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Technical note

Assessment of pose repeatability and specimen repositioning of a robotic joint testing platform

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ABSTRACT

This paper describes the quantitative assessment of a robotic testing platform, consisting of an industrial robot and a universal force-moment sensor, via the design of fixtures used to hold the tibia and femur of cadaveric knees. This platform was used to study the contributions of different soft tissues and the ability of implants and reconstruction surgeries to restore normal joint functions, in previously published literature.

To compare different conditions of human joints, it is essential to reposition specimens with high precision after they have been removed for a surgical procedure. Methods and experiments carried out to determine the pose repeatability and measure errors in repositioning specimens are presented. This was achieved using an optical tracking system (fusion Track 500, Atracsys Switzerland) to measure the position and orientation of bespoke rigid body markers attached to the tibial and femoral pots after removing and reinstalling them inside the rigs. The pose repeatability was then evaluated by controlling the robotic platform to move a knee joint repeatedly to/from a given pose while tracking the position and orientation of a rigid body marker attached to the tibial fixture.

The results showed that the proposed design ensured a high repeatability in repositioning the pots with standard deviations for the computed distance and angle between the pots at both ends of the joint equal to 0.1 mm, 0.01 mm, 0.13° and 0.03° for the tibial and femoral fixtures respectively. Therefore, it is possible to remove and re-setup a joint with high precision. The results also showed that the errors in repositioning the robotic platform (that is: specimen path repeatability) were 0.11 mm and 0.12°, respectively.

1. Introduction

The use of industrial robots is emerging as a powerful tool for studying the load bearing function of ligaments in different human joints. Compared to classical mechanisms, robots offer higher repeatability and can be controlled to apply a given wrench and/or motion to a subject, while recording the resulting motion, forces and torques.

The University of Pittsburgh was the first to use robotics technology to study knee function, measure the in situ forces of ligaments and analyse key parameters that can affect a replacement graft [12]. Their setup consisted of a commercial robotic manipulator equipped with six axis force/moment sensor.

Currently, similar systems are widely used in research facilities and institutions, such as those reported by Suggs et al. [11], Martínez et al. [9], Sasaki et al. [10], and Goldsmith et al. [4]. In all these systems, the two ends of a joint are bolted to two bespoke holders attached to the robot's end effector and to the ground. Their main application is to study the ability of a surgical technique to restore normal joint functions [3] or the contribution of a given ligament by performing sequential cutting and comparing different conditions of a given joint [6]. This requires sometimes removing the joint out of the robot to perform surgery and repositioning it back with high precision, as any error can generate residual forces.

Few studies have reported whether the specimen was removed from the robot and in the majority of cases, information about this subject was not disclosed. To our knowledge there is only one study that reported the effects of removal and reinsertion of a specimen, which showed that, with their setup, it created substantial forces. Consequently, the authors recommended not

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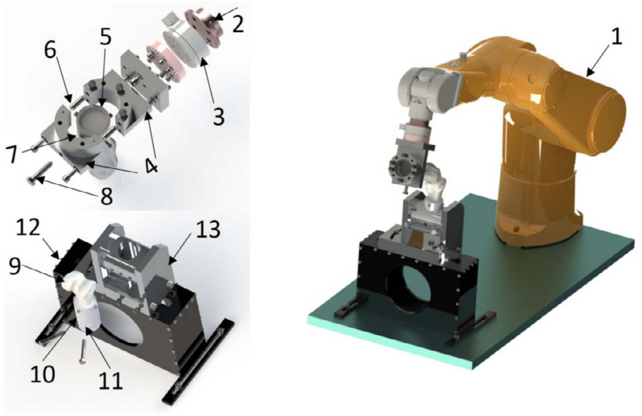

Fig. 1. Robotic testing platform composed of: 1: Staubli Tx90 Robot, 2: universal force-moment sensor (UFS)-robot adapter, 3: universal force-moment sensor (UFS), 4: tibial holder, 5: tibial pot, 6: location pin, 7: divot on the tibial pot, 8: conical headed screw, 9: femur, 10: femoral pot, 11: divot on the femoral pot, 12: 4 degrees of freedom femoral mounting and 13: femoral fixture.

removing the specimen out of the robot between the different stages of testing [5].

