PRELIMINARY ACCURACY ASSESSMENT OF A NEW BONE-MOUNTED ROBOT FOR UNICOMPARTMENTAL KNEE ARTHROPLASTY

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INTRODUCTION

Unicompartmental knee arthroplasty (UKA) has functional and financial advantage over total knee arthroplasty, but under-utilisation remains an issue due to higher revision rate and steeper learning curve (Willis-Owen 2009) (Zambianchi 2014). Commercial UKA robots have improved accuracy over conventional jig approach, but the robots entail high costs and are only compatible with proprietary navigation system (Lonner 2009) (Dunbar 2012). The robots' dependency on real-time knee position tracking also necessitates intra-operative maintenance of line of sight between the camera and optical trackers (Condit 2009).

We recently investigated the value of adapting a guidance concept in our lab called dynamic physical constraint (DPC) in the context of femoral surface resection for alignment and installation of UKA prosthesis. DPC facilitates actively moving contact-based constraints and allows smooth motion parallel to the constraints (Hungr 2008), making it ideal to realize three-dimensional virtual fixture for hand-operated spherical burr. Our robot is compact and femur-mounted. After registering its position with respect to the femur (using commercial navigation system), the robot tracks burr location standalone, using its own joint sensors. Immobilization or tracking of bone is unnecessary due to negligible relative motion between the femur and the mounting base.

Surgeons strive to reduce implant alignment error and prefer being able to make cutting decision (Condit 2009). Our robot thus incorporates surgeon in the control loop. We hypothesize that the DPC robot can enhance accuracy in simulated UKA femur resection. The goal of this study was to evaluate whether the proposed robot design enables the user to perform the surface resection with accuracy comparable to that of commercially available UKA robots.

MATERIALS AND METHODS

Our preliminary robot prototype facilitated rotary-prismatic-prismatic (RPP) joint configuration, holding a hand mill at its end-effector. The first joint allowed the mill to pivot around the transverse axis at the mounting point; the second joint enabled mill's medial-lateral translation, while the third one enabled perpendicular translation with respect to the transverse axis. We realized DPC using a motorised linear blocker (Haydon Kerk Motion Solutions, Inc. Waterbury CT) mounted parallel to the third joint; it actively translated to constrain the lowest joint travel, thereby defining the deepest possible cut (See Figure 1). A steel insertion rod was used as bone-mounting mechanism.

The accuracy assessment involved resecting 20 medium-density fibreboard (MDF) samples using the robot. The MDF samples had half-cylindrical contour (30.0mm outer radius, 6.0mm inner radius) and uniform thickness (25.4mm). The outer surface represented medial condyle, while the inner surface aligned the sample concentrically with the robot's insertion rod. The robot and the sample were clamped to a jig, which fixated the sample at 45°. A 5mm spherical burr (Robert Bosch Tool Corporation, Mount Prospect IL) was installed, and the DPC blocker was immobilised so that the resection uniformly reduced the radius of the half-cylinder from 30.0mm to 27.5mm. All resections were performed by one of the author (JK).

After each resection, we fit an MDF dummy implant (27.5mm-radius mating surface) to the resected sample. We scanned the implant-sample combination using Vivid 9I 3D laser scanner (Konica Minolta Sensing Americas, Inc. Ramsey NJ). Laser scans were transformed into 3D models using Rapidform XOR3 (3D Systems Corporation, Rock Hill SC). The reconstructed model was then imported to Rapidform XOV3 (3D Systems Corporation, Rock Hill SC) and compared to a ground-truth 3D CAD model of the implant. Transform between the scanned sample and the CAD implant was obtained by placing a local coordinate system on the corner of the CAD implant and manually aligning the CAD image to the scanned data. The results were reported as alignment deviation of the dummy implant in six coordinates.

RESULTS

The results of the accuracy test are shown in Figure 2 with the data presented as mean and standard deviation of the dummy implant alignment error in six coordinates. On average, implants deviated from ideal installation angle by 0.8° varus, 0.3° lateral rotation, and 2.3° flexional rotation. Implants were an average of 1.6 mm above the target surface and had average of 0.1mm posterior and 0.1mm lateral shifts.

