

Computer Navigation in Primary Total Knee Arthroplasty

James B. Stiehl, MD

INTRODUCTION

Numerous authors have investigated outcomes following total knee arthroplasty (TKA) and found that malalignment $>3^\circ$ resulted in a significantly higher potential for mechanical loosening and implant failure. Petersen and Engh³⁰ investigated the radiographic results of 50 patients who underwent primary TKA with conventional methods, noting a 26% failure to achieve alignment within the optimal 3° of varus or valgus from the mechanical axis. Jeffery et al¹⁵ noted satisfactory postoperative coronal alignment (mechanical axis deviation $<3^\circ$) in 68% of TKAs. In operated knees with mechanical axis deviation $>3^\circ$ in the coronal plane, a mechanical loosening rate of 24% occurred at 8 years, as opposed to 3% mechanical loosening for normally aligned knees.¹⁵ Berend et al⁴ investigated tibial component failure mechanisms, noting that malalignment of the tibial component $>3^\circ$ of varus increased the odds of failure.

Computer-assisted navigation of TKA has been shown to produce improved mechanical axis alignment in the clinical setting and offers significant advantage particularly in cases with severe deformity resulting from long-standing arthritis or traumatic etiologies.*

Access to the bony landmarks with open procedures has made TKA navigation a feasible system while using imageless referencing protocols. Saragaglia et al³³ introduced the first kinematic navigation protocol for determining the centers of the hip and ankle, and this paved the way for a reproducible and simple imageless approach. Optical tracking has been the primary data accrual method for most current systems, although ultrasound or electromagnetic

technologies are available.^{1,8,10,12,24} This review discusses the technology, clinical methods, and outcomes offered by current methods of computer navigation in TKA.

COMPONENTS OF A COMPUTER NAVIGATION SYSTEM

Three elements are required for computer navigation: 1) the computer platform, 2) the tracking system, and 3) the group of Dynamic Reference Bases, which constitute the target objects of the navigation procedure. These target objects include the patient's bones, surgical instruments, and implants that are used in the surgical procedure. The practicing surgeon is faced with important choices regarding each of these components as a variety of options exist. The surgeon should be knowledgeable of the possible sources of measurement error that may be demonstrated by a computer navigation system.

Computer Platform

The most basic component of a computer navigation system is the computer for which the system relies for coordination of inputs from the surgical field, mathematical interpretation of the data sets, and the display of the resultant information on a monitor. Currently used systems require hardware capable of a robust, real-time calculation. Commonly, this results in the pairing of powerful microprocessors and software platforms based on Unix or Linux systems. These base operating systems are considered more responsive and stable for the use of mission critical applications. The measurement system is designed in such a fashion that the three-dimensional position of objects or targets in the operative field can be determined with low error—much as a global positioning satellite system would function. Computer platforms may be considered “closed” or “proprietary,” if the navigation provides

Dr Stiehl is from the Medical College of Wisconsin, Columbia St Mary's Hospital, Milwaukee, Wisc.

Correspondence: James B. Stiehl, MD, 575 W Riverwoods Pkwy, #204, Milwaukee, WI 53212.

*2, 3, 5-7, 9, 13, 14, 16, 19, 23, 28, 29, 31, 33, 34, 36, 41-43

support limited to a specific implant system or surgical technique. The other possibility is an open system, which is more general and allows, for example, a software protocol to support the implantation of total knees from different manufacturers. The advantage of a proprietary system is that more elaborate representations usually are supported such that "virtual" implant sizing to a "virtual" reconstruction of the patient's anatomy can be performed. This, however, may add time and complexity to the surgical procedure and must be balanced against the simplicity of the open system.

A typical "capital" system will have a rolling cart with computer, keyboard, mouse, LCD monitor, foot pedal activator, and an optical tracking camera. The optical camera may be situated on a boom or separate tower to allow placement in the appropriate position during the operative procedure. The optical camera system typically will have two charged coupled device (CCD) receivers that will pick up laser impulses from an active tracker or reflected beam from passive balls attached to a passive tracker. Recently, portable options have been developed with virtually the same hardware and applications but with smaller desktop computers and cameras or tracking devices that may be quickly assembled from a suitcase. This allows manufacturers' representatives to conveniently bring in a full navigation system for limited one-time use as a service that may be purchased by the hospital. This is an available option for the surgeon new to computer navigation who may not be committed to asking his hospital to purchase a capital system, as well as low volume surgeons and hospitals that may not have resources to afford the large investment for more permanent systems.

