CURRENT CONCEPTS REVIEW

COMPUTER ASSISTED SURGERY FOR TOTAL KNEE ARTHROPLASTY

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The author has attempted to assess the value of computer-assisted surgery in arthroplasty of the knee. Basic requisites in TKR include adequate alignment and ligament balance. These requisites have become easier to meet as ancillary instrumentations have improved over time. Numerical tools are now available ; they are sometimes presented as an essential technical step. The author reviews the various available options, with their advantages and disadvantages. Satisfactory alignment in the three planes classically relies on anatomic landmarks, the reliability of which is limited, and on ligament tension. Targeting systems, intra- or extramedullary, all have a margin of error. Computer-assisted surgery aims at increasing the precision of implant positioning and achieving optimal ligament balance. Among the systems currently available, a distinction must be made between active and passive systems. The former correspond to the "surgical robots", which are capable of performing the various parts of the operation following adequate preparation, at least regarding the bone cuts. Passive systems remain under control from the surgeon and assist him in positioning the cutting jigs. Among localization systems, a distinction must be made between optical and magnetic systems. Certain systems require preoperative imaging – usually CT scan – in order to first reconstruct a 3-D model of the knee. This step is time-consuming, but this will likely improve in the future. Image matching requires the use of a software, with specific landmarks defined preoperatively by the surgeon. Such systems may be used in cases with major deformities ; their main drawback is the need for preoperative imaging. Other systems do not require preoperative imaging : a few points are identified by kinematic analysis of the hip, knee and ankle ; they are used for 2-D or 3-D reconstruction. Computer-assisted systems may improve the precision in defining anatomic landmarks and achieving accurate location and orientation of the bone cuts, but this must still be validated. Computer-assisted surgery allows for intraoperative control of the orientation of bone cuts, the mechanical axes, the ligament balance and the range of motion. It remains to be demonstrated that using these systems will result into a clinically relevant benefit for the patient, as several of the prostheses widely implanted so far have demonstrated high survivorship rates at 15 or 20 years, so that the demonstration of a possible superiority would need considerable investment. Using these techniques does not solve all problems anyway. The patellar cut remains empirical, and these techniques also do not give any information about femoropatellar joint function. The present systems make use of the classical instrumentation, but it may be anticipated that instrumentations especially intended for computer-assisted surgery will be developed in the future. Regarding imaging, some possibilities have not yet been explored, such as plain radiography or fluoroscopy. Computer-assisted surgery should be of particular interest in revision arthroplasties, but it poses additional problem. The indications are relatively scarce however, and no major advances should be anticipated in the near future. On the whole, this is an emerging technical field. Development is slow, none of the available products is fully mature and caution is warranted in the face of enthusiastic reports and presentations. The value of computer-assisted surgery in TKR has not been demonstrated and its real usefulness still needs to be evaluated. It will, anyway, by no means exempt the surgeon from mastering the classical operative technique.

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Total knee arthroplasty (TKA) is a technically demanding surgical procedure. The objectives are to achieve good alignment and good ligament balance in order to achieve a satisfactory functional outcome that will last for a long period of time. Even through a technically perfect arthroplasty does not automatically result in an excellent functional outcome or a satisfactory long term result, it is generally accepted that it is a fundamental goal to achieve.

In earlier times, only crude instruments were available to achieve this goal. They improved over time, allowing the surgeon to more often reach the necessary goals. Today, new numerical tools are available and are even presented as a crucial step for the improvement of the technique of TKA.

The aim of this review is to briefly introduce the main requirements of a technically perfect total knee arthroplasty. This analysis is based on current literature. The principles presented serve as a framework for the development of computer-aided surgery. In a second part, the different options that are currently available for computer-assisted surgery (CAS) in the specific field of TKA will be presented with their potential advantages and drawbacks. Finally, the potential future of theses systems will be discussed.

1. CURRENT TECHNICAL DATA

1.1. On surgical technique

1.1.1. *Peroperative technical goals*

In order to achieve an optimal result following total knee arthroplasty (TKA), several technical requirements must be met. These conditions are necessary but not sufficient because the surgeon does not control, or has limited actions on some factors such as range of motion, pre-operative anatomical conditions, or patient participation in the rehabilitation program .

These technical requirements are :

1. *Satisfactory alignment in the frontal plane*. From literature data it appears that alignment must be in the 2 or 3° range around a neutral alignment of the femoral and tibial mechanical axes. The mechanical axis of the limb goes from the center of the femoral head through the center of the knee to the center of the ankle (41). This alignment range is also considered as relevant in the International Knee Society grading system based on expert statements (18) ; however, it should be noted that in the latter grading system the anatomical and not mechanical axes are taken into account. This thought is demonstrated in two articles from Ritter *et al.* (56) and Jeffery *et al.* (25). Jeffery *et al.* (25) analyzed 115 Denham knee prostheses for which the mechanical axis on standing long-leg radiographs was determined. They observed that when the mechanical axis was in the 3° valgus-varus range, the loosening rate (defined by the association of pain, cement mantle fracture or progressive radiolucent lines) was 3% (2 of 78), whereas it was 24% (9 of 37) when the alignment was out of this range. The study by Ritter *et al.* (56) was less precise, especially with respect to the methodology of radiographic study and measurement, but it is the only study that demonstrated that prostheses implanted in a varus position had a lower survival rate than others implanted in a neutral or valgus position. However this study showed major weaknesses in methodology, since 16.6% of the patients were lost to follow-up before one year. A study by Ryd *et al.* (59) on 20 patients evaluated with RSA showed a significant correlation between migration of components and lower limb alignment.

