend ME, Ritter MA, Meding JB, Faris PM, Keating EM, Redelman R, Faris GW, Davis KE. Tibial component failure mechanisms in total knee arthroplasty. Clin Orthop Relat Res. 2004:26-34.
19. Fang DM, Ritter MA, Davis KE. Coronal alignment in total knee arthroplasty: just how important is it? J Arthroplasty. 2009;24:39-43.
20. Tew M, Waugh W. Tibiofemoral alignment and the results of knee replacement. J Bone Joint Surg Br. 1985;67:551-6.
21. Lotke PA, Ecker ML. Influence of positioning of prosthesis in total knee replacement. J Bone Joint Surg Am. 1977;59:77-79.
22. Takahashi T, Yamanaka N, Komatsu M, Ogawa Y, Yoshida S, Yamamoto H. A new computer-assisted method for measuring the tibio-femoral angle in patients with osteoarthritis of the knee. Osteoarthritis Cartilage. 2004;12:256-9.
23. Choong PF, Dowsey MM, Stoney JD. Does accurate anatomical alignment result in better function and quality of life? Comparing conventional and computer-assisted total knee arthroplasty. J Arthroplasty. 2009;24:560-9.
24. Longstaff LM, Sloan K, Stamp N, Scaddan M, Beaver R. Good alignment after total knee arthroplasty leads to faster rehabilitation and better function. J Arthroplasty. 2009;24:570-8.
25. Collier MB, Engh CA, Jr., McAuley JP, Engh GA. Factors associated with the loss of thickness of polyethylene tibial bearings after knee arthroplasty. J Bone Joint Surg Am. 2007;89:1306-14.
26. Jeffery RS, Morris RW, Denham RA. Coronal alignment after total knee replacement. J Bone Joint Surg Br. 1991;73:709-14.
27. Bankes MJ, Back DL, Cannon SR, Briggs TW. The effect of component malalignment on the clinical and radiological outcome of the Kinemax total knee replacement. Knee. 2003;10:55-60.
28. McGrory JE, Trousdale RT, Pagnano MW, Nigbur M. Preoperative hip to ankle radiographs in total knee arthroplasty. Clin Orthop Relat Res. 2002:196-202.
29. Ritter MA, Faris PM, Keating EM, Meding JB. Postoperative alignment of total knee replacement. Its effect on survival. Clin Orthop Relat Res. 1994:153-156.
30. Math KR, Schneider R, Pavlov H, Ghelman B. Imaging of the Knee. In: Insall, JN, and Scott, WN. *Surgery of the Knee*. Vol. 2. 3rd ed. Philadelphia, PA: Churchill Livingstone; 2001. p. 95-160.
31. Specogna AV, Birmingham TB, Hunt MA, Jones IC, Jenkyn TR, Fowler PJ, Giffin JR. Radiographic measures of knee alignment in patients with varus gonarthrosis: effect of weightbearing status and associations with dynamic joint load. Am J Sports Med. 2007;35:65-70.
32. Specogna AV et al. Reliability of lower limb frontal plane alignment measurements using plain radiographs and digitized images. J Knee Surg. 2004;17:203-10.

33. Colebatch AN, Hart DJ, Zhai G, Williams FM, Spector TD, Arden NK. Effective measurement of knee alignment using AP knee radiographs. Knee. 2009;16:42-5.
34. Kraus VB, Vail TP, Worrell T, McDaniel G. A comparative assessment of alignment angle of the knee by radiographic and physical examination methods. Arthritis Rheum. 2005;52:1730-5.
35. Hinman RS, May RL, Crossley KM. Is there an alternative to the full-leg radiograph for determining knee joint alignment in osteoarthritis? Arthritis Rheum. 2006;55:306-13.
36. Moreland JR, Bassett LW, Hanker GJ. Radiographic analysis of the axial alignment of the lower extremity. J Bone Joint Surg Am. 1987;69:745-749.
37. Jenny JY, Boeri C, Ballonzoli L. Coronal alignment of the lower limb. Acta Orthop. 2005;76:403-7.
38. Chang CB, Choi JY, Koh IJ, Seo ES, Seong SC, Kim TK. What should be considered in using standard knee radiographs to estimate mechanical alignment of the knee? Osteoarthritis Cartilage. 2010;18:530-8.