Tracking Technologies

An important element of any computer navigation system is the mechanism or technology chosen to track the target or object. The basic elements are trackers that can be attached to the patient's bones or surgical instruments. These trackers are used in an environment, which consists of a camera, electromagnetic coil, or ultrasonic probe, that will pick up laser or electromagnetic pulses that originate from these trackers. Recently, video monitoring has been added as a "real-time" tracking option, but this method has not reached significant clinical application.

Optical tracking systems require two or three CCD cameras to pick up laser impulses from the trackers, which are recognized by a minimum of three and possibly four or five active emitters or passive reflective balls. The computer calculates the three-dimensional position of the trackers based on the recognition of the spatial footprint of the tracker emitters. The footprint of each tracker is unique and allows differentiation of bones, instruments, and implants. Optical cameras function by being placed six to eight feet from the object trackers and must have an

unobstructed "line of sight" to the trackers. The operating personnel must be aware of this relationship, but if positioning is optimal, the staff readily adapt to the requirement. Clinical validation studies of optical tracking systems have demonstrated high reliability and accuracy with a typical translational error of 0.25 mm.^{22,31,44} This absolute measurement error increases trigonometrically with increasing distance from the camera position.³⁷

Electromagnetic tracking relies on small trackers that create an electromagnetic impulse, which is recognized by an electromagnetic coil placed 20-30 inches away.^{25,27} These trackers can be placed inside of the wound but require small wires that go directly to the computer system for activation. The magnetic coil measures the interference created by the tracker as it moves in the electromagnetic field. The disadvantage of current electromagnetic tracking systems is the distortion of the field created by ferrous metals that are inherently magnetic, but any metal such as brass or copper, and even non-metals, such as Kevlar (DuPont, Richmond, Va), may interfere. Current computer algorithms have been calibrated to shut down the system if distortion is recognized. However, the electromagnetic approach remains vulnerable to many other potential distorting fields found in a typical operating room. Clinical validation studies have identified this problem, and although the electromagnetic system seems to perform with the precision of current optical systems at the 0.5-mm level, the occasional outlier may be off by several degrees, which makes this method less reliable.^{1,10,12,23}

Referencing Methods

Referencing of the target objects is the most significant problem for the surgeon and requires a thorough knowledge of both the technology and desired anatomical points to be matched on the virtual computer model. The process is to define points in space with a tracker that can be triangulated by the tracking system. For surgical instruments, a referencing tool allows the surgeon to capture the marked instrument such as a pointer probe. The precision of the instrument will be within 250-500 μ m of error.²² Imageless referencing is possible if the targeted objects are directly visible, and is most applicable in TKA. Numerous studies have demonstrated the efficacy of imageless referencing compared to conventional instrumentation for TKA, but these results depend on the expertise of the surgeon to choose the correct reference points.¹⁹ Computer algorithms are written with the assumption that the ideal point will be selected. For example, referencing of one universal total knee protocol recommends that the femoral center be chosen as a point that is under the roof of the intercondylar notch and lies on both the transepicondylar line and the anteroposterior (AP) axis of Whiteside. Deviation from this "ideal" point adds error.



Figure 1. Medial percutaneous placement of trackers in the sagittal plane of lower extremity with active LED tracker on the tibia and passive tracker on the femur.

Kinematic referencing in TKA was a novel innovation to determine the center of the hip and ankle, markedly simplifying this procedure.³³ As the hip is not directly visible, a method was needed to accurately reference the hip center. This was accomplished by tracking the femur with the optical camera as the femur was rotated in a circular motion. The movement of the tracker described the base of a cone, which when projected to its zenith, closely approximates the center of the hip. The computer algorithm calculates either the root-mean-square error or the standard deviation, which must fall within a limited range for the computer to accept the hip center reference point.

A secondary method of referencing is bone morphing, which is selecting hundreds of surface match points by "painting" the bone with the pointer probe.^{39,40} This method does not require the segmented three-dimensional model typical of computed tomography (CT) but uses a virtual model that is constructed by the computer algorithm. The virtual image created allows enhanced capabilities such as prosthetic sizing, "live" bone resection, and kinematic assessment. However, this additional technology usually is proprietary, adds time and complexity to the operative procedure, and may limit the surgeon's choice of prosthetic implants.

