Light-weight robot stability for orthognathic surgery. Phantom and animal cadavar trials

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Abstract:

Despite significant improvements orthognathic surgery in the past years, there is still room for improvement. Since the objective of this surgery is to position one jaw in relationship to another (and base skull), orthognathic surgery is a good candidate for a systematic robotic approach.
Coupling and holding the maxilla by a robot has already been discussed in prior work; with this study we discuss the next stage of the surgical workflow which involves holding the target position while the surgeon drills and fastens the maxilla.
The LBR3 was tested in laboratory for its stability and usability. The results indicate a shift in target position almost 1.5mm and overshoot upon release of force. Recovery of the original position was established with errors below 0.01mm, and orientation up to 0.06º. Also identified with the LBR3 is the axis stability difference.
Finally this study concludes that the LBR3 is adequate to assist in orthognathic surgery.

Keywords: Robotic Assisted Surgery, Ortognathic surgery, Light-Weight robots

1 Problem

Surgeries which can benefit from robotic systems are diverse and much literature is provided, e.g. [1]. The use of light-weight robots in surgery on the other hand, is still under evaluation. In already presented approach to robotic assisted orthognatic surgery [2], the abilities of these robots are yet to be demonstrated.
In this study the light-weight robot LBR3 is employed in a realistic setting. This light-weight robot has approximately the same size as a human arm, and can manoeuvre a load equivalent to its own weight, up to 14Kg. The small size allows to easier integration with the conventional workflow. Each of the seven joints of the LBR3 integrates sensors for motor position, joint position and joint torque, allowing therefore the safe cooperation with the human operator [5]. The LBR3's ability to reconfigure its joints while maintaining the position and orientation of the instrument tip unchanged, adds to the characteristics of this robot.
In the context of medical applications the LBR3 is used with different projects, e.g. [6]. In this study we look in to the benefits and possibilities of this hardware. How steady can this robot hold the target position while maintaining the desired accuracy increase of the robotic approach to the conventional orthognathic surgery [2].

2 Method

The robot was tested in laboratory, simulating OR conditions, with a phantom patient as well as with a swine skull. The performed tests are intended to assert the behaviour of a light-weight robot in assistance procedures under realistic surgical conditions. In particular it is intended to determine the robot's stability when holding the maxilla in the target position during the single jaw surgery with maxillary repositioning.
To test this scenario a plastic phantom with detached maxilla was used. The maxilla is held to the skull with elastic rubbers simulating the soft tissues holding the bone segment after down-fracture. The maxilla is held by the robot in the target position using an end effector designed for this purpose [3] (Figure 1).

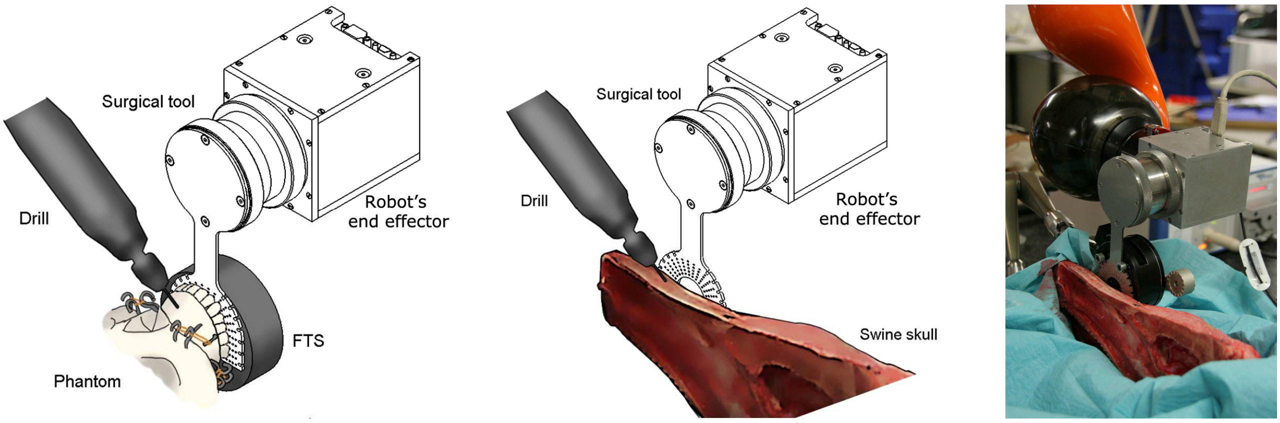

Figure 1 - Scheme of the experimental setup for drilling of the phantom's maxilla.

