A NAVIGATED DRILL GUIDE USING AN INSTRUMENTED LINKAGE FOR THE PLACEMENT OF CUTTING JIGS DURING TOTAL KNEE ARTHROPLASTY

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Abstract

An instrumented linkage, where the tip could be used as a 3-dimensional digitizer with an accuracy of 0.3 mm, was used to navigate a drill guide. The specific task was to resect an upper tibia using a slotted cutting guide and an oscillating saw. The cutting guide was placed over two pins that were tapped into predrilled holes in the upper tibia. These holes were drilled by the surgeon with the aid of the navigated drill guide and computer graphics to visualize hole placement. Three surgeons of varying experience cut ten artificial tibias each. There was a small learning curve and no difference in results between operators. The maximum errors in the depth and in the sagittal and frontal plane alignments of the final upper tibial resections were approximately 1 mm and 2 degrees with the wear values of about half those values. It was concluded that an instrumented linkage could be effectively used in a navigation system for total knees where the goals were speed, simplicity, accuracy and low cost.

Keywords: total knee replacement; total knee surgical technique; navigation for total knee; accuracy of cutting; total knee alignment.

1. Introduction

Current total knee replacement surgery utilized a series of jigs and fixtures to make the required femoral and tibial cuts. The bony cuts together with soft tissue balancing are intended to achieve joint stability and restore the mechanical alignment. Inaccuracies result from several of the steps such that final errors in excess of 3° in mechanical alignment have been described [1]. In a review of 203 consecutive knee revisions, Sharkey found that the majority of early failures occurred as a result of malposition, misalignment, or instability [2]. Sources of error using standard jigs and fixtures include a non-centralized intramedullary rod, inaccurate jig placement, movement of the jig during cutting, and bending of the saw blade, and variability of bone density across the cut [3]. Recent studies have shown that computer-assisted surgery using optical navigation for the placement of the slotted cutting jigs has reduced the number of outliers and has provided other advantages [4,5]. However, such navigation systems are expensive and still retain much of the original instrumentation. Electromagnetic trackers have been introduced recently, as an alternative to the optical system. The advantages include smaller attachments to the bone and no line-of-sight issues. However the accuracy of the device is negatively affected by interference from metallic objects in the operating field [6].

As an alternative to the above methods, navigation with an instrumented linkage allows for highly accurate tracking with low latency and without any line of sight problems [7,8]. We present a navigation system comprising an instrumented linkage and a graphical interface in which tools such as burrs, saws, or drill guides can be fastened to the linkage. In the current system a drill guide was attached to the linkage and used to navigate the insertion of fixation pins for a slotted cutting guide. The purpose of this study was to demonstrate the linkage system as a form of navigation and evaluate the accuracy in resecting the upper tibia by surgeons of variable experience.

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2. Methods

The experimental task was to resect the upper tibia at a required level, using an instrumented linkage, associated software, and a visual interface. Software was written in Microsoft Visual C++ on a Windows XP platform with an OpenGL graphics API. Foam plastic tibias (Sawbones; Vashon, Washington, USA) with mechanical properties comparable to those of bone were each securely mounted in a holder providing a reproducible position (Figure 1). An instrumented six degree-of-freedom linkage (Microscribe G2LX; Immersion, San Jose, CA, USA) was rigidly fixed to the operating table alongside the tibia. Following prompts on the graphical user interface, the operator used the linkage as a digitizer to select key reference points on the proximal tibia and tibial holder. These were used to align the predefined 3D graphical model with physical position. The points were also used to define the target resection plane at 10 mm below the tibial plateaus and the target resection angle at 0 degrees relative to the tibial platform in the frontal and sagittal planes.

Once digitization was completed, the digitizing tip was

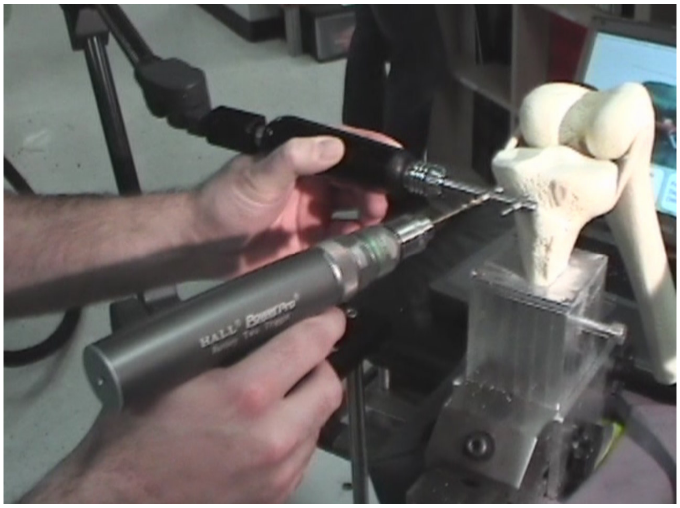

Fig. 1. Experimental set-up showing the drill guide attached to the linkage system. The operator uses the computer screen information to accurately drill the holes through the dual drill guides for the fixation pins. The slotted cutting guide is later placed on the pins.