Ultrasound image capture is a newer method of referencing that is evolving as a potential technique in which multimodal referencing is performed.^{8,24} Depending on frequency and the acoustical properties of the object, point localization is accurate to sub-millimeter levels on the order of 0.25-0.75 mm with ultrasound whether it is two-, 2.5-, or three-dimensional in the modality of image capture. Segmentation is possible in which this image may be matched with a preoperative CT or an intraoperative "bone morphed" image. However, the clinical applications remain limited for a variety of reasons. Definition

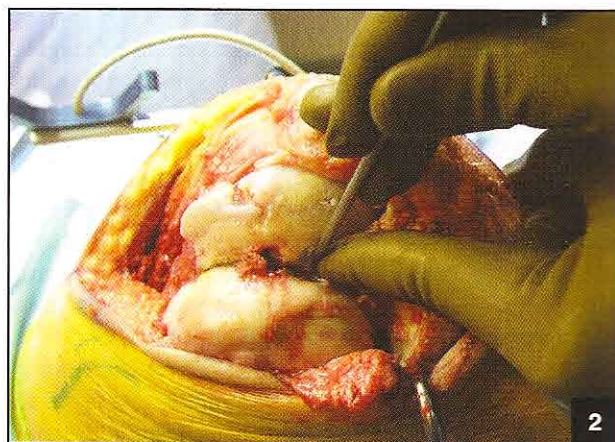


Figure 2. Touch point referencing of the femoral center, which is under the roof of the intercondylar notch and on the AP axis of Whiteside.

of the baseline anatomical points is difficult with ultrasound, creating an error on the order of 2-5 mm, which is unacceptable for clinical practice. However, the promise of ultrasound is that it can be done through the tissues intraoperatively without the need for skin incision or radiation exposure.

CLINICAL METHODS

The specifics of navigation referencing are an important element of the technique and detailed description is warranted. Tracker placement requires rigid fixation of the dynamic reference base to the femur and tibia, as any movement creates an error. Current systems have validation check points that can be established and remeasured throughout the procedure to monitor development of tracker error. Recent studies have favored two pins of 3-mm diameter.²⁶ Importantly, single 5-mm pins and bicortical placement should be avoided as incidental fractures have been described (P. Bonutti, MD, personal communication, January 2007). Placement of the femoral pins in the medial femoral condyle or in a percutaneous transepicondylar position avoids the potential for neurovascular injury³⁸ (Figure 1). Hip center determination is done using the kinematic method originally described by Saragaglia et al.³³

Anatomical referencing of the patient's landmark is the most critical step for the surgeon as well as the most likely source of error, and requires a thorough understanding of the system's software. For referencing of the Medtronic Universal Knee system (Medtronic, Minneapolis, Minn), the computer definition of the femoral center is a point under the roof of the intercondylar notch that is in the middle of the intercondylar notch and lies in the AP axis of Whiteside (Figure 2). From dissections, this point also lies directly on the transepicondylar axis of the distal

femur. The surgical epicondyle depression is the reference for the medial epicondyle and the lateral epicondyle is the most prominent point of that landmark.

For the tibial reference, the tibial center is defined as the bisection of the transverse tibial axis. The transverse tibial axis is a line that connects the AP midpoints of the medial and lateral condylar surfaces. The tibial center approximates the lateral insertion of the anterior cruciate ligament (Figure 3). The AP tibial axis is a perpendicular extension of the tibial center of the transverse tibial axis. This point typically matches the extension of the femoral AP axis, which can be extended on the anterior surface of the tibia. Great care must be taken to determine the tibial center, as this will affect both coronal and sagittal plane measurements. The posterior condylar axis of the tibia is 3° - 4° external to the transverse tibial axis. The center of the tibial tubercle is approximately 18° external to the AP axis of the tibia. Finally, the transverse tibial axis should approximate the transepicondylar axis in regards to coupled rotation. The center of the distal tibia is determined by picking points that center the medial and lateral malleoli, and the transmalleolar axis. The computer algorithm kinematically picks a point on the transmalleolar axis, which is 40% from the most medial point.

