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Short communication

A novel application of direct force control to perform in-vitro biomechanical tests using robotic technology

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ABSTRACT

This paper presents a novel application of direct force control to test biological specimens using a serial manipulator with 6 degrees of freedom

Direct force control compares actual force/moment values with desired values of load. The error is compensated by a proportional/integral controller (*PI*), a damping factor implemented with the velocity of the robot and acting in the direction of the force and a feedforward compensation. The controller works with a frequency of 0.5 kHz which enhances its performance due to the direct force feedback loop.

A fresh porcine cervical spine C2–C4 was used. All muscle tissues were removed while leaving intact all ligaments and bony tissue. The specimen was loaded separately with ±3 Nm in every spatial axis. The mean errors in the unconstrained axes in the present study were less than 1.70 N and 0.32 Nm.

Direct force control of 6 axes with a high controller frequency of 0.5 kHz developed in this methodology shows a successful procedure to perform biomechanical in-vitro tests. The controller demonstrated the ability to maintain zero load targets in the unconstrained axes. This control approach allows the application of pure moments in order to perform in vitro biomechanical experiments with spine segments.

1. Introduction

Biomechanical test methods consist in applying specific forces and moments in a given coordinate system. An accepted method to test biological spines described by Panjabi (1988); Wilke et al. (1998) consists in applying a rotation about a specific axis on the body while five remaining degrees of freedom (DoF) are left unconstrained. Several spine testers using robotic technology have been already described in the literature where forces and moments may be applied separately or combined in different spatial axes in order to follow Panjabi's protocol. Thompson et al. (2003) used a 6 DoF robot Kawasaki PH260 under position control. The centers of rotation for movements were taken from published studies. Gilbertson et al. (2000) used a serial robot PUMA 762 under hybrid control. Forces and moments that were not commanded were not explicitly controlled. Schulte et al. (2008) used a Kuka robot under hybrid control where at least one axis was under position control while the rest were under force control. Goertzen and Kawchuk (2009) presented a spine tester using a hexapod under velocity-based force control with frequency of 20 Hz.

Direct force control belongs together with hybrid, impedance and parallel control to the interaction control architectures. However, to the authors knowledge, the direct force control method has not been used in the robotic biomechanical field.

The goal of this paper was to present a new methodology where a serial robot under a high frequency direct force control was used in order to perform in vitro biomechanical tests where loads may be applied separately or combined in different spatial axes.

2. Materials and methods

The main components of the robotic system are:

- 6 DoF robot RX 90-B, Stäubli, Switzerland
- Host and target PC
- Force/torque sensor (FTS) with 6 DoF JR3 Inc., USA

Due to several disadvantages of the control structure given by the manufacturer of the RX 90-B, an alternative approach to control the robot was chosen. Such limitations are that the controller frequency works with a maximum of 100 Hz, the implementation of other control architectures increases the computational effort considerably, and the design of a complex controller in form of text is error-prone.

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The design of the controller, equations of motion, kinematics, dynamics and all calculations related to the manipulator are programmed in the development environment MATLAB & Simulink. With the real-time software xPC Target and using the compiler C/C++ it is possible to convert all these programmed applications in code that will be compiled and downloaded into a real-time PC which is in charge of the generation of signals to move every motor of the robot. Hence it is possible to develop an own control architecture to achieve a frequency of 0.5 kHz.

Direct force control (shown in Fig. 1) compares actual force/moment values F_a with reference (or desired) values F_r, thereby a closed-loop is implemented as described in Sciavicco and Siciliano (2000). The error is compensated by the proportional/integral controller (*PI*). A damping factor (kv) is designed with the Cartesian velocity of the robot (expressed by v) that acts in the direction of the force and serves as stabilizing action. The feed forward loop with F_r was implemented as described in Khatib (1987). The inclusion of a damper (in the way of a derivative of the position) stabilizes the system around the equilibrium posture based on the Lyapunov direct method as explained in Sciavicco and Siciliano (2000).

In this way, the velocity of the robot will be limited by the factor kv. The force regulation feedback loop together with the damper generates the control input for the motion control of the robot. The calculation of the dynamics in the control architecture gives the advantage to reject disturbances and compensate the nonlinear coupling terms of the model (Sciavicco and Siciliano (2000)). The feedforward action of F_r reduces the tracking error in the main tracking variable (force/moment). With this architecture the robot can perform specific movements in order to exert a desired force–moment in the environment.

3. Experiments

The RX 90-B together with the FTS attached to the last joint was used. The robot was operated under the described direct force control. The gravitational effects and offsets of the tool attached to the FTS were compensated.