Determination of the mechanical or anatomical femorotibial axis remains a difficult topic to evaluate in the literature. Two aspects are included in the evaluation of such an outcome :

- Variations due to the measurement technique (inter and intra-observer variability)
- Variations due to modifications of the radiological technique.

Only two studies have reported results on intra- and interobserver variability (5 , 33). Bach *et al.* (5), in a recent study, found a good interobserver reproducibility for the measurements of the International Knee Society criteria ; unfortunately no intraobserver measurements were available.

For technical variations, it is of note that in the study by Jeffery *et al.* the standard deviation for the measurement of the mechanical axis was 0.8° (25). In the Lonner *et al.* study (33), a synthetic femur with a fixed positioning in 5° valgus anatomical axis and in 2° varus tibial positioning was evaluated from 20° external rotation to 25° internal rotation, both in full extension and in 10° flexion. These authors showed that external rotation significantly decreased the valgus, whereas internal rotation increased valgus ; flexion increased the values of angulations in the frontal plane. As regard the anatomical axis, often used by the Anglo-Saxon authors, it can be modified by using different landmarks (47, 48). However, Wright *et al.*, showed in experimental conditions that an error of 10° either in external or in internal rotation did not affect determination of the femorotibial axis if a flexion contracture was not present (71). For some specific prostheses, it is possible to calculate a real alignment using correction factors when rotation or flexion contracture is present (16).

2. *Satisfactory alignment in the sagittal plane*. For the femoral component there is a lack of data concerning alignment in this plane. As to the tibial component, this issue is considered important not for the longevity of the prosthesis but mainly for function (flexion and antero-posterior stability) (62).

3. *Satisfactory alignment in the horizontal plane*. This point is of particular importance regarding extensor mechanism stability, patellar wear or loosening. Berger *et al.* in a case-control study including 30 patients with extensor mechanism problems (tilted patella, subluxation, dislocation or component loosening) and 20 patients with a well-functioning extensor mechanism, demonstrated that the group with extensor mechanism problems was systematically in combined internal rotation of the femoral and tibial components (7). There are two different ways to implant the femoral component in external rotation : some authors take into account the bony landmarks (2, 43, 67), others take into account the ligament balance when cutting the posterior femoral condyles (15, 63). The bony landmarks that can be considered are the posterior condyles, the biepicondylar line (which can have two different definitions, depending on the authors : one between the medial and lateral epicondylar crest ; the other between the sulcus of the medial epicondyle and the crest of the lateral epicondyle (7, 36)), and a line perpendicular to the trochlear groove (2, 67). Whatever the landmarks chosen, there is consensus to consider that external rotation of the femoral component is mandatory, corresponding to a parallelism of the prosthetic posterior condylar line and biepicondylar line. Olcott and Scott compared three methods to reach a symmetrical flexion gap ; they demonstrated that the biepicondylar line allowed this objective to be reached in 90% of the knees, whereas the Whiteside line reached this objective in 83% and a systematic rotation of 3° in only 70% (46). For some specific deviations such as valgus knees, the biepicondylar line also appeared more reliable (38). Katz *et al.* compared the reliability in determining different anatomic axes in rotation : they found that the antero-posterior and balanced tension axes most reliably defined the flexion-extension axis and best balanced the flexion gap with no significant interobserver differences ; the transepicondylar axis was found to be less reliable (28). For some authors, rotational positioning is such an issue that they considered it mandatory to perform CT-scan before surgery in some difficult knees where osteoarthritis is so advanced that the usual landmarks, especially the sulcus between the two medial crests, cannot be determined (72). Studies concerning the rotational landmarks are presented in table II. The difference observed between the two right-hand columns is due to the landmarks used. Some authors used the most salient point of the medial epicondyle (clinical **T**rans**E**picondylar**A**xis - **P**osterior **C**ondylar **L**ine) whereas others used as a landmark the sulcus between the two prominences (surgical **T**rans**E**picondylar**A**xis - **P**osterior **C**ondylar **L**ine). The clinical **T**rans**E**picondylar**A**xis - **P**osterior **C**ondylar **L**ine was in 3° external rotation more than the surgical **T**rans**E**picondylar**A**xis - **P**osterior **C**ondylar **L**ine ; this difference