39. Hood RW, Vanni M, Insall JN. The correction of knee alignment in 255 consecutive total condylar knee replacements. Clin Orthop Relat Res. 1981:94-105.
40. Ilahi OA, Kadakia NR, Huo MH. Inter- and intraobserver variability of radiographic measurements of knee alignment. Am J Knee Surg. 2001;14:238-42.
41. Dorr LD, Conaty JP, Schreider R, Mehne DK, Hull D. Technical factors that influence mechanical loosening of total knee arthroplasty. *The knee: papers of the first scientific meeting of the knee society*. Vol. ed.; 1984. p. 121-135.
42. Sanfridsson J, Svahn G, Jonsson K, Ryd L. Computed radiography for characterisation of the weight-bearing knee. Acta Radiol. 1997;38:514-9.
43. Petersen TL, Engh GA. Radiographic assessment of knee alignment after total knee arthroplasty. J Arthroplasty. 1988;3:67-72.
44. Patel DV, Ferris BD, Aichroth PM. Radiological study of alignment after total knee replacement. Int Orthop. 1991;15:209-210.
45. Skytta ET, Lohman M, Tallroth K, Remes V. Comparison of standard anteroposterior knee and hip-to-ankle radiographs in determining the lower limb and implant alignment after total knee arthroplasty. Scand J Surg. 2009;98:250-3.
46. McDaniel GE, Vail TP, Kraus VB. Comparison of knee alignment angle by x-ray and goniometer. Arthritis Rheum. 50(Suppl. 9): S343, 2004.
47. Lin WP, Lin J, Horng LC, Chang SM, Jiang CC. Quadriceps-sparing, minimal-incision total knee arthroplasty: a comparative study. J Arthroplasty. 2009;24:1024-32.
48. Sonoda M, Takano M, Miyahara J, Kato H. Computed radiography utilizing scanning laser stimulated luminescence. Radiology. 1983;148:833-8.
49. Lindhardt FE. Clinical experiences with computed radiography. Eur J Radiol. 1996;22:175-85.
50. Hsu RW, Himeno S, Coventry MB, Chao EY. Normal axial alignment of the lower extremity and load-bearing distribution at the knee. Clin Orthop Relat Res. 1990:215-27.
51. Shrout PE, Fleiss JL. Intraclass correlations: uses in assessing rater reliability. Psychol Bull. 1979;86:420-8.

52. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. J Strength Cond Res. 2005;19:231-40.
53. Insall JN, Dorr LD, Scott RD, Scott WN. Rational of the knee society clinical rating system. Clin Orthop Relat Res. 1989:13-14.
54. Sailer J, Scharitzer M, Peloschek P, Giurea A, Imhof H, Grampp S. Quantification of axial alignment of the lower extremity on conventional and digital total leg radiographs. Eur Radiol. 2005;15:170-173.
55. Goker B, Block JA. Improved precision in quantifying knee alignment angle. Clin Orthop Relat Res. 2007;458:145-9.
56. Tashiro Y, Miura H, Matsuda S, Okazaki K, Iwamoto Y. Minimally invasive versus standard approach in total knee arthroplasty. Clin Orthop Relat Res. 2007:144-150.
57. Lee JHE. Section One, Imaging Modalities. In: Johnson, TR, and Steinbach, LS. *Essentials of musculoskeletal imaging*. Vol. 1st ed ed. Rosemant, IL: American Academy of Orthopaedic Surgeons; 2004. p. 1-29.
58. Yamanaka N, Takahashi T, Ichikawa N, Yamamoto H. Posterior-anterior weight-bearing radiograph in 15 degree knee flexion in medial osteoarthritis. Skeletal Radiol. 2003;32:28-34.
59. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet. 1986;1:307-10.
