Medical Engineering and Physics 37 (2015) 524–530

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Precision of image-based registration for intraoperative navigation in the presence of metal artifacts: Application to corrective osteotomy surgery

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ARTICLE INFO

Article history:
Received 28 May 2014
Revised 6 February 2015
Accepted 22 March 2015

Keywords:
Computer-assistance
Cone-beam CT
Metal artifacts
Registration
Navigation

ABSTRACT

Navigation for corrective osteotomy surgery requires patient-to-image registration. When registration is based on intraoperative 3-D cone-beam CT (CBCT) imaging, metal landmarks may be used that deteriorate image quality. This study investigates whether metal artifacts influence the precision of image-to-patient registration, either with or without intermediate user intervention during the registration procedure, in an application for corrective osteotomy of the distal radius. A series of 3-D CBCT scans is made of a cadaver arm with and without metal landmarks. Metal artifact reduction (MAR) based on inpainting techniques is used to improve 3-D CBCT images hampered by metal artifacts. This provides three sets of images (with metal, with MAR, and without metal), which enable investigating the differences in precision of intraoperative registration. Gray-level based point-to-image registration showed a better correlation coefficient if intraoperative images with MAR are used, indicating a better image similarity. The precision of registration without intermediate user intervention during the registration procedure, expressed as the residual angulation and displacement error after repetitive registration was very low and showed no improvement when MAR was used. By adding intermediate user intervention to the registration procedure however, precision was very high but was not affected by the presence of metal artifacts in the specific application.
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1. Introduction

Bone fractures are very common [1] and are mostly treated by closed reduction. In this procedure the aim of the physician is to align the bone segments without surgical intervention. Approximately 5% of the distal radius fractures [2,3] result in a symptomatic malunion. Such a malunion [4] may lead to a reduced function of the limb, chronic pain, and may finally lead to early osteoarthritis. In severe malunion cases the bone segments may be realigned by surgical treatment with a procedure called a corrective osteotomy [4]. In this procedure the bone is cut at, or near, the original fracture location. After alignment of the bone segments, the new relative position is fixated, e.g., using an anatomical angular-stable locking plate and screws [5].

In conventional surgical treatment, 2-D imaging is used for planning [6] and to guide the surgeon during the intervention. Unfortunately, 2-D images hide rotations about the long axis of the bone, which may lead to suboptimal positioning [7]. In the last decade, 3-D techniques have been reported to navigate the distal bone segment to the preoperatively planned position with respect to the proximal bone segment [8–14]. Intraoperative navigation is either based on optical tracking [8,10] or intraoperative 3-D imaging with a cone-beam CT (CBCT) scanner [11,12,15]. These methods require linking the preoperatively obtained virtual bone to the actual intraoperative bone in a process called patient-to-image registration. When optical tracking is used for patient-to-image registration, the surgeon links bony landmarks to virtual landmarks by pinpointing a number of these landmarks in both physical and image space, which is sometimes felt as a cumbersome procedure. A disadvantage of optical tracking systems compared to 3-D image registration is the fact that positioning errors depend on the accuracy of pinpointing the landmarks, but also on the distance between the bone and the cameras of the tracking system [16,17]. This may lead to navigation errors of up to 2 mm [17–19]. Furthermore, a tracking device is an additional system in the operating room, while recent mobile CBCT imaging stations allow making standard 2-D fluoroscopy images as well as 3-D CBCT scans for evaluation and registration purposes.

When registration is based on an intraoperative 3-D CBCT-scan, metal landmarks can be used for detection and for navigation, such as the use of bone pins to bring bone segments to the planned position during corrective surgery [11]. However, such metallic landmarks introduce imaging artifacts in the reconstructed 3-D image. These metal artifacts [20,21] may hamper image-based navigation and are a

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http://dx.doi.org/10.1016/j.medengphy.2015.03.008
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potential source of error in positioning bone segments. Especially the variability in intraoperative registration is of interest since it affects both absolute and relative positioning of bone segments in 3-D space. A high precision, which refers to a low variability of repeated registrations [22], is of major importance for intraoperative positioning. However, precision is often neglected or considered synonymous to accuracy [18].

This paper focuses on the precision of intraoperative 3-D image-based registration of a virtual bone to an actual bone that includes metallic landmarks for bone realignment in an application dedicated to corrective osteotomy surgery of the distal radius. The research questions are: (1) to what extent is the precision of patient-to-image registration affected by adding intermediate user intervention during the registration process, and (2) does precision improve when metal artifact reduction is applied?

2. Materials and methods

In this paper we evaluate the precision of image-based intraoperative registration, which is part of a novel technique for realigning a malunited radius in 6 degrees of freedom (DOF) according to a preoperative plan [11]. This method includes interactive software for preoperative position planning based on a 3-D CT scan, and for intraoperative guidance based on an additional 3-D CBCT image. We first briefly describe the application and the procedural steps for preoperative position planning and actual intraoperative positioning of bone segments (Fig. 1), and subsequently delineate the part of the method that is focused on in the current study.