Table I. — Available studies on femoral rotation

–	*Ref : sulcus*	*Ref : Most prominent point of the medial epicondyle*
CT-scan based studies		
Arima *et al*., 1995 (2)		5.7 ± 1.7
Nagamine *et al*., 1998 (42)		5.8 ± 2.7 (normal)
–		6;.4 ± 2.4 (patellofemoral arthritis)
–		6.2 ± 1.9 (patellofemoral arthritis)
Akagi *et al*., 1999 (1)		6.8 ± 1.8 (before arthroplasty)
MRI based studies		
Matsuda *et al*., 1998 (37)		6.03 ± 3.60 (normal)
–		6.00 ± 2.35 (varus knee)
Griffin *et al*., 2000	3.11 ± 1.75 (total)	
–	2.75 ± 1.61 (male)	
–	3.33 ± 1.82 (female)	
–	2.71 ± 1.56 (± 41 ans)	
–	3.50 ± 1.86 (± 41 ans)	
Cadaveric studies		
Yoshioka *et al*., 1987 (73)		5.0 ± 1.8 (male)
–		6.0 ± 2.4 (female)
Mantas *et al*., 1992 (36)		4.9 ± 2.1 (right knee)
–		4.9 ± 2.3 (left knee)
–		4.4 ± 2.0 (male)
–		6.4 ± 2.2 (female)
Berger *et al*., 1993 (6)	3.5 ± 1.2 (male)	4.7 ± 3.5 (male)
–	0.3 ± 1.2 (female)	5.2 ± 4.1 (female)
Arima *et al*., 1995 (2)		4.4 ± 2.9
Katz *et al*.., 2001 (28)		6.1 ± 3.3
Surgical studies		
Poilvache *et al*., 1996 (51)		3.60 ± 2.02 (total)
–		3.58 ± 2.16 (male)
–		3.62 ± 1.93 (female)
–		3.51 ± 2.03 (aligned-valgus)
–		4.41 ± 1.83 (varus)
Griffin *et al*., 1998 (20)	3.6 ± 1.8 (male)	
–	3.7 ± 2.6 (female)	
–	3.3 ± 1.9 (varus)	
–	3.3 ± 2.3 (aligned)	
–	5.4 ± 2.3 (valgus)	

could in some cases be the cause of flexion imbalance (28).

4. A well-balanced knee with a quadrangular extension and flexion gap seems to be a factor of better clinical result as suggested by Laskin *et al*. (31). Moreover, as demonstrated by Attfield (4), proprioception is best restored in these well-balanced knees. In order to perform this step, several possibilities exist :

- (1) balance the knee in extension first and then cut the posterior condyles in order to obtain a quadrangular extension gap (19) ; this technique requires a perfect tibial cut to restore both the axes and the ligament balance since the cuts are interdependent.

- (2) perform first the femoral cut based on the rotational landmarks previously described and then balance the knee with sequential ligament releases depending on the location (medial or lateral) and the amount of imbalance (68, 69).

However it must be noted that ligament balancing remains subjective and mainly qualitative ; some quantification attempts have been made using pressure-sensitive FUJI films (64) or with specifically designed devices which took into account the visco-elastic properties of the ligaments (3).

1.1.2. *Efficiency of conventional methods*

Conventional ancillary devices are either intramedullary or extramedullary. The use of one or the other system is still a subject of debate. Some experimental studies have tried to evaluate the inaccuracy of the femoral intramedullary device by a trigonometric calculation or by using a cadaveric study (27, 45, 54). Novotny *et al*. (45) showed that the error was between 0.8° and 5.8° depending on the length of the intramedullary guide, its diameter and the diameter of the medullary canal. Reed and Gollish (54) and Harding *et al.* (21) demonstrated the importance of the femoral entry point. Reed and Gollish (54) demonstrated that it had to be 6.6 mm medial to the deepest point of the trochlear groove. Jeffery *et al*. demonstrated clinically the variations in the precision of femoral intramedullary cutting devices (24).

Table II lists the main studies on the performance of the ancillary devices. The methodological weakness of these studies should be noted since none of them was randomized and none tried to have the results evaluated by an independent observer.

1.2. On existing computer-assisted surgery systems

Whatever method is used, a computer-assisted system must allow the accomplishment of the goals cited above, i.e. (1) ensure optimal positioning in the three planes, frontal sagittal and horizontal (2) ; ensure optimization of the ligament balance with quantification despite the fact that, with current knowledge, it is impossible to know the clinical relevance of these data. Currently, none of the available systems reaches these objectives. This chapter will therefore only introduce the main technical possibilities with their respective advantages and disadvantages.

1.2.3. *Characteristics of active and passive systems*

It is possible to distinguish between active and passive systems as described by Picard *et al*. (50).

Active systems namely represent the surgical robots. They should be able to realize, following planned steps, the entire surgical procedure after the knee has been exposed through a conventional approach. Currently, robots are able to perform the bone cuts, which represent an important but limited part of the surgical procedure. The use of such complicated systems is viable only if the installation and the functioning during the surgical procedure can be performed within a reasonable time, if the consumable cost is not too high and if the expected benefit is technically or clinically relevant. The results of such systems have been presented in different meetings but remain incomplete (55, 65, 70).

Passive systems do not perform any part of the surgical procedure which stays under direct control from the surgeon. They simply offer him assistance in the positioning of the cutting guides (of course without the necessity of an analogic intramedullary or extramedullary device). Unlike conventional systems, the bone cuts, once they have been done, or the ligament balance, can be finely controlled with numerical data.

1.2.4. *Distinction between the location systems*

During the surgical procedure the bones and the instruments have to be positioned. From a general point of view, a collector fixed to the object and a collection tool is needed. Whatever the system is, there is a crucial need for a perfect and permanent fixation of the collector to the instrument or, with more difficulty to the bone, in order to permanently collect accurate information. Two systems are available with their own advantages and disadvantages : optical and magnetic.