DISCUSSION

In this preliminary assessment, the results provide some encouragement that our hypothesis of a DPC robot can enhance accuracy in simulated UKA femur resection procedure may be true, as the error in most coordinates is contained under 1mm or 1degree. The much higher flexional rotation and the overall upward implant offset are likely caused by joint mal-alignment and backlash in our preliminary prototype. More specifically, the imperfections deviated the burr during articulation and caused an under-resection of material on one side of the sample. As a result, implant mates with the prepared surface closely but is displaced rotationally.

The assessment entails a few limitations. Firstly, since the robot is a quick-prototype, we constructed some of the links in open-section geometry using sheet metal, which is deemed not optimal for stiffness. Resultant link deflection could have hindered the robot's true performance. Secondly, the resection setup was specifically designed to align the robot and the MDF sample, and thus potential error of intra-operative registration process using a navigation system was not accounted for. Moreover, lower rigidity of the dummy implant could have led to overestimation of conformity when forced to fit on the resected sample.

The results indicate that, under aforementioned simplifications, our preliminary robot prototype can achieve similar alignment accuracy as commercially available UKA robots. However, our prototype clearly struggles in obtaining good superior/inferior implant alignment. Note that distinctive measurement protocols were used to obtain alignment error in three robots, and thus the values are not directly compatible (Lonner 2014) (Citek 2013).

In future work, we intend to design a more rigid and well-aligned robot joints and links to reduce articulation error and also integrate the robot with proper bicortical screw bone-mounting mechanism. We also plan to assess the accuracy of DPC actuation, which was implemented but not quantified yet. Next iteration of robot design will enable testing of more complex implant geometries under more realistic surgical simulation.

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DISCLOSURES

One of the authors (AH) is named as an inventor on a patent application filed by OMNIlife Science relating to the Dynamic Physical Constraint concept. The authors have received no funding from OLS for the present study.

