Freehand Navigation For Bone Shaping

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Introduction

This chapter describes a method for carrying out knee-replacement surgery where the bone cuts are made freehand, guided by feedback from a computer screen or other means, as opposed to the standard surgical techniques using jigs and fixtures. The potential advantages of freehand navigation are speed, simplicity and accuracy, together with no increase in the cost per procedure. There are numerous total and unicompartmental knee systems, each with its own technique, frequently more than one for a particular design. However, there are many similarities between the techniques, the common element being a set of jigs and fixtures which are sequentially positioned on the bones in order to guide the cuts. The goal is to achieve an accurate fit of the components on to the bones, and an accurate overall limb alignment. While experience has shown that the components seldom fit exactly on to the bones, the size of the gaps and irregularities have not been quantified to our knowledge. When cement is used, small gaps may not be important, but that is not the case for uncemented components. Overall alignment has been measured in a number of studies. In a large case study, only 75% of the cases achieved a knee valgus angle of 4–10°, measured from radiographs [5]. When a navigation system was used to measure alignments, it was found that there was a greater spread of results using jigs and fixtures compared with navigation [9]. Several degrees error can result from the use of current intra-medullary rods [7]. The recent introduction of minimally-invasive techniques for total and uni knees [8, 11] similarly increased the range of error compared with standard incisions [2]. Nevertheless, the popularity of reduced incisions has continued to grow due to its advantages, but in contrast, navigation has not become widely used in the USA up to this time, probably because of cost and time. Knee replacement using standard techniques has had successful results as measured by survivorship, but many of the failures or unsatisfactory results that have occurred have been due to mis-alignment and instability, the latter due to incorrect ligament balancing. Alignment and balancing can both be improved using navigation techniques. Hence it can be proposed that, if knee replacements are to be performed more and more using smaller incisions, there needs to be a parallel improvement in the surgical technique with regard to alignment and fit. This chapter aims to show that freehand navigation, being a simplified version of present navigation methods, may be one step in this direction.

Accuracy of Freehand Cutting

Freehand bone cutting is not new, for even now with the availability of accurate instrumentation, some surgeons carry out some of the cuts freehand for the sake of convenience. For carrying out freehand bone sculpting using navigation, the Precision Freehand Sculptor was developed using a burr and the computer screen as a guide [10]. The system has recently been applied to a Repicci uni knee. We experimented with such a system where a burr was used to prepare the surface of foam plastic tibias as if for preparation of a unicompartmental component. RMS accuracies of the cut surface of better than 1 mm were achieved [4]. Due to the shape of the burr, the surface was characterized by numerous ripples, although an alternate tool could reduce that effect.

To test the accuracy of freehand cutting using a reciprocating saw, rectangular foam blocks the size of an
upper tibia were mounted and the task of the surgeon was to resect 10 mm from the top using metal bars mounted at each side of the block, the surfaces at the 10 mm level, as visual guides. After cutting, the frontal and sagittal angles of the cut surface were measured (Fig. 18.1). With the blocks mounted horizontally and the surgeon seated, mean frontal and sagittal errors were 0.6 and 1.2°, respectively. The use of an armrest which gave the surgeon’s arm freedom to move in a horizontal plane, gave similar results. When the blocks were mounted at 45° and the surgeon standing, more closely simulating surgery, mean errors were 0.4 and 1.1°. A rigid arm rest gave 0.4 and 0.6° mean errors. As a control, a fixture with a slot, pinned accurately to the block, gave mean errors of 0.3–0.5°. Standard deviations were 0.3–0.5° throughout. This study suggested that freehand bone cutting could produce acceptable accuracy. Future studies will determine whether computer assistance, as described below, can further improve the accuracy.

**Freehand-Navigation System**

The systems available today use optical navigation for the positioning of cutting jigs through which the bone cuts are made. The placement of the jigs is determined by digitizing various landmarks on the bones to determine the reference axes. In some systems, the mechanical axis of the femur is determined by a kinematic method where the leg is rotated and the center of the hip is thus calculated. Non-image systems rely on the points digitized at surgery and are concerned primarily with alignments. At the other extreme, CT scanning has been used to obtain a 3-D rendering of the patient-specific bone. This has more versatility in that component fit and the extent of the bone cuts can be visualized. An approximation of bone shapes has been achieved at the time of the procedure using fluoroscopy, or by using morphing where a 3-D bone shape stored in the computer is morphed to the patient’s bone shape using points digitized at surgery. A freehand-navigation system would use many of the features described above, the main difference being that rather than using the navigation system to position the cutting jigs, through which the bone cuts are made with a saw, the bone cuts are made freehand with the surgeon looking at the computer screen which shows the required planes of cut [12]. The cutting tool and the bone are rendered in real-time so that the surgeon can follow the cuts as they proceed (Fig. 18.2).
Goals and Criteria