The target position was held by the robot and its displacement measured as three holes were drilled in the maxilla; one hole from above and two laterals, from each side. The standard non-surgical drill rotated at 20 000 rpm. The phantom was not rigidly fixed, but held in position with the aid of a vacuum cushion. Likewise, the swine skull was not rigidly fixed, but held in position with the aid of a vacuum cushion.
Given that the swine dentition does not resemble that of the humans, the tool was fixed with four screws on the side of the nose cavity. Using a surgical drill at 40 000 rpm the bone was drilled three times along the bone near the surgical tool. Afterwards screws were inserted in these holes and tightened, simulating the fixation procedure during the maxillary repositioning. The used screws were not medical standard, but plain 3mm diameter steel screws. These three procedures were recorded and the robot position measured using the internal encoders of the LBR3, with a resolution of 0.001mm / 0.001°. The control method of the robot was supplied / implemented by KUKA, for this experiment, only the target position was given, and the controller attempts to hold it as the experiment takes place.

3 Results

In Figure 2 the results of the drilling process of the phantom's maxilla are illustrated.

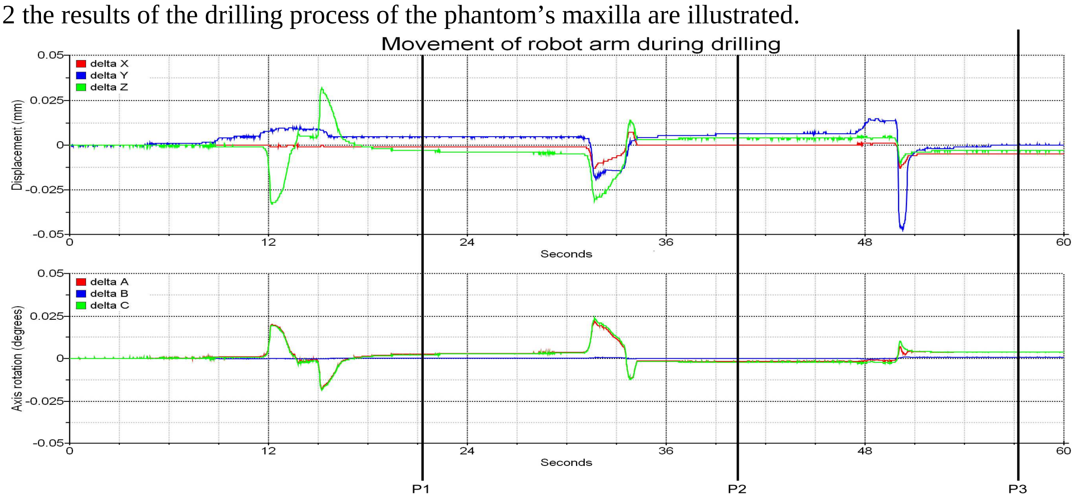

Figure 2 - Horizontal axis displays time in seconds. The top graphic displays the robot arm displacement in millimetres, the bottom graphic the robot arm displacement in degrees.

From this experiment it is observed that: From 0 to P1, a hole was drilled vertically and produced a displacement of 0.033mm downwards. This displacement was compensated by the robot arm, and upon removal of the drill the position overshot by 0.03mm. During this period angles A and C displaced 0.02° with same magnitude of overshoot upon release. Between P1 and P2 one lateral hole was drilled and displaced the vertical (Z) axis by 0.03mm. Upon release of this force, the robot did not return to the exact same position, but presented a constant error of approximately 0.007mm in the depth axis (Y) and 0.0045mm in the horizontal X axis. During this period the angular deviation was similar to the period 0 to P1. Between P2 and P3 a third drill hole was made in the opposing lateral wall of the phantom's maxilla.

This resulted in a displacement of 0.015mm in the direction of the target (depth, Y). The observed overshoot of the position was considerably higher, approximately -0.05mm. A residual offset of 0.005mm and 0.0042º at the end of the experiment was observed. The most sensitive axis to an external force is the Y.
The figure below illustrates the measured position during the drill procedure of the swine skull.