Once referenced, the computer system may be used to assess each step in the surgical technique. For the beginning surgeon, the logical method is to perform the standard surgical technique using the computer as an adjunct to the conventional instrumentation. This allows the surgeon to become comfortable with the navigated measurements and eliminates the early risk of errors from inexperience. With practice, the surgeon will learn to depend on the increased precision of the navigated steps and may be able make cuts without conventional instruments. The computer becomes an excellent source of information regarding the surgical procedure and will teach the surgeon of the potential measurement errors that exist with his conventional techniques.

CLINICAL OUTCOMES

Computer-assisted alignment devices were developed to improve the positioning of implants during TKA. Early data on the use of these imageless optical tracking systems appeared positive with improved mechanical alignment, frontal and sagittal femoral axis alignment, and frontal tibial axis alignment.* Furthermore, no studies have demonstrated increased complications compared with hand-guided techniques. Yau et al⁴⁵ compared the combined intraobserver error for imageless acquisition of reference landmarks during TKA, finding that the maxi-

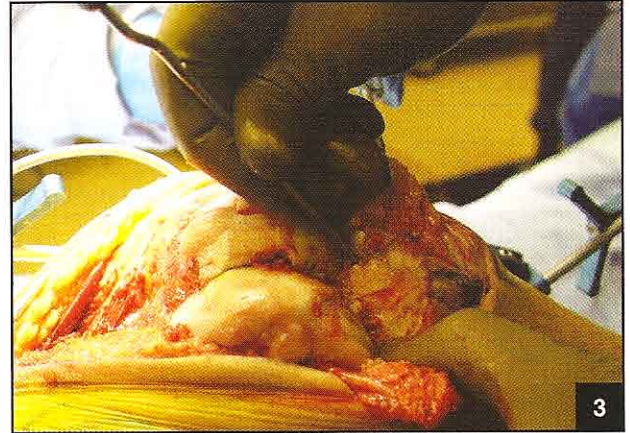


Figure 3. Touch point referencing of the tibial center, which bisects the transverse and AP axes of the proximal tibia.

imum combined error for the coronal plane mechanical axis alignment was 1.32° . Bathis et al³ compared an imageless navigation system to a conventional method using an intramedullary femoral guide and extramedullary tibial guide. They reported the postoperative mechanical alignment to be within 3° varus or valgus in 96% of the navigation cases versus 78% of the conventional cases.³ Sparmann et al³⁶ reported that an imageless navigation system produced a significant improvement in mechanical alignment, frontal and sagittal femoral alignment, and the frontal tibial alignment ($P < .0001$) compared with a hand-guided technique. The postoperative mechanical alignment was within 3° varus or valgus in 87% of the conventional group versus 100% of the navigation group. A significant number of recent studies compared the use of imageless computer-assisted navigation with conventional methods for TKA.† All studies were able to demonstrate a statistically significant improvement in terms of placing the final mechanical alignment of the knee within 3° of the ideal mechanical axis. Furthermore, 93% of the overall cases from these studies reached this level of precision with computer navigation compared to 73% with conventional methods (Table).

The results for the assessment of the transepicondylar axis or the AP axis of Whiteside are inconsistent compared to mechanical axis alignment. This most likely reflects the difficulty in reproducibly picking the epicondylar or AP axis landmarks. Prior studies have confirmed this problem, finding a large amount of variability both with the basic anatomical landmark and the ability of the surgeon to clinically define the structure.^{11,17,32,35} The problem with the AP axis for computer navigation referencing is the fact that distances for landmarking are short. Slight errors in judgment can be off by several degrees. This contrast with

*2, 3, 5, 7, 9, 13, 14, 16, 18, 23, 31, 33, 36, 43

†2, 3, 13, 14, 16, 19, 23, 28, 29, 34, 36, 43

TABLE

CLINICAL STUDIES COMPARING THE ABILITY OF CONVENTIONAL MANUAL SURGICAL TECHNIQUES WITH COMPUTER NAVIGATION FOR LIMB ALIGNMENT PLACEMENT*

Study	N	Limb Alignment Within $\pm 3^\circ$ of the Mechanical Axis of the Lower Extermy		% Difference
		Navigated (%)	Conventional (%)	
Haaker et al ¹³	100	96	75	21
Sparmann et al ³⁶	120	98	78	20
Victor & Hoste ⁴³	50	100	74	27
Jenny et al ¹⁹	235	97	74	23
Jenny & Boeri ¹⁶	30,30	83	70	17
Kim et al ²³	69, 78	78	58	20
Perlick et al ²⁸	40	93	75	28
Seon & Song ³⁴	47, 50	96	76	20
Bathis et al ³	160	96	78	18
Perlick et al ²⁹	50	92	72	20
Hart et al ¹⁴	60	88	70	18
Anderson et al ²	116, 51	95	84	11
Mean		93	74 ($P < .001$)	20

*In studies with two N values, one represents the number of conventional and the other the number of navigated surgeries.

the mechanical axis landmarking where an error of just 1° will require a point matching mistake of at least 3-4 mm (eg, if the distance from the hip center to the femoral center is about 400 mm, an error of 1° is about 4 mm).