In order for a freehand-navigation system to be viable, it would need to fulfill certain criteria, as follows:
- applicable to both standard incision or minimally-invasive techniques;
- time for surgery must be less than or equal to that for conventional methods;
- technique is simple to perform, especially for the surgeon who carries out less than 20 operations per year;
- uses only cutting instruments (e.g. reciprocating saw, milling burr), but not conventional jigs and fixtures;
- provides a means for accurate alignment, avoiding “outliers” (errors outside of acceptable limits);
- capability to aid the surgeon in ligament balancing;
- must be able to work with all TKR designs and manufacturers, given CAD data of implant components;
- automatically produces an operating report of all data, measurements, alignments, etc. (this data can be used in future outcome studies);
- must reduce the cost of surgery per case.

Components

The system consists of the following hardware and software (see Fig. 18.2):
- an optical or electromagnetic tracking system to provide the 3D navigation of the cutting tools and bones;
- a digitizer as a registration tool and for defining key points on the bones;
- an intra-medullary rod which projects outwards from the entry point, to define the long axes of the bones;
- a computer to perform the necessary calculations of bone shape, component positioning, and tracking of the surgery in real-time;
- a computer screen for providing real-time visualization to the surgeon on the required planes of cutting and the progress of the cutting;
- cutting tools such as a reciprocating saw, and a milling burr (mainly for uni and minimally invasive);
- a knee support for stability and distraction of the knee at any angle of flexion;
- an arm support to steady the surgeons arm and maximize the accuracy of cuts.

Procedural Steps

The following describes the system at this time although there will be variations depending on preferences and experience (Fig. 18.3). The computer has several representative femurs and tibias stored in STL format. The format has the advantage that the images can be recalculated and moved on the computer screen in real-time. At the time of surgery, key landmarks are digitized on the bones, sufficient to define the extremities of the bones for scaling, with other points determining axes and shape [3]. Special intra-medullary rods which project outwards...
from the entry point are placed in the bones to define the long axes. Points on the rods are digitized. The computer then selects one of the stored images and morphs it to match the patient being operated on [1]. The computer has CAD models of the implant system being used. For the femoral component for example, the computer will select the most suitable size and its optimal placement. The size selection will be based primarily on the AP dimensions while the positioning will be based on the thickness of the distal cut and the avoidance of notching the anterior cortex. Rotation will be based on the chosen transverse axis whether from the posterior condyles or from the epicondylar line [6]. The required valgus angle will be determined from the intra-medullary rod. The computer will then display the required cutting planes one by one (see Fig. 18.2). The surgeon will advance the saw to the start of the cut until it is correctly positioned. The saw will be switched on and the cut advanced. The starting point is critical to the subsequent accuracy, because once the cut proceeds, the saw will be largely constrained to follow the same path, which is an advantage. The benefit of having an accurate rendering of the bone shape on the computer screen is that the position of the saw blade relative to the bone boundaries can be visualized, important for the restricted visualization of a minimally-invasive technique. At a suitable stage in the bone preparation, tests will be carried out for ligament balancing along the lines that already exist with some navigation systems [13]. In order to achieve the maximum accuracy using such a freehand technique, an arm support is likely to be a benefit. A design which readily swivels into position is required. Similarly, a leg support where the knee can be flexed at the required angle and held in position, together with the capability of rotation and distraction, will improve stability and accuracy. The screen display shown in Fig. 18.2 is but one method for providing the required information to the surgeon. Different graphics can be used for the best possible visualization and control, the principle being to align the plane containing the saw blade with the plane of the required cut. A small screen mounted near the knee itself will allow the surgeon to quickly flip from the actual knee to the screen. A display panel mounted directly on the body of the saw itself is yet another option. The most important factor, which will require extensive experimentation, is to determine how accurately surgeons with different experiences and capabilities can perform the cuts, and how much basic training is required to reach optimum performance. Early tests indicate that freehand navigation is viable and the task now is to systematically develop the system to a practical level.

References