A fresh porcine cervical spine C2–C4 was used. All muscle tissues were removed while leaving intact all ligaments and bony tissue. C2 and C4 were embedded in resin and attached to a vise from the lower side and to the sensor with a tool from the upper side. The absolute coordinate system of the robot (also called World Coordinate System, WCS) was used in order to control and measure all forces and moments. The WCS is an absolute coordinate system which position and orientation remain constant no matter the pose of the end-effector. The global coordinate system of the spine was aligned with the WCS of the robot (Fig. 2). The specimen was loaded with ±3 Nm about *Y* axis (flexion extension FE), about *X* and *Z* axis (lateral bending LB and axial rotation AR, respectively). Every movement was three times repeated and the third cycle was reported as indicated in Wilke et al. (1998). The setup is shown in Fig. 2.

4. Results

Figs. 3 and 4 show the sequence of the forces and moments applied on the specimen when a moment about *Y* axis was applied. The mean errors in the unconstrained axes in the present study were less than 1.70 N and 0.32 Nm. Table 1 shows the mean tracking errors in the unconstrained axes. Noise was reduced by

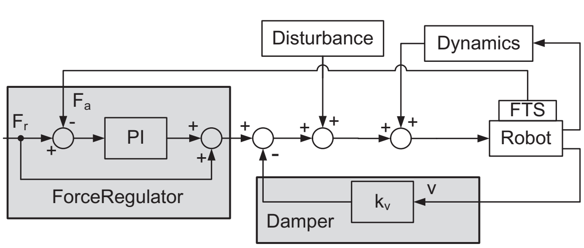

Fig. 1. Direct force control. It consists in the following parts: 1. Comparison of force/moment values with the proportional/integral (PI) control action. 2. Damper action proportional to the Cartesian velocity that acts in the direction of force. 3. Feedforward with Fr values. 4. Calculation of the dynamics which helps to reject disturbances and compensate nonlinear terms.

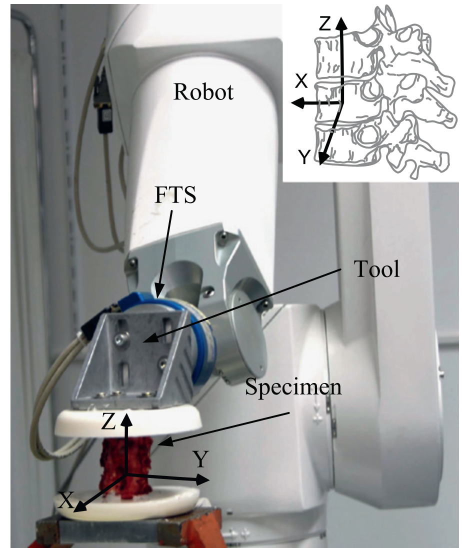

Fig. 2. Specimen attached to the robot. The global coordinate system (top) of the spine is aligned with the world coordinate system (WCS) of the robot (bottom).

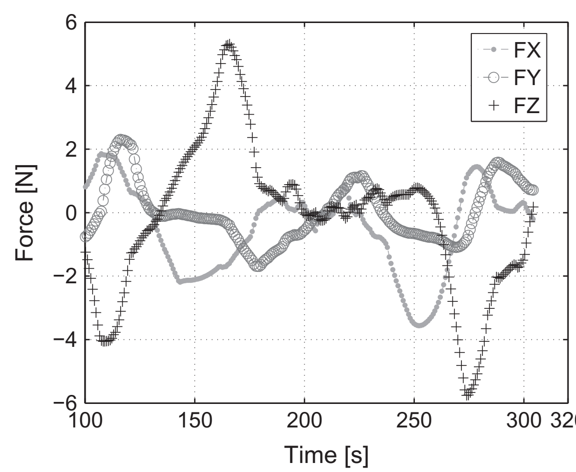

Fig. 3. Forces reported by the force/torque sensor when a moment about *Y* axis was applied.

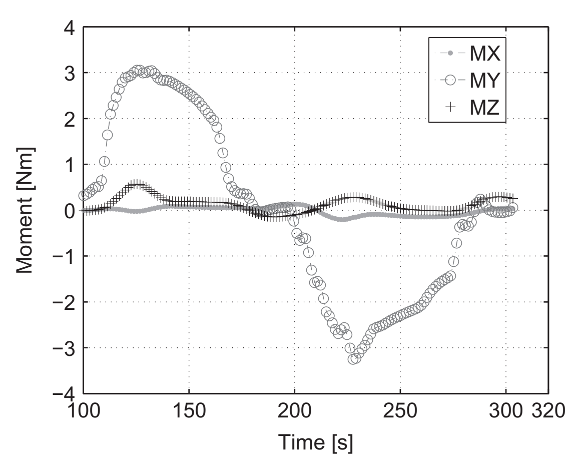

Fig. 4. Moments reported by the force/torque sensor when a moment about *Y* axis was applied.