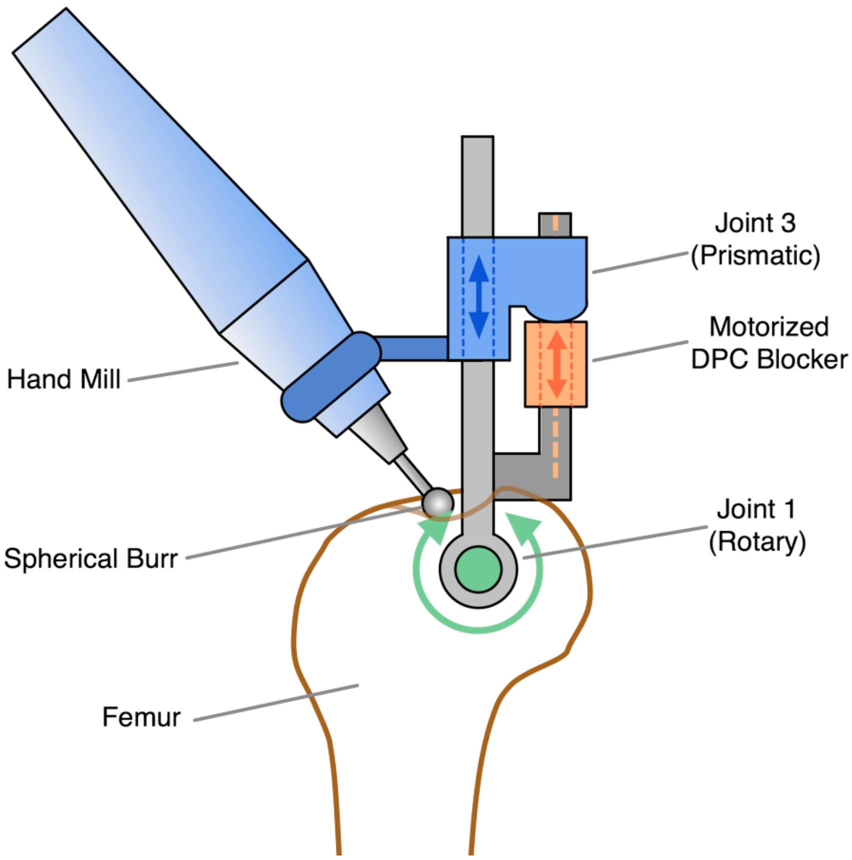

Figure 1: 2D Schematic representation of Rotary-Prismatic configuration and Dynamic Physical Constraint.

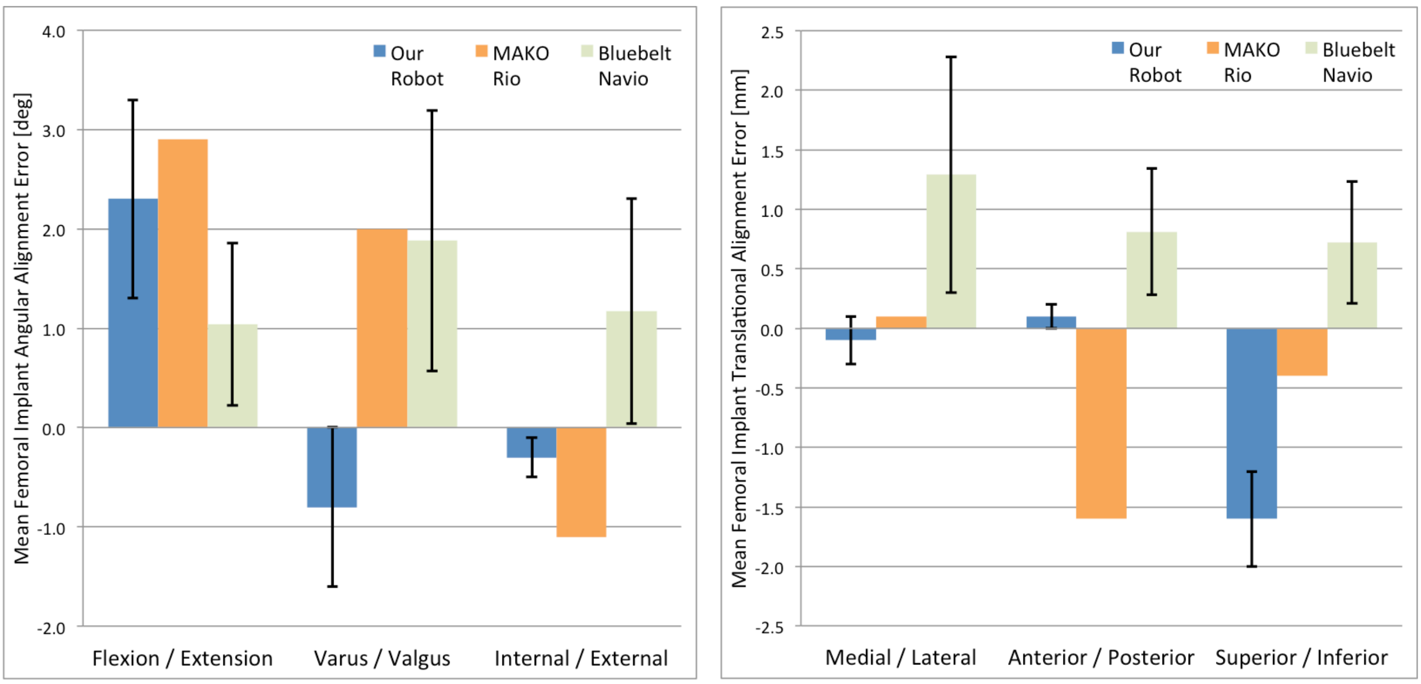

Figure 2: Comparison of three robotic systems in femoral component angular alignment error (left) and translational alignment error (right).