60. Sheehy L, Felson D, Zhang Y, Niu J, Lam YM, Segal N, Lynch J, Cooke TD. Does measurement of the anatomic axis consistently predict hip-knee-ankle angle (HKA) for knee alignment studies in osteoarthritis? Analysis of long limb radiographs from the multicenter osteoarthritis (MOST) study. Osteoarthritis Cartilage. 2011;19:58-64.
61. Felson DT, Cooke TD, Niu J, Goggins J, Choi J, Yu J, Nevitt MC. Can anatomic alignment measured from a knee radiograph substitute for mechanical alignment from full limb films? Osteoarthritis Cartilage. 2009;17:1448-52.
62. Felson DT, Zhang Y, Hannan MT, Naimark A, Weissman BN, Aliabadi P, Levy D. The incidence and natural history of knee osteoarthritis in the elderly. The Framingham Osteoarthritis Study. Arthritis Rheum. 1995;38:1500-5.
63. Kellgren JH, Lawrence JS. Radiological assessment of osteo-arthrosis. Ann Rheum Dis. 1957;16:494-502.
64. Oliveria SA, Felson DT, Reed JI, Cirillo PA, Walker AM. Incidence of symptomatic hand, hip, and knee osteoarthritis among patients in a health maintenance organization. Arthritis Rheum. 1995;38:1134-1141.
65. Bellamy N, Buchanan WW, Goldsmith CH, Campbell J, Stitt LW. Validation study of WOMAC: a health status instrument for measuring clinically important patient relevant outcomes to antirheumatic drug therapy in patients with osteoarthritis of the hip or knee. J Rheumatol. 1988;15:1833-40.
66. Laskin RS, Beksac B, Phongjunakorn A, Pittors K, Davis J, Shim JC, Pavlov H, Petersen M. Minimally invasive total knee replacement through a mini-midvastus incision: an outcome study. Clin Orthop Relat Res. 2004:74-81.
67. Fisher DA, Watts M, Davis KE. Implant position in knee surgery: a comparison of minimally invasive, open unicompartmental, and total knee arthroplasty. J Arthroplasty. 2003;18:2-8.

68. Haas SB, Cook S, Beksac B. Minimally invasive total knee replacement through a mini midvastus approach: a comparative study. Clin Orthop Relat Res. 2004:68-73.
69. Stern SH. Surgical Exposures in Total Knee Arthroplasty. In: Fu, FH, Harner, CD, and Vince, KG. *Knee Surgery*. Vol. 2. ed. Baltimore, MD: Williams and Wilkins; 1994. p. 1289-1302.
70. Insall JN, Easley ME. Surgical Techniques and Instrumentation in Total Knee Arthroplasty. In: Insall, JN, and Scott, WN. *Surgery of the Knee*. Vol. 2. 3rd ed. Philadelphia, PA: Churchill Livingstone; 2001. p. 1553-1620.
71. King J, Stamper DL, Schaad DC, Leopold SS. Minimally invasive total knee arthroplasty compared with traditional total knee arthroplasty. Assessment of the learning curve and the postoperative recuperative period. J Bone Joint Surg Am. 2007;89:1497-503.
72. Insall J. A midline approach to the knee. J Bone Joint Surg Am. 1971;53:1584-6.
73. Scuderi GR, Tenholder M, Capeci C. Surgical approaches in mini-incision total knee arthroplasty. Clin Orthop Relat Res. 2004:61-7.
74. Whiteside LA, Arima J. The anteroposterior axis for femoral rotational alignment in valgus total knee arthroplasty. Clin Orthop Relat Res. 1995:168-72.
75. Arima J, Whiteside LA, McCarthy DS, White SE. Femoral rotational alignment, based on the anteroposterior axis, in total knee arthroplasty in a valgus knee. A technical note. J Bone Joint Surg Am. 1995;77:1331-4.
76. Schroer WC, Diesfeld PJ, Reedy ME, Lemarr AR. Surgical accuracy with the mini-subvastus total knee arthroplasty a computer tomography scan analysis of postoperative implant alignment. J Arthroplasty. 2008;23:543-9.
77. Tria AJ, Jr., Coon TM. Minimal incision total knee arthroplasty: early experience. Clin Orthop Relat Res. 2003:185-90.