Optical systems are based on the detection of three reflecting spheres by an infrared camera. The

Table II. — Studies of ancillary devices
(Comp : comparative, Y : yes, N : no, IM : intramedullary, EM extramedullary, NS : non significant, P = prospective, R = retrospective)

Author	*Comp/P/R*	*Nb*	*Knee system*	*Outcome measure*	*Result*	*Observations*
Petersen (49)	N/N/N	50		Anatomical femoro tibial alignment	26% out of the 4-10° range	Comparison between long and short film : significant difference of 1.4° average
Tillett (66)	Y/Y/N	50		6° ± 2° anatomical valgus on knee film	IM vs EM NS	Comparison only on the femoral side
Engh (17)	Y/N/N	72	Synatomic Knee F : Comp EM/IM	Anatomical femoral axis	IM>EM p < 0,1 87.5% vs 68.8 % between 4 and 10° of valgus	
			T : EM	Tibial axis	82% à ± 2°	
Brys (8)	Y/N/N	114	F : EM	Mechanical axis	NS	Tibial instrumentation was different
			T : IM ou EM	Lateral tibial axis (90° ± 2)	IM > EM p < 0,05	
				Medial femoral axis	NS	Extramedullary femoral instrumentation
				Mechanical and anatomical axis	NS	
Dennis (13)	Y/N/N	120		Lateral tibial axis	88 % with EM vs 72% with IM in 90° ± 2	Better positioning with extramedullary instruments
				Mechanical and anatomical axis	NS	
Harvey (22)	N/N/N	101	Johnson-Elloy IM	Anatomical axis	72% in ± 3°	
Cates (10)	Y/N/N	200		Mechanical axis	NS	Femoral instrumentation was different. Extramedullary instrumentation for the tibia
				Lateral tibial axis	IM > EM p = 0.019	
				Medial femoral axis	IM > EM p= 0,052	
				Mechanical and anatomical axis	NS	
					11 to 24% of the cuts were not satisfactory	
Ishii (23)	Y/N/N	100		Mechanical axis	NS	Tibial instrumentation was different
				Lateral tibial axis	NS	
				Medial femoral axis	NS	Intramedullary femoral instrumentation
				Mechanical and anatomical axis	NS	
					88 to 92% of the cuts were satisfactory in the 90° ± 4 range	
Maestro (34)	Y/Y/N	116		Mechanical axis	NS (90.1% vs 87.2% in 7°±5°)	Tibial instrumentation was different
				Lateral tibial axis	IM>EM p<0,01 (85.2% vs 87.2% in 90° ± 4°)	Intramedullary femoral instrumentation
				Medial femoral axis	NS (98.3% vs 94.5% in 90± 4°)	
				Angle anat/méca	NS	
Coull (12)	N/N/N	79	T : EM Système Kinemax	Medial tibial axis	Average :86.88°± 2.84 48% were more than 3° varus	
Mahaluxmivala (35)	N/N/N	673	F : IM T : EM PFC System	7 ± 3° anatomical valgus on the knee X-ray	± 3° : 75.3% of the cases	No difference due to surgeon experience

main advantage of such systems is that the answer is binary without any possibility of distorted information. The main potential cause for mistakes would be the proximity of two collectors. The main disadvantages are the size of the collectors, the volume of the infrared camera in the operating room, the need for perfect initial placement of the collectors, wear of reflecting spheres, and the necessary adaptation of the surgical technique (position of the surgeon, the scrub nurse or the assistant) to the system since the collectors have to be permanently located by the camera.

Magnetic systems are based on an emitter that generates a cylindrical field with a diameter of 80 centimeters in which the collectors fixed to the instruments or to the bones are located. This type of system does not require any modification of the surgical technique since the surgeon or the assistant can move freely around the patient. On the other hand, they are disturbed by electromagnetic perturbations generated by ferromagnetic elements such as some conventional instruments (retractors, hammer…), drill, as well as watches or mobile phones when they enter the generated field. Moreover, the collectors are linked to the computer by wires which can be troublesome during the surgical procedure. But despite the fact that these systems necessitate perfect control of the environment for routine use, they have major potential for evolution with, in the near future, the possibility of recognition of electromagnetic perturbation. Moreover, miniaturization is possible, which would allow its use in some difficult conditions, such as attached to an instrument that could work inside the medullary canal.

1.2.5. *The need for pre-operative imaging*

Foe knee applications some systems require an imaging modality (most often a CT-scan) to first reconstruct a 3-D model and then, after a registration process, navigation becomes possible. Some other systems do not need this step and are based on the location of the specific points (center of the femoral head, of the knee and of the ankle) to reconstruct the main landmarks : axes of the limb, level of the inferior condyle, level of tibial plateau.

1.2.5.1. Image-based systems (39, 44)

As previously mentioned, pre-operative acquisition of the morphologic data is necessary. Today this is done with a CT scan (the best performing imaging modality for bone definition) which allows 3D reconstruction of the bones using a specially designed software (fig. 1). MRI could be used in order to have information on soft tissue but today the definition of bone with MRI is far inferior to that of the CT scan.

3D reconstruction is probably the most time-consuming step for the surgeon ; it may take 30 to 60 minutes depending on the experience of the surgeon and of the knowledge he has of image interpretation. It is highly probable that this step will be improved in the future, requiring minimal human intervention, and will be made almost completely automatic and quicker.

A registration process during the operation is needed in order to match reality and the image seen on the screen. Several mathematical techniques facilitate this step, but all of them need identification of special points, determined pre-operatively, which have to be recognized during the operation. The software is able, using a mathematical algorithm (based on transformation matrix), to help the surgeon identify these points during the matching process. The initial choice of the points has to be made by the surgeon (fig. 2) since he is the only one able to easily identify some of the special points on the 3D model (related to the location of anatomic landmarks or to osteophytes specific to the patient).