Other image acquisition and tracking methods beyond the current standard imageless total knee systems include CT, fluoroscopy, and electromagnetic tracking. Perlick et al²⁹ compared CT with imageless referencing methods in TKA, finding that 92% with CT versus 97% with imageless methods produced TKA mechanical axis alignment $<3^\circ$. Victor and Hoste,⁴³ using fluoroscopic image acquisition in a randomized study of TKA, reported 100% of navigated knees had a mechanical alignment within $\pm 3^\circ$ whereas only 73% of conventional TKAs were within $\pm 3^\circ$. Lionberger²⁵ compared electromagnetic trackers versus optical line of site trackers in a prospective study using an imageless referenced TKA system and reported 93% of cases with electromagnetic trackers had an alignment $<3^\circ$ from the mechanical axis compared with 90% of cases in which optical trackers were used.

Because of the recent popularity of electromagnetic trackers, a short discussion of accuracy issues is warranted. Lionberger²⁵ studied the various facets of electromagnetic technologies, pointing out the important weaknesses of signal distortion from any conductive material and degradation of the signal by any ferrous or magnetic material. Although software optimization has been developed

with system lockout for various forms of signal degradation, this has not been comprehensive enough to include materials such as copper or brass. In these examples, an error may be registered before the system can detect abnormality. The other problem has come from unknown electromagnetic interferences in the standard operating environment, which may cause rare outliers of measurement. This fact must be recognized and understood as the technology continues to advance to a greater level of clinical precision.

Blood loss has been significantly reduced with the use of computer navigation and avoidance of intramedullary rods. In 60 patients, Kalairajah et al²¹ were able to significantly reduce the mean blood loss from 1747 to 1351 cc by using the pin placed trackers instead of intramedullary guided femur and tibia jigs. Kalairajah et al²⁰ also performed a transcranial Doppler study on 14 patients, reporting that all patients who had undergone intramedullary instrumentation of the femur and tibia with conventional TKA had documented intracranial microemboli compared to only 50% of those who had undergone procedures where only intracortical tracking pins had been placed.

CONCLUSION

Computer-assisted navigation offers significant advantages for improving the precision of surgical technique

with TKA. This review has attempted to clarify the general nature of the technology and to point out the strengths and weaknesses of various approaches. Improved mechanical axis alignment is the pivotal refinement offered to TKA, and this may also be applied to unicondylar and revision arthroplasty. Navigation also offers the ability to assess ligamentous balance and the overall kinematics after prosthetic reconstruction. However, certain elements, such as determining the femoral and tibial rotational axes, are less precise with current applications. Although technology is constantly evolving, the overall advantages of computer navigation in TKA have been recognized and will not change substantially in the near future.