2.1. Overview of the application

In the application for realigning the distal radius with respect to the proximal radius, a CT-scan is made of both the affected and contralateral healthy lower arm, in step (1) (Fig. 1). The contralateral arm serves as reference for preoperative position planning. Then, the affected radius is segmented (2), resulting in a polygon mesh for visualization. This polygon mesh is also used to extract a double-contour polygon (3) by sampling the image intensity 0.3 mm toward the inside (high CT value) and outside (low CT value) of the bone contour, along the surface normal vector. The double-contour polygon contains many geometrical landmarks for accurate registration [11,23] and is referred to as the "virtual bone". It is used during pre- and intraoperative registration. Next, the virtual bone is cut interactively (4) providing distal and proximal segments, which exclude the deformity. These segments are aligned, by registration (5), with the mirrored image of the contralateral healthy radius yielding the matrices $\mathbf{M}_d$ and $\mathbf{M}_p$, for aligning the distal and proximal bone segments (Fig. 2a). These matrices provide the correction matrix $\mathbf{M}_c = \mathbf{M}_p{}^{-1}\,\mathbf{M}_d$, which brings the distal segment from the affected to the planned position in 3-D space.

Intraoperatively, pin pairs (80 mm long, 3 mm diameter) are inserted in the distal and proximal radius (6), and marker tools (containing three 5-mm stainless steel spheres each) are slid over the pin pairs (7) for accurate pin-position detection (Fig. 2b). Next, an intraoperative 3-D CBCT scan is made (8) using a mobile scanner. It enables marker-tool detection (9), which effectively define local coordinate systems for the distal and proximal pin pairs. The intraoperative image is further used for registration of the virtual bone to the patient bone (10), yielding matrix $\mathbf{M}_W$, which enables calculating the distal pin-pair position (11) with respect to the proximal pin-pair position (Fig. 2b), that is in agreement with the preoperative plan, using matrix $\mathbf{M} = \mathbf{M}_W\,\mathbf{M}_p{}^{-1}\,\mathbf{M}_d\,\mathbf{M}_W{}^{-1}$. The pin pairs further serve to navigate the bone segments to the planned position after the osteotomy. This is accomplished using a passive positioning clamp, which is very similar to an external fixator, with the big difference that it is first adjusted

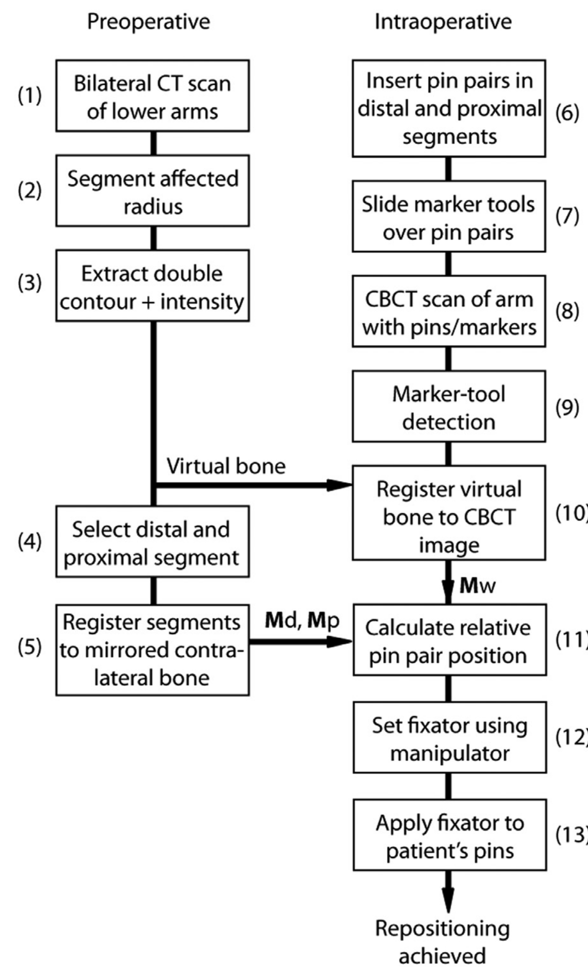

Fig. 1. Block diagram visualizing the pre- and intraoperative steps for bone repositioning in the distal radius osteotomy application. The current study focuses on the precision of intraoperative registration, step 10.

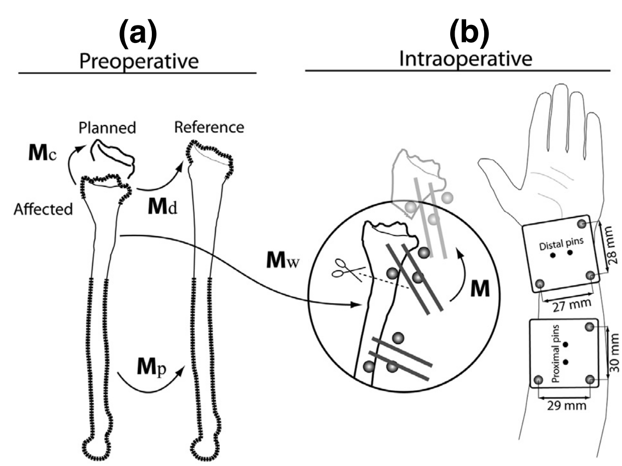

Fig. 2. (a) A virtual model of the affected bone is obtained (left) from a preoperative CT scan by segmentation. Next, a distal and proximal segment, excluding the deformity, are cut and registered to the mirrored contralateral bone (right) that serves as reference. Planning provides the correction matrix $\mathbf{M}_c = \mathbf{M}_p{}^{-1}\,\mathbf{M}_d$. (b) Two pin pairs are intraoperatively inserted into the distal and proximal bone segments (right). After the osteotomy these pins are used to reposition the bone segments. The marker tools are slid over the pin pairs to determine pin-pair positioning (size exaggerated for clarity). The circle indicates the limited field of view of the CBCT scanner (left). Registration provides the transformation ($\mathbf{M}_W$) between the coordinate spaces of the virtual bone and the intraoperative 3-D CBCT image.

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