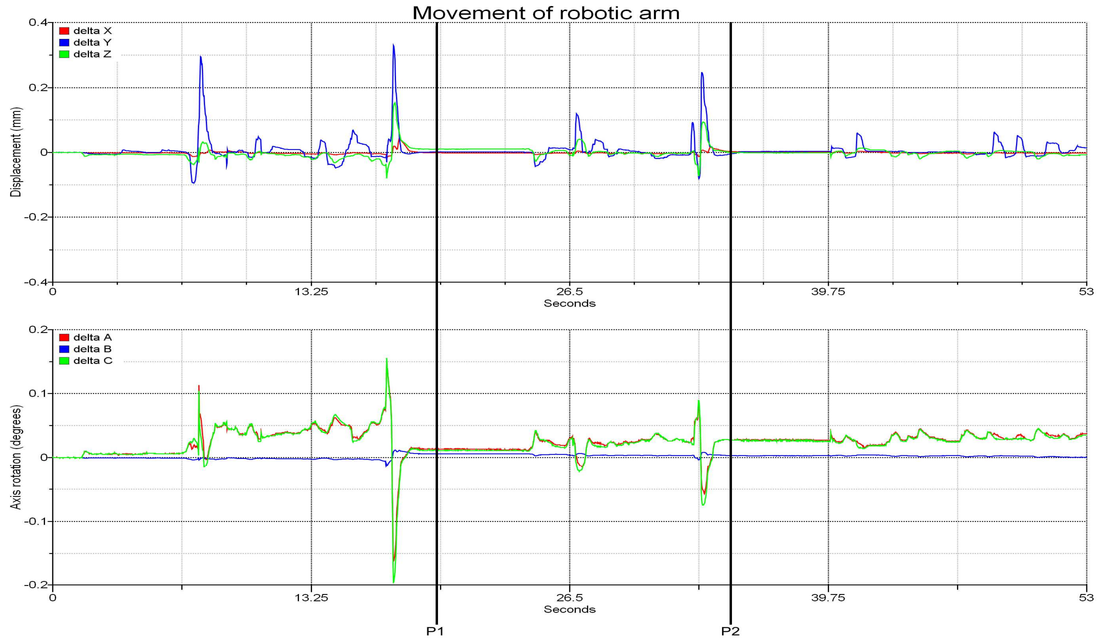

Figure 3 - Horizontal axis displays time in seconds. On the top graphic the vertical axis displays the robot arm displacement in millimetres, the bottom graphic the robot arm displacement in degrees.

From this experiment it is observed that: From 0 to P1, one hole was drilled until the drill end pierced the bone and reached the nasal cavity. This caused two spikes in position with amplitudes of 0.3mm and 0.33mm respectively. The two displacement spikes lasted for 0.76 and 0.74 seconds.
During the same period angles A and C suffered similar displacements oscillating between 0.155º to -0.2º together with the second Y (depth) displacement spike. After the second drill hole (P1 to P2), the orientation error offset was 0.029º. The position offset was approximately zero. Between P2 and the end of the experiment the third hole was drilled.
During this period the robot oscillation reached a maximum of 0.06mm. The angle oscillation was lower than the remaining offset of the previous drill position. The observed overall behaviour is that drilling bone is not as smooth as drilling the phantom skull. The robot's ability to recover the original position after the application of these forces is recognized with the largest offset error being found in the rotation axis A and C.
The next illustration shows the measured position during the screw fixation procedure of the swine skull.