The main advantages of the image-based system are the fact that it can be used in cases with extreme deformations including those seen in Paget's disease or post-traumatic malunion, and the fact that it is specific to the patient's anatomy. The determination of the anatomic landmarks is precise and this theoretically provides ideal technical precision during the operation. It is possible to reconstruct 3D models if a total hip replacement is present above the knee to be operated, and also in cases of revisions of unicompartmental arthroplasties or with the presence of a temporary spacer in two-stage revision of infected knees. In such cases, the choice of the points for registration is crucial.

Fig. 1. — 3-D femoral reconstruction

The main disadvantage of these systems is that it is mandatory to obtain a CT-scan which can be considered as an additional expense and an unreasonable source of irradiation for the patient. Moreover the time needed to reconstruct the 3D model can also be considered as unacceptable since it is time consuming for the surgeon.

1.2.5.2. Imageless systems

They are the oldest systems available for TKR. The main points to be identified are the center of the femoral head, the center of the knee and the center of the ankle. The junctions between these points define the mechanical axis of the limb in the frontal plane as well as in the sagittal plane. Several options are available to define these points :

- the center of the femoral head is located in all the systems using a kinematic analysis of the hip ; passive mobilization of the hip is needed to determine this center. Most of the available systems allow for this step without the need for a reference point on the iliac crest. In the earlier versions this point was essential and an additional incision at that level was needed.
- There are two ways to define the center of the knee :

Fig. 2. — Registration points. These points have been defined pre-operatively by the surgeon, and have to be recognized during operation in order to match the image and the reality.

  - The first is based on a kinematic analysis of the knee and requires passive mobilization of the knee just before the operation.
  - The second is based on the definition of an anatomic landmark as described by several anatomic studies (73, 74).
- The center of the ankle can also be determined using two methods :

  - A kinematic analysis of the ankle can be done with passive motion of the ankle
  - Anatomical points on the medial and lateral malleoli can determine the center of the ankle as mentioned by Moreland *et al*. (41).

Two kinds of information can be given by these systems ; they can be in either two or three dimensions. In two-dimensional systems, only the axes in the frontal and the sagittal plane are available. In 3D systems, digitization of anatomical structures allows reconstruction of an almost complete distal femur or proximal tibia using either statistically reshaped bony structures or completely redesigned bony structures from direct digitization (fig. 3).

The main advantages of these imageless systems are the avoidance of a CT-scan and its irradiation and the time needed to reconstruct the 3D model. Sarragaglia *et al.* calculated the additional time needed during the operation to be 20 minutes (60).

