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The importance of position and path repeatability on force at the knee during six-DOF joint motion

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ABSTRACT

Mechanical devices, such as robotic manipulators have been designed to measure joint and ligament function because of their ability to position a diarthrodial joint in six degrees-of-freedom with fidelity. However, the precision and performance of these testing devices vary. Therefore, the objective of this study was to determine the effect of systematic errors in position and path repeatability of two high-payload robotic manipulators (Manipulators 1 and 2) on the resultant forces at the knee. Using a porcine knee, the position and path repeatability of these manipulators were determined during passive flexion–extension with a coordinate measuring machine. The position repeatability of Manipulator 1 was 0.3 mm in position and 0.2° in orientation while Manipulator 2 had a better position repeatability of 0.1 mm in position and 0.1° in orientation throughout the range of positions examined. The corresponding variability in the resultant force at the knee for these assigned positions was 32 ± 33 N for Manipulator 1 and 4 ± 1 N for Manipulator 2. Furthermore, the repeatability of the trajectory of each manipulator while moving between assigned positions (path repeatability) was 0.8 mm for Manipulator 1 while the path repeatability for Manipulator 2 was improved (0.1 mm). These path discrepancies produced variability in the resultant force at the knee of 44 ± 24 and 21 ± 8 N, respectively, for Manipulators 1 and 2 primarily due to contact between the articular surfaces of the tibia and femur. Therefore, improved position and path repeatability yields lower variability in the resultant forces at the knee. Although position repeatability has been the most common criteria for evaluating biomechanical testing devices, the current study has clearly demonstrated that path repeatability can have an even larger effect on the variability in resultant force at the knee. Consequently, the repeatability of the path followed by the joint throughout its prescribed trajectory is as important as the repeatability of the joint at reaching positions making up its trajectory, particularly when joint contact occurs.

1. Introduction

Many testing devices such as kinematic linkages, material testing machines, and robotic manipulators have been designed to study diarthrodial joint and ligament biomechanics [1–7]. These devices have been used to record joint kinematics accurately in 3D space throughout the entire range of motion as well as to determine the resultant force at the joint and in the soft tissue structures in response to externally applied loads [3,8–10].

The most common measure utilized to evaluate the ability of a device to position a joint during biomechanical testing is position repeatability, which is a measure of the device's ability to return to the same assigned trajectory position and orientation [11,12], regardless of the direction of approach. Recent research has suggested that diarthrodial joints are sensitive to small changes in their paths of motion [1,13–15]. From a biomechanical testing prospective, poor path repeatability may cause changes in joint contact due to meniscal motion, and/or a greater interaction between joint structures. These changes could have significant implications for the forces in the tissue at a joint [1] and be the result of a systematic error in the assigned path. They could also mask changes occurring due to simulated joint pathology or other treatment affects. Therefore, path repeatability, which is a measure of the ability of a manipulator to follow the same path when moving continuously between assigned joint positions [12] or a measure of the trajectory, seems to be critical for the evaluation of soft tissue function for both a mechanical testing and clinical evaluation.

Robotic manipulators have been used extensively during the last decade because they provide superior position repeatability [3–5,7,16–18]. In addition, low-payload manipulators have been

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utilized because of their large range of motion and superior position repeatability compared to high-payload manipulators. However, more recently high-payload manipulators have been used to apply physiological loads to diarthrodial joints to more closely model the *in vivo* motions. Robotic manipulators have variable position repeatability (the ability to reach assigned positions in their trajectory) and path repeatability (the interpolation of the manipulator between assigned positions). Higher payload manipulators will suffer from alterations in the path between assigned positions more than low-payload manipulators due to manipulator dynamics and the physical constraints of their construction. In general, interpolation between assigned positions is approximately linear, but varies depending on the direction of approach, sequence of motions utilized and pose of the manipulator. Therefore, the objective of this study was to determine the effect of position and path repeatability (systematic errors) of two manipulators on the resultant force at the knee. These two manipulators were selected because they had differences in position repeatability of ~300% as reported by their manufacturers.

2. Methods

Many different types of biomechanical devices have been used to examine the function of diarthrodial joints. Two robotic manipulators were selected for this study: Manipulator 1 – a FANUC S-900W robotic manipulator (FANUC Robotics America Inc., Rochester Hills, MI) and Manipulator 2 – a KUKA KR210 robotic manipulator (KUKA Robotics Corporation, Sterling Heights, MI). Manipulator 1 had a payload of 3400 N and Manipulator 2 had a payload of 2100 N. The manufactures' specifications for position repeatability at maximum payload, reach, and speed are 0.5 mm for Manipulator 1 and 0.12 mm for Manipulator 2 [19,20]. Path repeatability changes throughout each manipulator's work volume and was not provided by the manufacturers. A universal force-moment sensor (UFS) (ATI Industrial Automation, Theta Model; accuracy ±3.5 N and 0.35 N m) was attached to the end-effector of each manipulator to allow measurement of forces and moments [21].