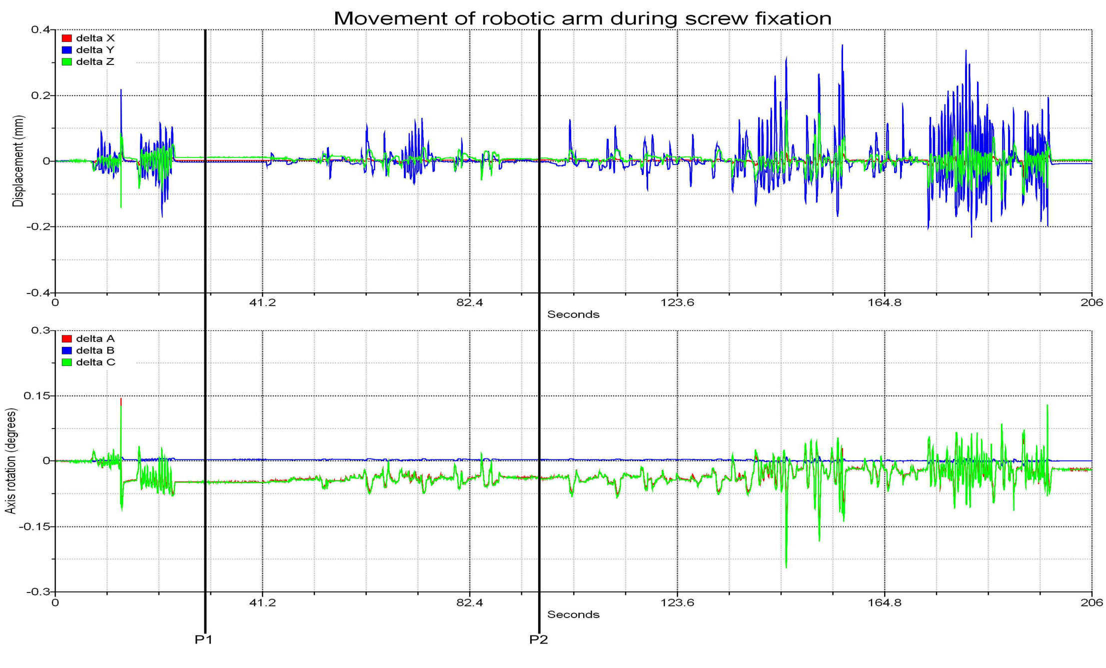

Figure 4 - Horizontal axis displays time in seconds. On the top graphic the vertical axis displays the robot arm displacement in millimetres, the bottom graphic the robot arm displacement in degrees.

Contact between the end effector and the surgeon was noted throughout this experiment, in particular when fixating the third screw. From this experiment it is observed that: From 0 to P1, one screw was inserted with forces oscillating at a frequency of 1.47Hz. The maximum displacement of the robot arm was 0.22mm and 0.15º. The offset of the robot arm at P1 was 0.013mm in the Z (vertical) axis and -0.05º.at both rotation axis A and C. Between P1 and P2 a second screw was inserted which resulted in similar oscillation as the previous screw, but with lower displacement amplitude, approximately 0.2mm. The rotation axis also suffered less oscillation and maintained the previous offset of -0.05º.
From P2 to the end of the experiment, the maximum displacement measured was 0.36mm on the depth (Y) axis, and -0.25º on both A and C rotation axis. After the screw had been inserted the error from the original position was 0.005mm on the X and Z axis and -0.02º in the A and C angles. Similar to the drilling procedure the robot showed ability in recovering the original position after the application of these forces, with a residual error.

4 Discussion

To assist the orthognathic surgeon in this task and provide a more accurate and stable target position fixation, a robotic approach has been suggested [2]. Several research examples exploit the light-weight robot option since they do not consume too much space in the operating room and yet enables precise targeting and guidance. However their usability in surgery has yet to be proven. For the case of the LBR3, depending on the amount of force which it is applied, the target position can shift almost 1.5mm. Upon release of the applied force, the robot arm overshoots the target position, often more than the original displacement. Although the target position was recovered with a minimal error in position (below 0.01mm), the orientation of the robot fledge presented a more significative error. This error in axis A and C (horizontal and vertical axis respectively), could grow up to almost 0.06º, in the worst case observed. As it is known, a small rotational error can produce a large error at the end of a lengthy tool.
From drilling both the phantom and the swine skull, the speed of the drill did not create a visible vibration on the robot position. The opposite happens when rotating the screws. The applied force is dynamic with every thrust and twist of the screwdriver.
Also noted with the LBR3 is the stability difference in its axis. The most sensitive axis to external forces is vertical with the maxilla. In opposition the horizontal direction towards the patient is the most resistant.
The resulting amount of error observed is medically tolerable for orthognathic surgery. The direction of the largest displacement error (vertical to the maxilla), could tolerate an error up to one millimetre without the necessity of further bone removal or down-grafting.
The results do not seem to justify the attempt to implement an improved control mechanism.
The experiments presented in this article were conducted using the KUKA LBR3 and therefore these results apply only to this particular robot arm. Further extensive testing should be made with patients to assert the final usability. However it provides an idea of what is to be expected from such robots. Finally this study concludes that the LBR3 is adequate to handle the proposed robotic assisted orthognathic surgery [2].

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