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Combined pre-operative planning and intra-operative navigation to precisely restore patient-specific anatomy in total hip replacement procedures

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Abstract

The paper presents an approach for computer-assisted implantation of artificial hip joints. It is based on a novel solution combining pre-operative planning and intra-operative navigation in a way that the natural anatomy of the joint before surgery can be restored as close as possible, or with exactly planned modifications. A surgical workflow has been developed which highly focusses on the registration and restoration of patient specific parameters instead of using generalized criteria like the Lewinnek safe zone. The feasibility of the approach has successfully been demonstrated by a laboratory setup of Sawbone models.

1 Introduction

Total hip replacement procedures are among the most frequent surgical interventions in all industrialized countries. Although it is a routine operation literature reports that important parameters regarding for example cup orientation and leg length discrepancy often turn out to be not satisfying after surgery [1], [2]. One of the reasons is based on the fact that generalized criteria like the Lewinnek safe zone do not lead to proper results in particular patient-specific anatomical cases. Existing computer-assisted commercial products are either based on software solutions just for pre-operative planning, or on imageless navigation systems that are only used during surgery in the operating theatre. The approach presented here is based on a novel integrated computer-assisted solution combining pre-operative planning and intra-operative navigation in a way that the natural anatomy of the joint before surgery can be restored as close as possible, or with exactly planned modifications.

2 Materials and Methods

Pre-operative planning

The software used for pre-operative planning is based on the commercial product modiCAS||3D [3] which can process both, 3D CT images and standard 2D x-ray images. Availability of 3D images offers extended possibilities to precisely determine desired parameters, but on the other hand this can be a time-consuming procedure because it usually includes segmentation of the femur head and the acetabulum. In contrast, planning on the base of planar 2D x-ray images can be done faster but has of course limitations to extract all information one may be interested in. However, in combination with intraoperative navigation this may be compensated to some extent, as described below. Accurate patient-specific scaling of the 2D x-ray image image is a very important prerequisite for exact determination of relevant parameters. We have designed a low-cost localization system to be mounted close to the x-ray apparatus. It localizes the 3D position of the rotation center above the x-ray detector by small motions of the leg and eliminates uncertainties of conventional methods that are caused by improper positioning of a calibration body [4]. Important parameters determined during pre-operative planning include cup inclination, CCD angle, lateral offset, leg length discrepancy and location of the resection line for the femur head. The planning software transmits the values of these parameters to our navigation system for further processing.

Intra-operative navigation

We have designed a custom-built optical navigation system. In contrast to existing imageless systems it combines data from pre-operative planning with additional information which is acquired during surgery. The first intra-operative step consists in digitizing the rotation center of the natural joint by femur motions. Data are measured with regard to two reference bodies of the navigation system, one attached to the pelvis and another one to the femur. After resection of the femur head further anatomical landmarks at the acetabulum are recorded. The key objective of our approach is to implant the artificial joint such that the natural anatomy of the joint before surgery is restored as close as possible, or with exactly planned modifications. This is achieved by a unique integration of numerical values determined during pre-operative planning with measurement data acquired intra-operatively. The navigation system can thus show clear instructions how to guide the surgical instruments for both, cup and stem preparation and insertion of implant components.

3 Results

Implementation and validation of the new concept so far has been carried out by a laboratory setup consisting of a Sawbone model of pelvis and femora. All major steps of the surgical workflow including pre-operative planning have been intensively discussed with collaborating surgeons. The Sawbone model facilitates investigation of the complete intra-operative workflow, including resection of the femoral head and insertion of the implant components. Easy and robust setup and application have been key objectives for the development of our custom-built navigation system which includes the design of reference bodies to be fixed at the surgical instruments. In addition to graphical visualization on the main computer screen it is possible to attach a mini-display to the surgical instruments which receives relevant information from the main computer by wireless transmission [5]. Thus the surgeon can position the instrument in the desired way without having to change his viewing direction between computer screen and operating area.

During reaming of the acetabulum and insertion of the cup prosthesis the system shows how to orient the instrument to achieve the planned inclination and anteversion of the cup. Preparation of the femur and insertion of the stem prosthesis are better supported if pre-operative 3D planning is available, because in this case the desired antetorsion of the femur can be determined. In case of 2D planning only the location of the artificial femur head after implant insertion is measured by the navigation system and compared to the stored natural position. Deviations can be compensated to a certain extent in “femur first procedures” by selecting the cup anteversion after stem insertion such that the combined anteversion is restored as close as possible. Laboratory tests have turned out that the target values for important parameters can be met with an accuracy of $\pm$1 mm, which is comparable to very good results reported in literature [6]. This includes for example the 3D position of the joint rotation center, determining leg length and lateral offset.

4 Conclusion

The suggested integration of computer-based pre-operative planning and intra-operative navigation offers new opportunities for accurate implantation of artificial hip joints without demanding high technical efforts like use of robotic systems. A surgical workflow has been developed which highly focusses on the registration and restoration of patient specific parameters instead of using generalized criteria like the Lewinnek safe zone. This paper describes the basic concepts and a first laboratory implementation with bone models. Based on promising results further steps towards clinical application will be investigated together with collaborating surgeons.

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