In this paper, the robotics platform developed at Imperial College (London, UK) is described and the designs of the tibial and femoral holders are presented. This platform has been used to assess the contribution of soft tissues [7] and the ability of implants [1,2] and reconstruction surgeries [8] to restore normal knee functions. Simulated clinical tests were performed at chosen angles of knee flexion, with starting points along the path of flexion defined previously, by applying 90 N forces in the Anterior and Posterior (AP) directions, 5 N m Internal-External (IE) Rotation torques, 8 N m Varus and Valgus (VV) torques and a combined 4 N m and 8 N m IE and VV rotations, which was intended to simulate the clinical Pivot-Shift (PS) knee instability test. During the AP, IE, VV and PS tests, the robot was controlling force/torque in one or more given directions, while keeping the angle of flexion constant. The remaining forces and torques were controlled to be minimized and secondary coupled components of motion recorded. Some of these studies required removing the knee out of the platform and repositioning it back after surgery. This has led to the design of fixtures that ensure high precision in repositioning of the bones at each end of the specimen.

The purpose of this paper was to evaluate novel human joint testing fixtures in terms of the precision of specimen repositioning after a surgical intervention, thus allowing specimen removal for surgical procedures followed by retesting. The experiments carried out to quantify the errors in repositioning the pots are described. The pose repeatability of the system was assessed by tracking the position and orientation of rigid body markers attached to the robot's tool and to the femoral fixture, while repeatedly moving the robot's end effector to a given pose.

2. Materials and methods

2.1. Biomechanical testing platform

The Biomechanical platform was composed of a Stäubli industrial robot (TX90, Stäubli Ltd, Switzerland) combined with a 6 axis universal force-moment sensor (UFS, Omega85, ATI Industrial Automation, Apex, USA, as in Fig 1). According to the manufacturer's specifications, the six degrees of freedom robotic manipulator had a payload of 200 N and a repeatability of ±0.03 mm in translation. The UFS was mounted between the tibia of the specimen and the robotic manipulator. This study used a fresh-frozen human cadaveric knee under the terms of research ethics permit ICHTB HTA licence 12275. The tibia and the femur were secured inside custom made cylindrical stainless steel pots using PMMA bone cement. The tibial pot was locked inside a custom made holder attached to the UFS that was mounted on the robot's end effector. This holder was composed of two mating parts, where the tibial pot was locked in a slide fit. One side was attached to the robot and to the second part of the holder using two metallic screws. The pot was locked into position in the holder using a conical-tipped screw inserted in a matching conical recess drilled into the pot's surface. The pot holding the femur was locked in a slide fit to a rigid mounting using two conical-tipped screws. This mounting had four degrees of freedom (two rotations and two translations) that could be adjusted manually.

Custom written software was developed using the VAL 3 language (i.e. the programming language specific to Stäubli robots) to simulate clinical tests for the knee joint. The first task was to control the robot to flex and extend the knee in a neutral path of motion, such that the forces and torques in other degrees of motion were minimized in real time, as per [7].

2.2. Assessment of repositioning error

Passive marker rigid bodies with triads of marker spheres were attached to each pot and to the tibial and femoral holders (Fig. 2). The experimental protocol consisted of removing, reinserting and locking the pot inside each of the holders twenty times. In this framework, the robot was kept in the same position and was not moved between trials. A fusion track 500 (Atracsys, Switzerland) was used to track the pose of the passive rigid bodies. The distance between the optical tracking system and the rigid body markers was set to be less than 2 m to ensure high precision for optical tracking which was, according to the manufacturer, equal to 0.09 mm. The distance between the centres of each holder, in the frame of reference of the rigid body marker, and that on the pot was calculated for each trial. The rotation angle was then calculated using the Euler–Rodrigues formula and the values of the mean and the standard deviation were reported for the distance and the angle.

2.3. Repeatability of the robotic platform

The repeatability was defined as the ability of the manipulator to return to a previously reached position. To assess the repeatability of the system under load, the robotic platform was controlled to perform repetitive movements of the end effector toward a given pose. For this purpose, a knee joint was used and a path of flexion-extension from 0° to 30°, recorded from previous experiments, was played 16 times. Two rigid body frames were attached to the tibial and femoral holders, respectively. In every trial the robot was controlled to move from 0° to 30° flexion and back to 0°. The distance and rotation angle between the rigid bodies were then calculated for each trial at 0° and their means and standard deviations were computed.

3. Results

Figs. 3 and 4 show the box plots of the distances and angles calculated from the 20 trials carried out to reposition the pots in the femoral and tibial holders. The standard deviations for the computed distance and angle for the tibial holder were 0.1 mm and 0.13°. For the femoral holder these standard deviations were 0.01 mm and 0.03°.

To compute the repeatability of the robotic platform in translation and in rotation, the distance and angle between the rigid bodies on the tibial and femoral holders were computed for each

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