78. Wulker N, Lambermont JP, Sacchetti L, Lazaro JG, Nardi J. A prospective randomized study of minimally invasive total knee arthroplasty compared with conventional surgery. J Bone Joint Surg Am. 2010;92:1584-90.
79. Karpman RR, Smith HL. Comparison of the early results of minimally invasive vs standard approaches to total knee arthroplasty: a prospective, randomized study. J Arthroplasty. 2009;24:681-8.
80. Boerger TO, Aglietti P, Mondanelli N, Sensi L. Mini-subvastus versus medial parapatellar approach in total knee arthroplasty. Clin Orthop Relat Res. 2005;440:82-7.
81. Engh GA, Holt BT, Parks NL. A midvastus muscle-splitting approach for total knee arthroplasty. J Arthroplasty. 1997;12:322-31.
82. Haas SB, Manitta MA, Burdick P. Minimally invasive total knee arthroplasty: the mini midvastus approach. Clin Orthop Relat Res. 2006;452:112-6.
83. Hofmann AA, Plaster RL, Murdock LE. Subvastus (Southern) approach for primary total knee arthroplasty. Clin Orthop Relat Res. 1991:70-7.
84. Pagnano MW, Meneghini RM. Minimally invasive total knee arthroplasty with an optimized subvastus approach. J Arthroplasty. 2006;21:22-6.
85. Chin PL, Foo LS, Yang KY, Yeo SJ, Lo NN. Randomized controlled trial comparing the radiologic outcomes of conventional and minimally invasive techniques for total knee arthroplasty. J Arthroplasty. 2007;22:800-6.

86. Kolisek FR et al. Clinical experience using a minimally invasive surgical approach for total knee arthroplasty: early results of a prospective randomized study compared to a standard approach. J Arthroplasty. 2007;22:8-13.
87. Dalury DF, Dennis DA. Mini-incision total knee arthroplasty can increase risk of component malalignment. Clin Orthop Relat Res. 2005;440:77-81.
88. Rozzanigo U, Pizzoli A, Minari C, Caudana R. Alignment and articular orientation of lower limbs: manual vs computer-aided measurements on digital radiograms. Radiol Med. 2005;109:234-8.
89. Korner M, Weber CH, Wirth S, Pfeifer KJ, Reiser MF, Treitl M. Advances in digital radiography: physical principles and system overview. Radiographics. 2007;27:675-86.
90. Bansal GJ. Digital radiography. A comparison with modern conventional imaging. Postgrad Med J. 2006;82:425-8.
91. Ritenour ER. Physics overview of screen-film radiography. Radiographics. 1996;16:903-16.
92. Mose K. Methods of measuring in Legg-Calve-Perthes disease with special regard to the prognosis. Clin Orthop Relat Res. 1980:103-9.
93. Freedman M, Steller D. Digital radiography of the musculoskeletal system: the optimal image. J Digit Imaging. 1995;8:37-42.
94. Buckwalter KA, Braunstein EM. Digital skeletal radiography. AJR Am J Roentgenol. 1992;158:1071-80.
95. Murphey MD, Quale JL, Martin NL, Bramble JM, Cook LT, Dwyer SJ, 3rd. Computed radiography in musculoskeletal imaging: state of the art. AJR Am J Roentgenol. 1992;158:19-27.
96. Wong AK, Inglis D, Beattie KA, Doan A, Ioannidis G, Obeid J, Adachi JD, Papaioannou A. Reproducibility of computer-assisted joint alignment measurement in OA knee radiographs. Osteoarthritis Cartilage. 2009;17:579-85.
97. Lança L, Silva A. Digital radiography detectors - A technical overview: Part 1. Radiography. 2009;15:58-62.
98. Pettersson H. Digital skeletal radiology. J Digit Imaging. 1995;8 Suppl. 1:43-4.
99. Choplin RH, Boehme JM, 2nd, Maynard CD. Picture archiving and communication systems: an overview. Radiographics. 1992;12:127-9.
100. Prakash U, Wigderowitz CA, McGurty DW, Rowley DI. Computerised measurement of tibiofemoral alignment. J Bone Joint Surg Br. 2001;83:819-24.