

Technical Issues in Using Robots to Reproduce Joint Specific Gait

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Reproduction of the in vivo motions of joints has become possible with improvements in robot technology and in vivo measuring techniques. A motion analysis system has been used to measure the motions of the tibia and femur of the ovine stifle joint during normal gait. These in vivo motions are then reproduced with a parallel robot. To ensure that the motion of the joint is accurately reproduced and that the resulting data are reliable, the testing frame, the data acquisition system, and the effects of limitations of the testing platform need to be considered. Of the latter, the stiffness of the robot and the ability of the control system to process sequential points on the path of motion in a timely fashion for repeatable path accuracy are of particular importance. Use of the system developed will lead to a better understanding of the mechanical environment of joints and ligaments in vivo.
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1 Introduction

The ligaments of the knee are complex structures that act to support and guide the motion of that joint. To accomplish this, these ligaments function in a full six degrees of freedom space. The need to apply more realistic joint loads has been combined with the technological advancements in the field of industrial ro-

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botics in the development and use of six degrees of freedom robots for studying joint kinematics and load response [1–4]. A system has been developed for the reproduction of in vivo motion of the ovine stifle joint. The motion of the joint is recorded in vivo through the capture of 3D positions of rigid markers as the animal walks normally on a treadmill, using a motion analysis system (Expert Vision, Motion Analysis Corporation, Santa Rosa, CA). Reproduction of the in vivo motion of joints was made possible using a parallel robotic manipulator system in conjunction with the motion capture system described above. The parallel robot was selected as the tool for driving joint motion because of its high accuracy, repeatability, and ability to reproduce physiological motion in six degrees of freedom. The trade-off with this type of manipulator is that while parallel robots have excellent stiffness and accuracy, they operate in a small volume compared with serial robots. Due to the large loads developed, and the manipulator accuracy required to determine in vivo loads during normal gait, the relatively higher stiffness and accuracy offered by a parallel robot were favored, despite the inconvenience of the smaller range of motion, for testing the ovine stifle joint.

This communication will discuss some of the technical challenges that have had to be addressed in accomplishing the objective of accurately determining relevant in vivo ligament loads.

2 Accuracy

Recently, a study of tibio-menisco-femoral kinematics using finite element modeling emphasized the importance of improving the precision and accuracy of kinematic readings [5]. In a comparison between two robotic manipulators (a FANUC S-900W robotic manipulator (FANUC Robotics America, Inc., Rochester Hills, MI) and a KUKA KR210 robotic manipulator (KUKA Robotics Corporation, Sterling Heights, MI)), the authors reported that the kinematics of the joint in a robotic testing system are not only affected by the rigidity and accuracy of the robotic manipulator but also by its path accuracy [6]. Furthermore, this study also indicated that poor path repeatability of the robotic manipulator can cause varying and potentially excessive joint contact between the articulating surfaces of the femur and tibia. In addition, the authors demonstrated that the robotic manipulator that exhibited a higher degree of position and path repeatability yielded lower variability in the resultant forces at the knee [6].

There are several factors in the system that contribute to the overall accuracy. Some of these are inherent in the manipulator design while others can be controlled by the design of the testing system and procedures.

2.1 Robot and Load Floor Stiffness. The current methodology involves attaching one end of the joint (the tibia) to a “fixed” frame and attaching the other end (the femur) to the robot’s end-effector. The joint is then registered, and the robot path determined using inverse kinematics. This inherently open-loop control scheme is susceptible to any event or disturbance that may cause the joint to be in a different location relative to either the fixed end or the robot end-effector. This problem is somewhat unique to this type of joint testing, where the loads that develop across the tibia and femur can be quite high (>2 kN). These high loads would easily cause large deflections in a system that was not properly designed for rigidity. It was for this reason that a stiff load floor and fixture assembly was developed (Fig. 1) [7]. Further, when selecting a robot to perform these tests, consideration must be taken to ensure that the robot is sufficiently stiff, such that its deformation under the developed loads can be considered negligible. The alternative is that corrections for frame and robot deformations must be made to the movement of the end-effector during the motion, so that the motion of the joint is maintained as measured in vivo.

2.2 Determining Robot Zero and Marker Registration. Accurate determination of joint position relative to the robot glo-

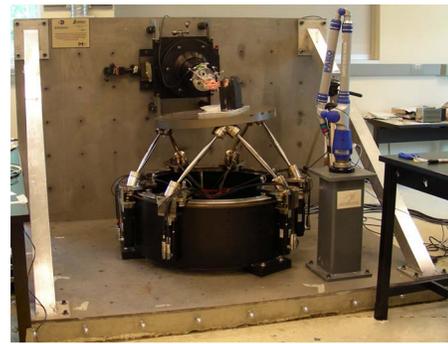


Fig. 1 The parallel robotic testing system for gait kinematics. The system consists of a stiff L-shaped resistive frame that supports a parallel robotic manipulator (R-2000, Mikrolar, Hampton, NH) and a FaroArm® Coordinate Measuring Machine. The loads resulting from joint motion are measured with a universal force-moment sensor (UFS) (Omega 160, ATI Industrial Automation Apex, NC).

bal is critical in maintaining a high level of accuracy when calculating the robotic path. In the system that was developed, the location of the joint is measured by using a FaroArm® Coordinate Measuring Machine (Faro Technologies, Lake Mary, FL) to measure the marker tetrads that are attached to the bone. It was found that the individual spherical markers can be located to within 0.08 mm [8].