REFERENCES

- Amin DV, Kanade T, DiGioia AM III, Jaramaz B. Ultrasound registration of the bone surface for surgical navigation. *Comput Aided Surg.* 2003;8:1-16.
- Anderson KC, Buehler KC, Markel DC. Computer assisted navigation in total knee arthroplasty: comparison with conventional methods. *J Arthroplasty.* 2005;20:132-138.
- Bathis H, Perlick L, Tingart M, Luring C, Zurakowski D, Grifka J. Alignment in total knee arthroplasty. A comparison of computer-assisted surgery with the conventional technique. *J Bone Joint Surg Br.* 2004;86:682-687.
- Berend M, Ritter M, Meding J, et al. Tibial component failure mechanisms in total knee arthroplasty. *Clin Orthop Relat Res.* 2004;428:26-34.
- Bolognesi M, Hofmann A. Computer navigation versus standard instrumentation for TKA: a single-surgeon experience. *Clin Orthop Relat Res.* 2005;440:162-169.
- Chauhan SK, Clark GW, Lloyd S, Scott RG, Breidahl W, Sikorski JM. Computer assisted total knee replacement. *J Bone Joint Surg Br.* 2004;86:818-823.
- Chauhan SK, Scott RG, Breidahl W, Beaver RJ. Computer-assisted knee arthroplasty versus a conventional jig-based technique. A randomised, prospective trial. *J Bone Joint Surg Br.* 2004;86:372-377.
- Chen K, Abolmaesumi P, Pichora DR, Ellis RE. A system for ultrasound-guided computer-assisted orthopaedic surgery. *Comput Aided Surg.* 2005;10:281-292.
- Decking R, Markmann Y, Fuchs J, Puhl W, Scharf HP. Leg axis after computer-navigated total knee arthroplasty: a prospective randomized trial comparing computer-navigated and manual implantation. *J Arthroplasty.* 2005;20:282-288.
- Frantz DD, Wiles AD, Leis SE, Kirsch SR. Accuracy assessment protocols for electromagnetic tracking systems. *Phys Med Biol.* 2003;48:2241-2251.
- Fuiko R, Kotten B, Zettl R, Ritschl P. The accuracy of palpation from orientation points for the navigated implantation of knee prostheses [German]. *Orthopade.* 2004;33:338-343.
- Glossop et al. Accuracy evaluation of the Aurora magnetic tracking system. *Comput Aided Surg.* 2001;6:112.
- Haaker RG, Stockheim M, Kamp M, Proff G, Breitenfelder J, Ottersbach A. Computer-assisted navigation increases precision of component placement in total knee arthroplasty. *Clin Orthop Relat Res.* 2005;433:152-159.
- Hart R, Janecek M, Chaker A, Bucek P. Total knee arthroplasty implanted with and without kinematic navigation. *Int Orthop.* 2003;27:366-369.
- Jeffery RS, Morris RW, Denham RA. Coronal alignment after total knee replacement. *J Bone Joint Surg Br.* 1991;73:709-714.
- Jenny JY, Boeri C. Computer-assisted implantation of total knee prostheses: a case-control comparative study with classical instrumentation. *Comput Aided Surg.* 2001;6:217-220.
- Jenny JY, Boeri C. Low reproducibility of the intra-operative measurement of the transepicondylar axis during total knee replacement. *Acta Orthop Scand.* 2004;75:74-77.
- Jenny JY, Boeri C, Picard F, Leitner F. Reproducibility of intra-operative measurement of the mechanical axes of the lower limb during total knee replacement with a non-image-based navigation system. *Comput Aided Surg.* 2004;9:161-165.
- Jenny JY, Clemens U, Kohler S, Kiefer H, Konermann W, Miehle RK. Consistency of implantation of a total knee arthroplasty with a non-image-based navigation system: a case-control study of 235 cases compared with 235 conventionally implanted prostheses. *J Arthroplasty.* 2005;20:832-839.
- Kalairajah Y, Cossey AJ, Verrall GM, Ludbrook G, Spriggins AJ. Are systemic emboli reduced in computer assisted knee surgery? A prospective, randomised, clinical trial. *J Bone Joint Surg Br.* 2005;87:198-202.
- Kalairajah Y, Simpson P, Cossey AJ, Verrall GM, Spriggins AJ. Blood loss after total knee arthroplasty: effects of computer assisted surgery. *J Bone Joint Surg Br.* 2005;87:1480-1482.
- Khadem R, Yeh CC, Sadeghi-Tehrani M, et al. Comparative tracking error analysis of five different optical tracking systems. *Comput Aided Surg.* 2000;5:98-107.
- Kim SJ, MacDonald M, Hernandez J, Wixson RL. Computer assisted navigation in total knee arthroplasty: improved coronal alignment. *J Arthroplasty.* 2005;20:123-131.
- Kowal J, Amstutz CA, Nolte LP. On B-mode ultrasound-based registration for computer assisted orthopedic surgery. *Comput Aided Surg.* 2006;6:47.
- Lionberger R. The attraction of electromagnetic computer-assisted navigation in orthopaedic surgery. In: Stiehl JB, Konermann W, Hacker R, eds. *Navigation and MIS in Orthopaedic Surgery.* Heidelberg, Germany: Springer Verlag; 2006:44-53.
- Mihalko WM, Duquin T, Axelrod JR, Bayers-Thering M, Krakow KA. Effect of one- and two-pin reference anchoring systems on marker stability during total knee arthroplasty computer navigation. *Comput Aided Surg.* 2006;11:93-98.
- Milne AD, Chess DG, Johnson JA, King GJ. Accuracy of an electromagnetic tracking device: a study of the optimal operating range and metal interference. *J Biomech.* 1996;29:791-793.
- Perlick L, Bathis H, Lerch K, Luring C, Tingart M, Grifka J. Navigated implantation of total knee endoprotheses in secondary knee osteoarthritis of rheumatoid arthritis patients as compared to conventional technique [German]. *Z Rheumatol.* 2004;63:140-146.
- Perlick L, Bathis H, Tingart M, Perlick C, Grifka J. Navigation in total-knee arthroplasty: CT-based implantation compared with the conventional technique. *Acta Orthop Scand.* 2004;75:464-470.
- Petersen TL, Engh GA. Radiographic assessment of knee alignment after total knee arthroplasty. *J Arthroplasty.* 1988;3:67-72.