One porcine knee was utilized on Manipulator 1 and another porcine knee was utilized on Manipulator 2. The same clamps and methodology was used on both manipulators. Porcine knees were used because the force distribution in the soft tissues has been shown to be similar to human knees in response to specific loading conditions [22,23]. Each knee was visually screened for bony and ligamentous abnormalities, stored at −20 °C and thawed at room temperature 24 h before testing [24]. All soft tissue was removed approximately 10 cm away from the joint line on the femur and tibia. Throughout the experiment, the knees were kept moist with 0.9% saline. The same clamps and methodology were used on both manipulators. The femur and tibia were secured in custom-made stainless steel clamps with transfixing bolts and transcortical pins using an epoxy compound (Bond-Title Products, Cleveland, OH). The femur was rigidly fixed relative to the base of the robotic manipulator, and the tibia was mounted to the end-effector of the robot through the UFS (Fig. 1). Six degrees-of-freedom motion of the tibia with respect to the femur was determined using Cartesian coordinate systems fixed to the tibia and femur of the knee [25].

The position and path repeatability of the manipulators was assessed in a working volume and under conditions used during previous biomechanical testing [26]. A single path of flexion–extension was determined by each manipulator in 1° increment between 35° and 55° of flexion using a hybrid control algorithm [10,27–29] while a small joint compression force was applied to the joint (~5 N). The path determined using our force control algorithm with Manipulators 1 and 2 is repeatable for the input parameters used (joint stiffness estimates, force tolerance for convergence, and optimization function) [27]. The position and path repeatability of each manipulator as well as the effect on the resultant force at the knee were determined using these positions.

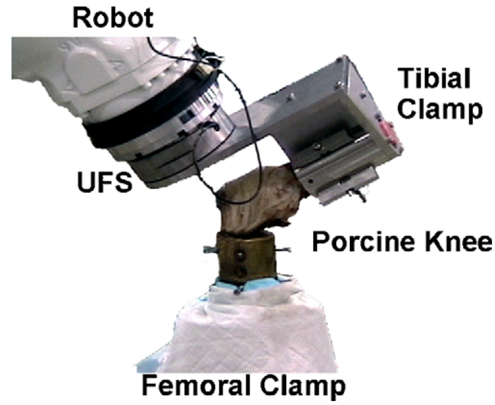

Fig. 1. Manipulator 2 with a left porcine knee mounted for testing. Tibia is attached to the end-effector through a tibial clamp and UFS and the femur is rigidly attached to the floor by the femoral clamp.

Position repeatability was determined at five assigned positions (49–53°) along the path of flexion–extension that included joint contact. Deviations between the assigned and achieved position and orientation of the end-effector for these measurements was determined using a coordinate measuring machine (MicroScribe™-3DX, Immersion Corp., San Jose, CA) that was used to digitize the faces of a registration block (Fig. 2) to create a local coordinate system. The accuracy of this methodology to establish the coordinate system on the registration block is 0.1 mm [30]. This process was repeated four times while approaching the assigned positions from opposing directions. The resultant force at the knee was also recorded with the UFS [28].

Path repeatability of both manipulators was measured by attaching the coordinate measuring machine to the end-effector of each manipulator using a custom-made ball joint and standard c-clamps (Fig. 3). Differences in the trajectory of the end-effector of each manipulator were recorded continuously while moving from extension-to-flexion (35–55°) and flexion-to-extension (55–35°). The accuracy of this methodology to measure the location of a point in space continuously is 0.23 mm [31]. Finally, the resultant force at the knee was recorded with the UFS throughout the entire trajectory, including the motion between the assigned positions that represented each flexion angle.

Position repeatability was calculated as the root mean square (RMS) error in the position between successive trajectories for

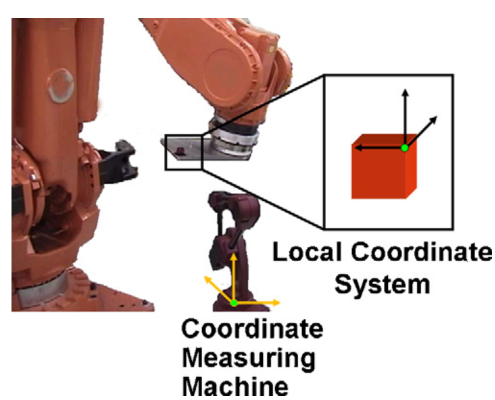

Fig. 2. Experimental set-up for evaluation of position repeatability using registration blocks and coordinate measuring machine (CMM). The registration block is rigidly attached to the end-effector. The three faces of the registration block are digitized by the CMM to create a local coordinate system.