Proper determination of the robot’s global coordinate system is also essential for accurate path determination. Two methods were used to determine its location/orientation. The first involved measuring a precise sphere affixed to the end-effector at a strategic set of locations and orientations and then calculating the origin and axes of the robot global coordinate system from those measurements. The second method involved measuring specific features on the robot end-effector from which the coordinate frame was constructed. It was found that both methods yielded repeatable results, and that the location of the origin of the robot global system could be determined to 0.05+/-0.02 mm [8].

2.3 Number of Positions Along Path. Preliminary studies in the development of force control methodologies by Woo and colleagues found that when joint perturbations under force control cause movements greater than 1 mm, the joint can be damaged [9,10]. Therefore, the distance between two sequential joint positions to reproduce in vivo kinematics should be less than 1 mm. This condition may require a large number of trajectory positions.

The calculated robot path of motion was initially divided into 100 intervals representing 101 positions/orientations corresponding to 0–100% of the gait cycle. It was found that some consecutive positions during the swing phase of the gait cycle required manipulator motions of up to 5 mm. Since the joint moves most quickly between those positions that are farthest apart, to improve path accuracy, those larger motions must be divided into a series of smaller ones to ensure that the path is followed accurately.

Initially, all testing was performed with an R-1000 parallel manipulator (Mikrolar, Hampton, NH). The Baldor NextMove® (NM) PCI card in the R-1000 controller allows for less than 100 trajectory positions to be accumulated in memory and can only effectively process roughly 80 positions at a time. Increasing the number of manipulator positions in the R-1000 led to buffer overload and mal-aligned forces, even for paths of only 101 positions.

To improve the path accuracy and overcome computational buffering limitations of the R-1000 controller, the R-1000 parallel robotic manipulator was replaced with the next generation R-2000 parallel manipulator. The R-2000 utilizes the SynqNet-XMP control system from Motion Engineering Inc. (MEI). This solution offers improved proprietary firmware. This firmware buffering

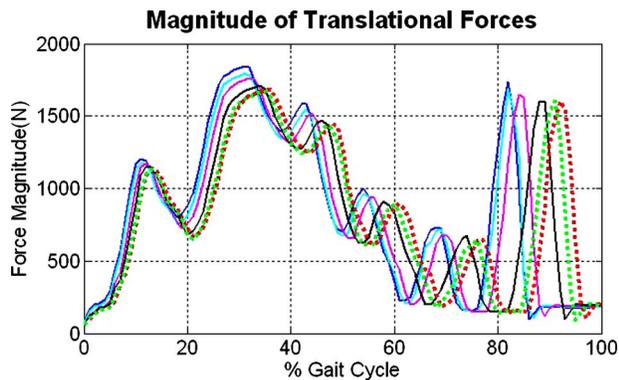


Fig. 2 Load magnitude measured from sequential repetitions of the same robotic path. Timing issues resulted in the data to be temporally mal-aligned.

system can handle trajectories of any length due to the embedded firmware processor and improved distribution of processor power between motor drives. The time to process and load a position with the SynqNet-XMP control system is less than 1 ms. In addition, the accumulated positions and velocities are fit with a B-spline to provide smooth operation. Path positions can be specified at 4 ms intervals (and even closer in some situations) to achieve precise replication of motion.

In many robotic applications, the choice of control systems is relatively unimportant when based on point-to-point positioning requirements. However, when high accuracy is required while undergoing complex motions, such as in vivo gait, care should be taken to select the appropriate motion control card in order to maintain appropriate path accuracy.

3 Data Acquisition

An adequate data acquisition system is imperative to measure the loads that occur during these experiments. Data acquisition was initially employed, whereby loads were recorded continuously and aligned to motion by a time synchronization signal at the beginning and end of each gait cycle [11]. The interval time, the time between manipulator positions, was also written to a file and used to align the data between the beginning and the end of each gait cycle using a spline resampling method. This alignment was necessary because, although an interval time was specified, the true time between positions varied. Unfortunately, inconsistencies in manipulator speed, combined with the unreliability of the Windows® operating system (OS) clock, led to temporally mal-aligned force data. This can be seen in Fig. 2, where sequential repetitions of the same path are shown. Note that the load patterns start at the same place but due to these timing issues, do not end at the same time.