removed from the linkage and replaced with the dual drill guide (Figure 2). During navigation, the software established the position and orientation of the drill guide with respect to the tibia. This drill guide consisted of two parallel sleeves separated by a distance that corresponded to that between the pin holes of the slotted cutting guide to be later used with an oscillating saw (Hall Powerpro, Conmed Linvatec, Largo, FL). The dual parallel drill guide was calibrated so that its position and orientation were known with respect to the linkage and consequently to the sawbone. The drilling location was determined based on the desired cut plane and geometry of the slotted cutting guide.

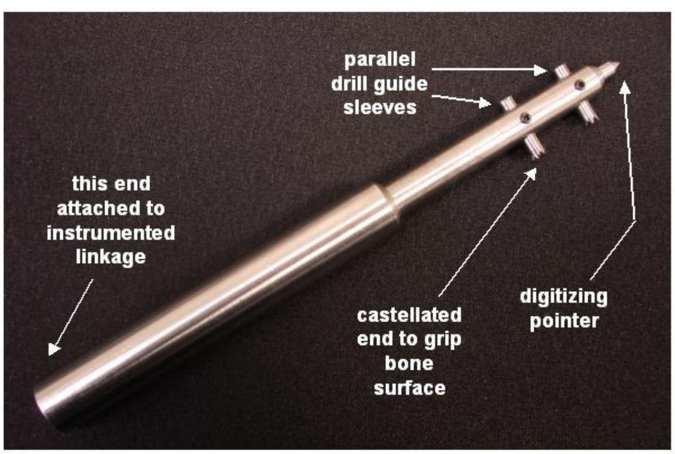

Fig 2. The parallel dual drill guide with digitizer tip. The two drill sleeves are the same spacing as the slotted cutting guide. The ends of the sleeves are castellated to grip the bone surface for ease of alignment.

The graphical interface prompted the surgeon to align one sleeve of the drill guide with the desired target by giving visual feedback on its location with respect to the target. The task of the operator was to align two pairs of circles on the computer screen by moving the drill guide (Figure 3), where one circle representing the drill guide had to be superimposed on the target circle. The first pair of circles represented the position of the drill guide on the bone, and the other pair represented the orientation. The castellated end of the sleeve enabled the operator to first establish the correct location, and then the rotation could be determined independently without slippage of the sleeve on the bone.

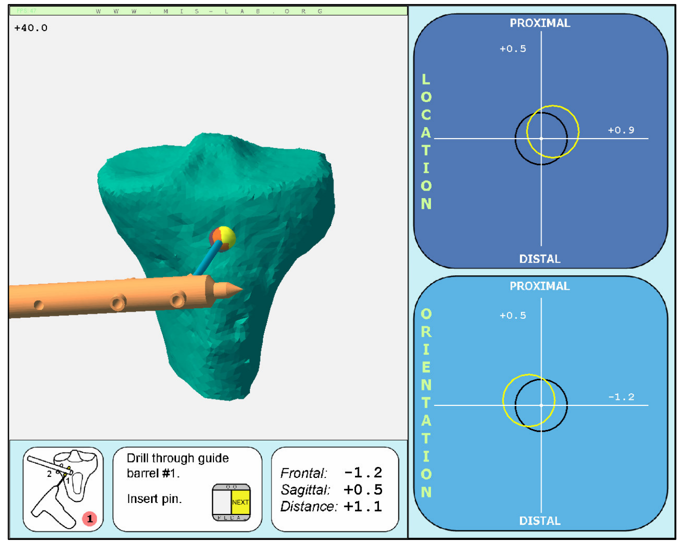

Fig 3. Screen shot of the graphical user interface. The main section shows a 3-D image of the drill guide with respect to the tibia, with the target drilling location indicated by the sphere. The upper right hand section gives detailed feedback on the position of this drill guide sleeve (yellow circle) with respect to the target (black circle) corresponding to the movement of their projections on the surfaces of the bone. The lower right hand section simultaneously relates the orientation of the drill guide (yellow circle) with respect to the desired orientation (black circle). The bottom of the screen displays instructional text and quantitative data.