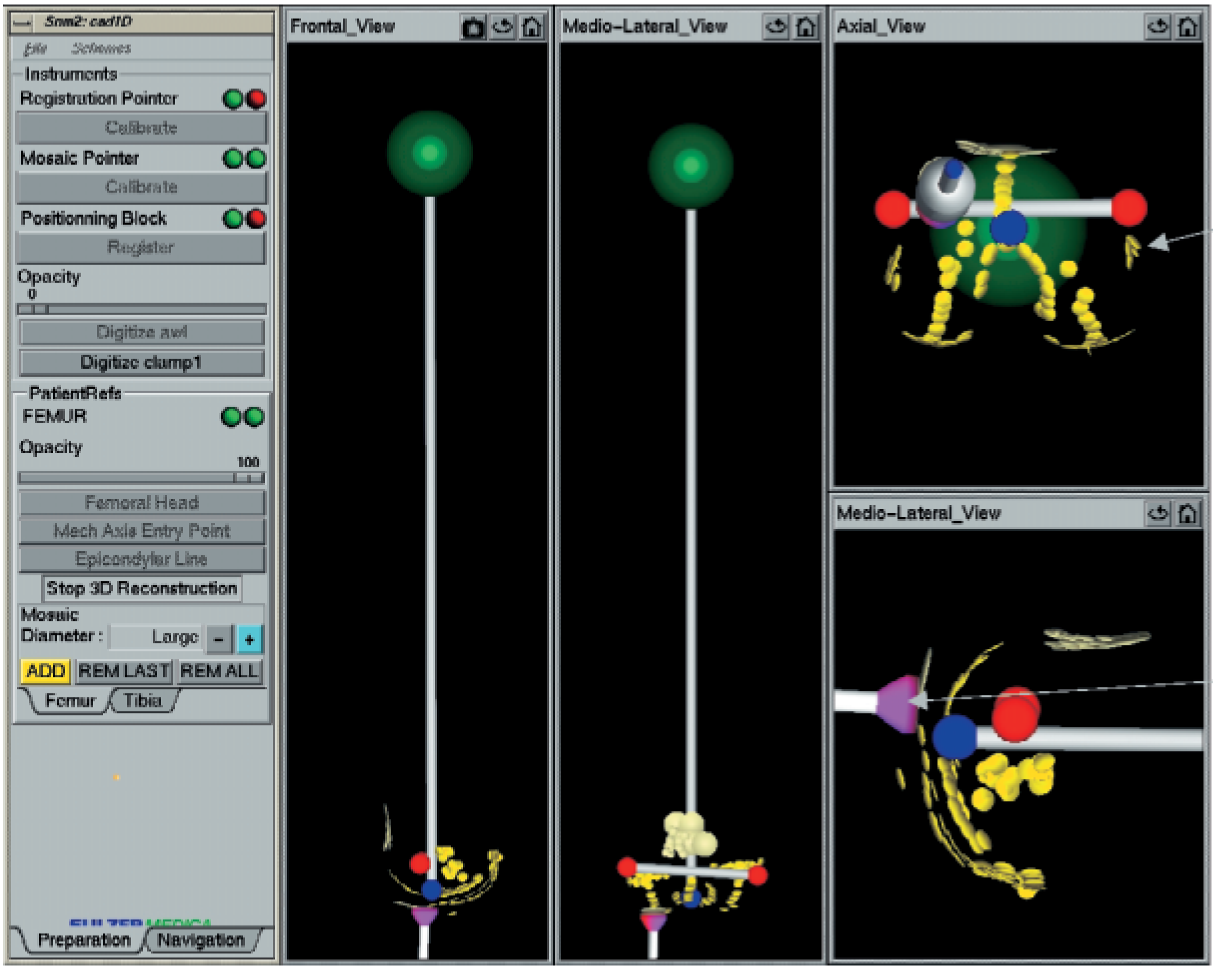

Fig. 3. — 3D reconstruction from a CT-less system. The digitizer (pink) indicates the relevant surfaces necessary to implant the prosthesis. The longitudinal grey axis represents the mechanical femoral axis from the center of the femoral head to the center of the knee.

However the information concerning the rotational positioning of the implants is questionable. Sarragaglia evaluated rotation of the femoral component through the dynamic modification of the tibial axis at 0°, 30° and 90° of knee flexion. Other software uses the peroperative determination of the trochlear groove, of the epicondyles or of the tibial tubercule, but the precision of such determination remains uncertain, as demonstrated by Arima *et al.* (2) or Katz *et al.* (28).

The first results reported with these systems are encouraging (11, 26, 29, 60), but they need confirmation before routine use. In a randomized study Sarragaglia compared 25 knees operated with a conventional technique and 25 knees operated with the Orthopilot® system. No statistical difference was noted but a satisfactory alignment in the frontal plane, defined as a mechanical axis between 3° varus and 3° valgus alignment, was observed more often with the navigation system (84% versus 75%). In a case-control study, Jenny *et al.* compared 60 prostheses implanted with the Orthopilot system to 60 prostheses implanted using a conventional technique. With the navigation system, 53 prostheses were in the 3° valgus-3° range whereas only 43 of 60 were in this range with conventional system ($p < 0.05$). Significant improvement in other positioning criteria (individual positioning of the components in the frontal and in the sagittal plane) was also observed.

1.2.6. *Intra-operative control*

This particular point is probably one of the main advantages of all computer-assisted systems. During conventional surgery, controls exist but although some authors have developed specific tools (40), these are not widely used and are often insufficiently precise or indirect. These conventional controls are bone resection thickness, direct visualization of the mechanical axis that can be helped by the use of external rods, ligament balance subjectively evaluated, passive movement of the knee and a good restitution of passive flexion and extension.

On the contrary, all computer-assisted surgery systems allow direct visualization of bone cut accuracy, restitution of a satisfactory mechanical axis and quantitative evaluation of the ligament balance and range of motion. With some of the systems, it is even possible to observe the knee behavior during passive flexion and extension. However, the relevance and even the utility of these controls need to be evaluated.

2. LIMITS OF THE AVAILABLE SYSTEMS

2.1. Methodological limits

In a cost-containment environment computer-assisted surgery for TKR needs to prove its efficiency, which is probably one of the most challenging issues. To do so, the few published studies considered positioning of the implants (individual positioning of the femoral or tibial implant or mechanical axis or anatomical axis) as the primary criterion. The relevance of these criteria may be discussed, since the most important points for the patient remain function, range of motion, satisfaction, and survivorship. However, government or manufacturers, when they agree to give financial support for research, require results, and if possible very quickly. From this point of view it is obvious that technical considerations are the most relevant. But surgeons and probably patients have to know that, with conventional techniques, survival of the most widely used prostheses reach high levels even at 15 or 20 years follow-up (9, 14, 30, 32, 52, 53, 57, 58, 61) ; the chance to show a significant improvement with innovative techniques is therefore very small and needs considerable investment.

2.2. Technical limits

They are numerous, but this can be considered as “acceptable” considering the time necessary for new development and the recent advent of these systems.

2.2.7. *On the patellofemoral joint*

None of the existing systems deals with the functioning of the patellofemoral joint except through the determination of the rotational positioning of the femoral and tibial components. Two aspects may be discussed on that point :

- The patellar cut poses specific problems related to the size of the patella with no existing possibilities to fix a sensor with sufficient reliability. It is therefore impossible to address one of the important difficulties in surgical technique and one of the most frequent factors of unsatisfactory results for the patient
- Moreover, the information must not be limited to the patellar cut but must include the whole functioning of the patellofemoral joint including the relationship between the prosthetic patellar groove and the patellar component. But we have to consider that, in the best case, this functioning will be observed only in a passive condition.