31. Pitto RP, Graydon AJ, Bradley L, Malak SF, Walker CG, Anderson IA. Accuracy of computer-assisted navigation system for total knee replacement. *J Bone Joint Surg Br.* 2006;88:601-605.
32. Robinson M, Eckhoff DG, Reinig KD, Bagur MM, Bach JM. Variability of landmark identification in total knee arthroplasty. *Clin Orthop Relat Res.* 2006;442:57-62.
33. Saragaglia D, Picard F, Chaussard C, Montbarbon E, Leitner F, Cinquin P. Computer-assisted knee arthroplasty: comparison with a conventional procedure. Results of 50 cases in a prospective, randomized study [French]. *Rev Chir Orthop Reparatrice Appar Mot.* 2001;87:18-28.
34. Seon JK, Song EK. Functional impact of navigation-assisted minimally invasive total knee arthroplasty. *Orthopedics.* 2005;28:S1251-S1254.
35. Siston RA, Patel JJ, Goodman SB, Delp SL, Giori NJ. The variability of femoral rotational alignment in total knee arthroplasty. *J Bone Joint Surg Am.* 2005;87:2276-2280.
36. Sparmann M, Wolke B, Czupalla H, Banzer D, Zink A. Positioning of total knee arthroplasty with and without navigation support. A prospective, randomised study. *J Bone Joint Surg Br.* 2003;85:830-835.
37. Stiehl JB. Transepicondylar femoral pin placement for dynamic reference base placement in total knee arthroplasty. *Journal of Computer Assisted Surgery.* In press.
38. Stiehl JB, Heck DA, Lazzeri MA. Accuracy of acetabular component placement with a fluoroscopically referenced CAOS system. *Comput Aided Surg.* 2005;10:321-327.
39. Stindel E, Briard JL, Merloz P, et al. Bone morphing: 3D morphological data for total knee arthroplasty. *Comput Aided Surg.* 2002;7:156-168.
40. Stindel E, Perrin N, Briard JL, Lavallée S, Lefevre C, Trocraz J. Bone morphing: 3D reconstruction without pre- or intra-operative imaging. In: Stiehl JB, Konermann W, Hacker R, eds. *Navigation and MIS in Orthopaedic Surgery.* Heidelberg, Germany: Springer Verlag; 2006:36-43.
41. Stockl B, Nogler M, Rosiek R, Fischer M, Krismer M, Kessler O. Navigation improves accuracy of rotational alignment in total knee arthroplasty. *Clin Orthop Relat Res.* 2004;426:180-186.
42. Stulberg SD, Loan P, Sarin V. Computer-assisted navigation in total knee replacement: results of an initial experience of thirty-five patients. *J Bone Joint Surg Am.* 2002;84:90-98.
43. Victor J, Hoste D. Image-based computer-assisted total knee arthroplasty leads to lower variability in coronal alignment. *Clin Orthop Relat Res.* 2004;428:131-139.
44. Wiles AD, Thompson DG, Frantz DD. Accuracy assessment and interpretation for optical tracking systems. *Proceedings of the Society of Photo Optical Instrumentation Engineers.* 2004;5367:1-12.
45. Yau WP, Leung A, Chiu KY, Tang WM, Ng TP. Intra-observer errors in obtaining visually selected anatomic landmarks during registration process in nonimage-based navigation-assisted total knee arthroplasty: a cadaveric experiment. *J Arthroplasty.* 2005;20:591-601.