The inconsistencies in manipulator speed were caused by shortcomings in the R-1000 controller (point-to-point processing and limited buffering), as well as the Windows® OS interruption of motion control software. The Windows® OS timer cannot reliably perceive elapsed time at the millisecond level, which causes miscalculations in processes, such as load acquisition, and results in an inability to maintain a constant sampling rate.

These errors were resolved by updating the robot and controller to improve the robot's performance, as previously described. Additionally, the data acquisition scheme was modified so that the load data were recorded once the robot reached a commanded position. This ensures that subsequent path repetitions will align correctly, something that is crucial when employing the principle of superposition [12].

4 Reproduction Speed

The speed of motion reproduction is limited by the control systems' processor, the on-board memory, the distribution of processing power by the system software, the efficiency of the firmware, and the manipulator dynamic limitations. Thus, improved control system hardware and software, motors, and encoders would be necessary to replicate the kinetics of the ovine stifle joint at in vivo speed.

Previous research on the anterior cruciate ligament (ACL) indicates that the ligament load is strain rate independent for normal physiological activities [13,14], and only at traumatic strain rates, such as those associated with injury or extreme sporting activities, does the ACL strain rate become a contributing factor [15]. Beynon and Fleming's work with strain transducers indicates that the local surface strain in the anterior-medial (AM) band of the ACL does not exceed 4.4% for a variety of daily activities [16]. Pioletti et al. demonstrated that the modulus of elasticity in the linear region of the stress-strain relationship was not affected by strain rate but that the toe region of the relationship was affected [17]. The medial collateral ligament (MCL) demonstrates strain rate independence during axial and shear loading [13,18,19]. The effect of strain rate has been demonstrated to be small on the patellar tendon [20] for rates up to 560 mm/s or $1250 \pm 123\% s^{-1}$. Similarly, strain rates from 5% to 50%/s were shown to have a small and inconsistent effect on the stiffness of the superficial flexor tendon in horses [21]. Therefore, previous in vitro and in vivo works indicate that strain rate is not a significant variable affecting the loads in ligaments and tendons in response to the low impact activities of daily living. However, it has been demonstrated that ligament strain rate sensitivity is dependent on the methodology used, the orientation of the ligament [22], as well as the age [13,23], thereby highlighting the importance of accurate replication of in vivo kinematics. Test orientation is especially important for the cruciate ligaments because of their nonlinear fiber orientation [22].

In order to confirm these findings, a pilot study was undertaken, whereby the speed of motion reproduction was varied from 1/15th to 1/60th of that recorded in vivo. To discern as closely as possible the effect on the ligaments, the in vivo path was run with all surrounding soft tissues and any bony contact removed except for the posterior cruciate ligament (PCL). This was done to measure the load in the PCL directly.

The difference in load measured in the PCL between 1/15, 1/30, and 1/60 in vivo gait speed were generally quite small, the average difference being 1N, and the maximum difference being 3 N. Hence, the speed at which in vivo motion is reproduced has little effect on the determined ligament loads, at least in the PCL, at these slower speeds. An example of the recorded load in the anterior-posterior direction is shown in Fig. 3.

5 Discussion

To characterize ligament function fully, we must know the loads that these tissues experience during normal motions. A robotic testing platform has been developed to provide a tool to study ligament function and mechanical characteristics during dynamic activity. In developing this system, we have unearthed several challenges of which other researchers should be aware.

Motion reproduction is highly sensitive to the accuracy of the robotic system. Often, we are limited by the performance of the manipulator being used but testing platforms must be designed to reduce or eliminate any further error. The stiffness of the manipulator and supporting frames should be quantified, and sufficient to resist significant deformation under the prescribed loadings. Furthermore, one must use enough positions to represent the trajectory accurately, ensuring acceptable path accuracy.

Data acquisition systems can often be unpredictable when dynamic loads are being measured. By recording force at a specified

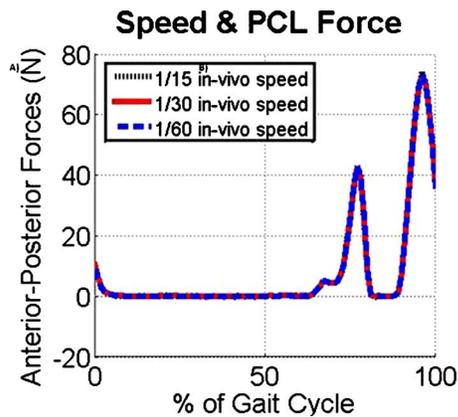


Fig. 3 Direct force in the PCL in response variation in the speed from 1/15 to 1/60 in vivo speed

position, as opposed to time based, we were able to compare loads from different path repetitions reliably, thus making the use of superposition possible.

It was found that although this system was unable to reproduce motion at in vivo speeds, there was little influence of speed on the direct measurement of load in the PCL from 1/15th to 1/60th of in vivo speed.

The continued use of robotic testing systems to study joint loads will continue to improve our knowledge of these tissues. However, these test systems must be able to reproduce in vivo joint motions accurately and repeatedly for the resulting data to be useful and reliable.

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