2.2.8. *Minimally invasive techniques*

All the available systems today come from conventional instrumentations. This can be considered acceptable as a first step, but it will not be appropriate for future steps if companies and surgeons wish these instruments to be really innovative. Indeed, ancillary devices will need to be developed specifically for computer-assisted surgery with suitable materials for magnetic systems or less bulky optic trackers. In other surgical specialties, a minimally invasive technique was one of the initial goals for the development of computer-assisted systems ; this particular point that has not been considered yet by most of the surgeons and the companies, has to be addressed in the immediate future. We know that prosthetic volume will remain an unavoidable problem but surgical aggression, especially on the soft tissue and the extensor mechanism, should be reduced.

2.2.9. *Imaging techniques*

For total knee replacement, options with and without pre-operative CT-scan both exist. We do not know which could be the most precise and most relevant option since no comparative study is available. Some possibilities have not been explored yet, especially the use of conventional xrays or the use of fluoroscopy. However, we have to observe that the importance of imaging techniques is increasing and is essential for most other applications such as the hip or spine, or in tumor surgery.

2.2.10. *Revision surgery*

Revision surgery is more complex and the use of such techniques in that field is probably of particular relevance.

Some additional difficulties exist with the use of CT-based systems : (1) 3D reconstruction is more demanding due to artifacts and difficulty in the interpretation of such modified images (2) ; registration may be difficult since prosthetic elements may be mobile and cannot be the location of registration points, moreover bone loss may be important enough to make it difficult to adequately define these points. For CT-less systems, definition of the center of the knee may be difficult either with the use of kinematic analysis or with the use of anatomic landmarks that may be difficult to define under such conditions. Furthermore, the market of revision surgery is narrower and for reasons of profit earning and efficiency, companies are probably less committed to invest money in such projects. In that field, it is probable that some specific instruments will have to be designed.

3. CONCLUSIONS

It is difficult to draw definite conclusions in such an emerging field. Development of software is as usual in that industry, quite quick but also as usually, time between specification definitions, official launch and effective availability of the products does not always correspond to companies announcements. Today, we can still consider that none of the available products is mature, and we have to be cautious in the face of enthusiastic reports or presentations. The use of computer-assisted surgery has not proved to be relevant and its real usefulness needs to be examined. Accurate knowledge of conventional techniques remains essential since the surgeon may have to face situations where the computer, for various reasons, may be out of order. These techniques may help the surgeon to improve his technique and accuracy but it doesn't exempt him from being perfectly qualified. Besides, it is tempting for some care structures or for some surgeons to use the acquisition of such a system to demonstrate that they are in the forefront of knowledge and high technology but such a presentation is fallacious since, based on current knowledge, it is impossible to demonstrate a relationship between the use of computer-assisted surgery and an improved subjective and objective result.

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SAMENVATTING

R. NIZARD en de GUEPAR groep. Computer gestuurde heelkunde bij totale knie arthroplastie.

De auteur evalueert de huidige stand van zaken in computer geleide heelkunde bij knie arthroplastie. Basis voorwaarden voor een geslaagde kunstknie zijn adequaat alignement en juiste ligamentaire balans. De realisatie van deze fundamentele eisen is vergemakkelijkt met het huidige numeriek instrumentarium. De bestaande systemen worden overlopen met hun voor- en nadelen. De realisatie van een bevredigend alignement in de drie ruimtelijke vlakken steunt op de herkenning van anatomische referentie punten, die niet altijd evident zijn, en op de spanning van de ligamentaire structuren. Intramedullaire zowel als extramedullaire richtmethodes zijn onderhevig aan mogelijk fouten.

De computer gestuurde heelkunde moet precisie verbeteren bij de plaatsing van de prothesis en het evenwichtig opspannen van de banden. Er zijn actieve en passieve systemen voorhanden.

De actieve systemen, de zogenaamde heelkundige robots, voeren na een adequate botcoupe de verschillende verdere stappen uit. De passieve systemen, gebaseerd op optische ofwel magnetische referentiepunten, zijn hulpmiddelen voor de chirurg bij de plaatsing van het geleidingsmateriaal. Sommige systemen vereisen bijkomende tijdrovende preoperatieve beeldvorming, meestal CT scan, om een drie-dimensioneel beeld van de knie te bekomen. Preoperatief door de chirurg bepaalde "bakens" of referentiepunten en een aangepaste software brengen het beeld in overeenstemming met de specifieke anatomie. Het nadeel van dit systeem is de bijkomende beeldvorming ; eventueel te gebruiken bij de grote misvormingen. Andere systemen vragen geen preoperatieve bijkomende beeldvorming en baseren een twee- of driedimensionele reconstructie op kinematische gegevens van de heup, de knie en de enkel.

Er moet nog veel worden bewezen : computer geleiding kan de precisie bij het vinden van anatomische bakens, en bij het localiseren en richten van de botcoupes verbeteren. Het laat toe intra-operatief de botcoupes te controleren, evenals de mechanische assen, de ligamentaire balans en de het bewegingsbereik. Klinisch bewijs moet worden geleverd of dit nu leidt tot een werkelijk voordeel voor de patiënt, gezien de huidige technieken overlevingscijfers verzekeren van 15 tot 20 jaar en verdere verbetering aanzienlijke investering betekent. Computersturing lost zeker niet alle problemen op : de voorbereiding van de patella en het patellofemoraal functioneren vallen buiten zijn mogelijkheden. Nu worden met de computer geleide heelkunde de klassieke instrumenten nog gebruikt. Mogelijk worden meer geëigende instrumenten ontwikkeld. Het gebruik van standaard röntgenbeelden en peroperatieve beeldversterking zijn nog niet uitbeproefd. Het nut is theoretisch het grootst bij revisiechirurgie met al haar bijkomende problemen. Al bij al blijven de indikaties zeldzaam en voorspeld kan worden dat verdere verbetering traag zal komen.