When both pairs of circles were aligned, a hole was drilled through the sleeve and a pin (3 mm diameter) was tapped into the hole. With the first sleeve placed over the first pin, the drill guide was then rotated around the pin to align the second sleeve with the second target. This reduced the motion of the drill guide to one degree-of-freedom and kept the two drilled holes parallel and at the correct spacing. Once the second sleeve was aligned with the target, the operator drilled the second hole and tapped in the pin. The slotted cutting guide was then placed over the two pins and the upper tibia was resected, using the oscillating saw (Figure 4).

A smooth steel plate was placed on the top of the cut surface to simulate the placement of a tibial component. The Microscribe was used to digitize three points on the surface of the plate. The software created a plane from these points and calculated the mean difference in depth, frontal angle and sagittal angle of this plane with respect to the target plane. Statistical significance was determined using a Student's t-test in Microsoft Excel.

The system was tested by a medical student, a resident trainee (PGY-3), and an experienced surgeon with fellowship training in knee arthroplasty. Each operator was allowed 1-2 trial cuts to become familiar with the system, after which 10 tibias were cut.

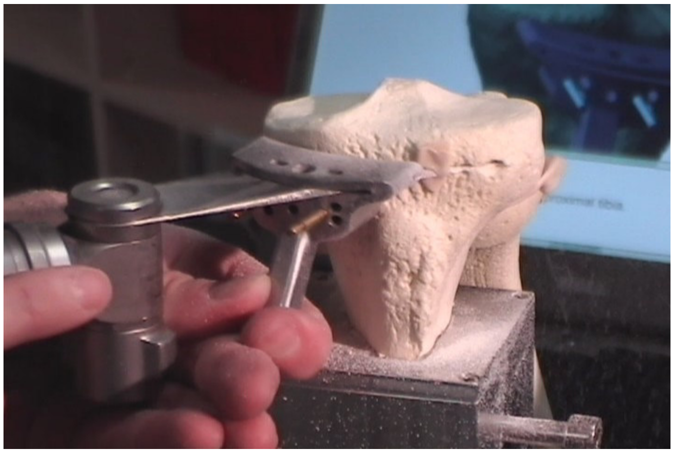

Figure 4. Tibial resection using an oscillating saw with slotted cutting guide placed over two pins.

3. Results

All three operators were able to use the visual display and complete the drilling procedure with the minimum of practice.

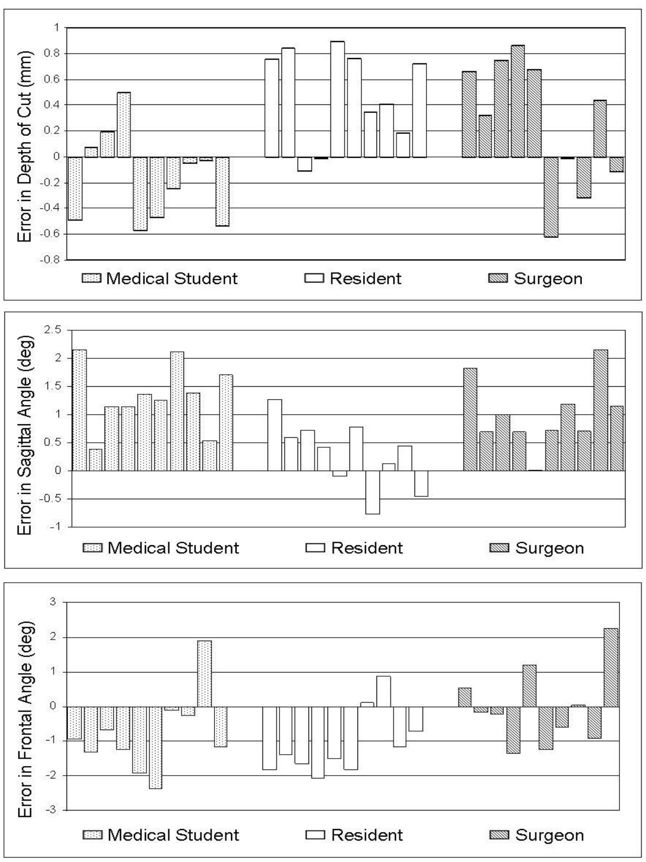

Fig 5. The error in depth of cut, sagittal angle and frontal angle are shown for each of ten sawbones cut in succession by three different operators. A positive value represents an excessive cut, a posterior tilt, or a varus tilt for depth of cut, sagittal angle and frontal angle respectively. The absence of a 'learning curve' is notable.