Het gaat hier om een nieuwe traag evoluerende techniek, waarvan de realisatie nog ver van volwassen is.

Voorzichtigheid is dus geboden vooral in het licht van sommige enthousiaste publicaties en demonstraties.

Computer gestuurde heelkunde bij totale knie arthroplastie heeft zijn waarde nog niet bewezen en zijn nut moet nog worden aangetoond. Het zal de chirurg niet ontslaan van een degelijke kennis van de klassieke technieken.

RÉSUMÉ

R. NIZARD et le groupe GUEPAR. Chirurgie assistée par ordinateur et arthroplastie totale du genou.

L'auteur cherche à évaluer l'intérêt actuel de la chirurgie assistée par ordinateur dans l'arthroplastie totale du genou. Un alignement correct et un bon équilibre ligamentaire comptent parmi les exigences de base de l'arthroplastie totale du genou. Les instrumentations, au

départ assez rustiques, se sont perfectionnées, ce qui a permis de mieux répondre à ces exigences. Des outils numériques sont maintenant à notre disposition ; ils sont parfois présentés comme une étape technique capitale dans l'arthroplastie du genou. L'auteur passe en revue les différentes options actuellement disponibles, avec leurs avantages et leurs inconvénients potentiels. L'obtention d'un alignement satisfaisant dans les trois plans de l'espace se base classiquement sur des repères anatomiques dont la fiabilité n'est pas absolue, et sur la tension ligamentaire. Les méthodes de visée, aussi bien intra-médullaires qu'extra-médullaires, comportent une certaine marge d'erreur. Le recours à un système de chirurgie assistée par ordinateur a pour ambition d'améliorer la précision du positionnement des implants et d'optimiser l'équilibre ligamentaire. Parmi les systèmes disponibles, il faut distinguer les systèmes actifs et les systèmes passifs. Les premiers correspondent à ce qu'on appelle les «robots chirurgicaux», capables de réaliser les différentes étapes de l'opération après une préparation adéquate, du moins en ce qui concerne les coupes osseuses. Les systèmes passifs au contraire restent sous le contrôle du chirurgien et l'aident dans le positionnement des guides de coupe. Parmi les systèmes de localisation, il faut distinguer les systèmes optiques et les systèmes magnétiques. Certains systèmes ont besoin d'une imagerie préalable – généralement le CT scan- pour reconstruire tout d'abord un modèle en trois dimensions du genou. Cette étape prend beaucoup de temps, mais ceci s'améliorera vraisemblablement dans l'avenir. Le recalage de l'image nécessite le recours à un logiciel, sur base de points de repère définis en peropératoire par le chirurgien. Ces systèmes peuvent être utilisés dans des cas de déformation importante ; leur inconvénient principal est la nécessité d'une imagerie préalable par scanner. D'autres systèmes ne requièrent pas le recours à une imagerie préalable : quelques points de repère sont identifiés par analyse cinématique de la hanche, du genou, et de la cheville. Ils permettent une reconstruction en deux ou en trois dimensions. Avec de tels systèmes, on peut améliorer la précision dans le repérage anatomique et l'orientation des coupes, mais ceci doit encore être validé.

Les systèmes de chirurgie assistée par ordinateur permettent de contrôler en peropératoire l'orientation des coupes osseuses, les axes mécaniques, l'équilibre ligamentaire et l'amplitude de mobilité. Il reste à démontrer que le recours à ces systèmes entraîne un avantage cliniquement significatif, car plusieurs des prothèses largement utilisées jusqu'à présent ont montré des taux de survie élevés à 15 ou 20 ans, si bien que la démonstration d'une amélioration représente un investissement considérable. Le recours à ces techniques ne résout pas tous les problèmes dans l'état actuel des choses. Ainsi, la réalisation de la coupe rotulienne reste empirique, et ces techniques ne renseignent pas non plus sur le fonctionnement de l'articulation fémoro-patellaire.

Les systèmes actuels font usage des instrumentations classiques, mais il est à prévoir que des instrumentations spécifiquement destinées à la chirurgie assistée par ordinateur devront être mis au point dans l'avenir. Concernant le recours à l'imagerie, certaines possibilités n'ont pas encore été explorées, comme le recours à la radiographie conventionnelle ou à la radioscopie.

Le recours à la chirurgie assistée par ordinateur devrait être particulièrement intéressant pour les reprises d'arthroplastie du genou, mais des problèmes supplémentaires se posent dans ce contexte. Ce n'est cependant pas un créneau porteur, et il ne faut pas s'attendre à des développements rapides.

Au total, il s'agit d'un domaine technique en plein développement. Ce développement est très lent, pour des raisons compréhensibles. Aucun des produits disponibles actuellement n'est parvenu à maturité, et il faut rester prudent en regard de rapports ou de présentations enthousiastes. L'intérêt de la chirurgie assistée par ordinateur dans l'arthroplastie du genou doit encore être validé ; il ne dispensera en tout cas jamais d'une connaissance adéquate des techniques classiques, qui reste une exigence de base.