Figure 5 shows the errors in the final resection cuts for the 10 cases in succession for each of the three operators, while Figure 6 shows the averages of the absolute values. There was no evidence of a learning curve in terms of improved accuracy over the 10 cases. The errors in the depth of cut were mostly less than 1 mm. For the sagittal plane angles there was a bias towards a posterior tilt of around 1 degree, and for the frontal plane angles, a bias towards a varus tilt of around 1 degree. While there were some statistical differences between operators in both the distance and the angle, no single operator over-or-under performed relative to the others. The mean errors themselves for the combined results were small, less than 0.5 mm and 1 degree.

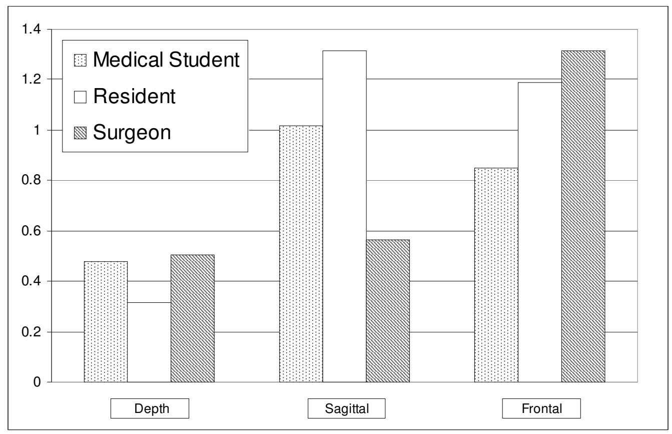

Fig 6. The average of absolute values of the errors for the three operators.

4. Discussion

There was a small learning curve involved with this experiment. Each operator was given only 1-2 trial cuts which were sufficient for the operators to feel comfortable with the system. There was no noticeable trend of an increase or decrease in accuracy as the operators gained more experience over the course of their ten cuts. The procedure was divided into simple steps which were easy to perform, accompanied by intuitive graphics and instructions. The technique of navigating the dual drill guide incorporated the simplicity of guiding a drill bit with minimal risk associated with a drilling procedure, even though the operator needed to view the computer screen at the start of the drilling. Overall, no one operator was more accurate than any other. Although there was variability in technique from operator to operator, the errors were still small enough that it was mostly contained within the range of error of the overall system.

The accuracy of digitizing single points using the particular linkage used was 0.23 mm RMS error. Inconsistencies would result from various stages of the procedure however. Tapping of the pins into the bone caused inaccuracies in both sagittal and frontal planes. The direction of the error varied with the angle and intensity with which the pins were tapped. In order to avoid such inaccuracies, pins or headless screws could be power driven directly into the bone. To prevent movement of the slotted cutting guide on the pins, a third cross pin tapped in at an angle could be used to further anchor the cutting guide once it has been placed on the tibia. Angular errors could also be due to the motion of the slotted cutting guide relative to the bone during cutting. Additionally there was some bending of the saw blade as it progressed across the tibia, due in part to variability in material density as in the normal tibia. The final alignment data was collected from the surface of a metal plate (the simulated tibial component) which may have been resting on small protrusions that were not removed during cutting.

The use of the navigated drill guide using an instrumented linkage resulted in accurate proximal tibial resections with results that were reproduced by operators of variable training levels. The mean errors in the depth of cut and in the frontal and sagittal angles were smaller than those reported using traditional instrumentation [1]. This technique has the potential to be highly accurate, inexpensive and reproducible. Traditional intramedullary and extramedullary instrumentation is not needed thereby permitting the technology to be particularly important in the trend towards smaller incisions and less invasive surgery.

The use of an instrumented linkage can have many potential applications in orthopaedic surgery, and already it has been applied to surface replacement hips [9]. Using the linkage as a simple digitizer, or as in our experiments, for drilling hoes in bones, are simple steps which can be incorporated into complete procedures. However if the linkage is rigidly attached to the operating table, it has the limitation that movements of the bones are not tracked in real time, as in the optical or electromagnetic systems. Hence a digitization sequence of many points on the femur or tibia would be subject to errors from bone movements between points. One solution is to use a clamp fixed to the operating table, with which to clamp the bone being digitized. Another solution is the use of a small ad lightweight linkage which is clamped to the bones themselves. Both methods would include registration by digitizing key landmarks as well as a procedure to determine the center of the femoral head. A further limitation of a linkage is that once the bone cuts have been made, subsequent monitoring of relative bone positions for ligament balancing and measuring overall alignment is difficult in real time. However solutions to these problems can be envisaged.

On the positive side, the linkage is unobtrusive and has no line of sight problems. It is highly accurate, more so than alternate systems at this time. The costs of such linkages are only a fraction of those for the alternate systems. Hence it is proposed that instrumented linkages can find a useful place in total knee (and other joint) procedures where the primary goals are accuracy, speed and simplicity.

Acknowledgement

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