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Short communication

Adaptive velocity-based six degree of freedom load control for real-time unconstrained biomechanical testing

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ABSTRACT

Robotic biomechanics is a powerful tool for further developing our understanding of biological joints, tissues and their repair. Both velocity-based and hybrid force control methods have been applied to biomechanics but the complex and non-linear properties of joints have limited these to slow or stepwise loading, which may not capture the real-time behaviour of joints. This paper presents a novel force control scheme combining stiffness and velocity based methods aimed at achieving six degree of freedom unconstrained force control at physiological loading rates.

1. Introduction

Robots have great potential to further the field of biomechanics. They present the capacity for more advanced and more physiological testing of whole joints, bones, soft tissues and implants than previously possible (Fujie et al., 1993; Walker and Dickey, 2007; Goertzen et al., 2004; Gilbertson et al., 2000; Bell et al., 2013; Kelly and Bennett, 2013). Parallel robots are particularly well suited to biomechanical testing due to their high stiffness, precision and force capacity (Ding et al., 2011). Furthermore, robotic methods in general enable advanced, integrated testing techniques such as the reproduction of recorded *in vivo* kinematics, closed loop position and force feedback control, four-dimensional vectoring and broad biomechanical applicability.

The utility of *in vitro* testing is highly dependent on the physiological relevance of the testing methodology. With particular respect to the spine but regardless of testing platform, the prevalent stepwise or quasi-static methods do not capture the dynamics of human movement and have been shown to produce differing results (Goertzen et al., 2004). Despite contention and a bias toward the flexibility protocol in the literature (Goel et al., 1995; Wilke et al., 1998, Panjabi, 2000, 2007a,b, Crawford, 2007), we recognise that the stiffness, flexibility and hybrid protocols are each situationally appropriate. All three protocols can be achieved with robots, however system compliance has a large influence on the performance (Walker and Dickey, 2007). Confounded by the unknown, nonlinear, biphasic, viscoelastic and anisotropic material properties of biomechanical applications, deployment of the load control algorithms required for dynamic flexibility and hybrid protocols remains limited and has yet to be optimized.

Goertzen and Kawchuk (2009) introduced velocity-based load control for biomechanical testing with an approach that does not depend on specimen stiffness. In this method the magnitude of the difference between the force command and force feedback (force error) is used to linearly regulate a velocity in position control within a predefined force error window. Outside this window, a maximum velocity threshold is set which ensures stability and minimises overshoot. If this threshold is low enough to guarantee stability, the velocity can be independent of specimen stiffness, which is advantageous for biomechanical testing. This method is broadly applicable to any robot with a jog function, however the limitation of this approach is the very slow realisation of force targets and restriction to step inputs. These limitations are also encountered with hybrid position-load control (Walker and Dickey, 2007; Fujie et al., 1993; Tian and Gilbertson, 2004; Bell et al., 2013; Gilbertson et al., 2000), wherein a stepwise method calculates the stiffness matrix of the previous motion step and predicts the displacement required in the next iteration to achieve the desired force. This method is computationally expensive and has been restricted to stepwise quasi-static loading.

The overall objective to which this work contributes is to enable more physiologic, dynamic *in vitro* biomechanical joint and tissue testing. This study specifically aims to build on the work of Goertzen and Kawchuk (2009) and develops an adaptive stiffness velocity-based six degree of freedom (6DOF) unconstrained load control method in an effort to increase the loading rate

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and command complexity of dynamic testing beyond that which has previously been possible. The algorithm is applied to a hexapod robot (Ding et al., 2011, 2014) (Fig. 1, Table 1) but is similarly applicable to other parallel or serial robots.

2. Methods

Briefly, the hexapod robot was based on the concept of the Stewart Platform and employs six servo-controlled ball screw driven actuators that precisely position a mobile upper plate with respect to a fixed base plate (Fig. 1). Specimens are bolted between the fixed base and the mobile upper plate. Displacements and rotations of the specimen were directly measured by six linear optical encoders with a resolution of 0.5 µm (B366784180185 LDM54, MicroE Systems, USA) that were positioned independently to the loading frame and load cell. This configuration eliminated system compliance from the measurement of specimen behaviour, as detailed in Ding et al. (2011, 2014). Forces and moments were measured by a six axis load cell (MC3A-6-1000, AMTI, USA) having a maximum axial compressive force capacity of 4450 N and 56.5 N m of axial torque. The displacement measurements were independently validated prior to this study to NATA standards (ISO 10360-2, 2009) and the load accuracies were based on NATA calibrations provided by AMTI (Table 1).

Dynamic stiffness based velocity control was developed by relating the velocity to force error through an adaptive gain representative of the system stiffness. Since it is very difficult to know the 6×6 stiffness matrix of a biological specimen, six decoupled adaptive gains were introduced that account for the 6DOF anisotropic, non-linear modulus:

$$\mathbf{K}_g^{-1} = \begin{pmatrix} k_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & k_6 \end{pmatrix} \tag{1}$$

where $\mathbf{K}_g^{-1}$ is the decoupled time-varying stiffness matrix having non-zero diagonal terms only and $k_i (i = 1:6)$ is the gain representative of the specimen stiffness in each of the six degrees of freedom. The scheme (Fig. 2) applies an upper level force feedback controller running at 100 Hz to calculate the desired velocities of the specimen $\boldsymbol{v}_d^s$, which is then integrated to obtain the required specimen displacements $\boldsymbol{d}_d^s$ for the robot's lower-level position control stage, which has been implemented on two field-programmable gate array (FPGA) boards at 10 kHz. Each gain in the decoupled stiffness matrix is optimized based on the force tracking performance in the corresponding DOF. This implicitly allows the force controller to adapt to unknown system non-linearities, specimen coupling and robot dynamics.

The adaptive gain algorithm monitors the command and feedback load signals from the previous second and decides to increase, decrease or maintain the gain based on the root mean square (RMS) error, oscillation frequency and time-weighted average of the feedback with respect to the command (Fig. 3).

System stability and performance were improved by reducing the sensitivity of the velocity response to signal noise. Relating velocity to force errors by a hyperbolic sine function below a tunable threshold reduces both noise sensitivity and overshoot by ensuring steep but smooth and continuous deceleration as the force error converges to the noise floor of the load cell (Fig. 4, Eq. (2)):

$$\boldsymbol{v}_f = \begin{cases} \varphi, & k_j e_c \ge \varphi \\ k_j e_c, & k_j \delta \le |k_j e_c| < \varphi \\ \sinh\left(\operatorname{asinh}(k_j \delta) \dfrac{e_c}{\delta}\right), & |e_c| < \delta \\ -\varphi, & k_j e_c \le -\varphi \end{cases} \tag{2}$$

It has been demonstrated that both the inclusion and method of application of compressive preload affect the stiffness of the spine (Cripton et al., 2000; Patwardhan et al., 2003; Gardner-Morse and Stokes, 2004). Similar to Bennett and Kelly (2013), the load control algorithm was used to develop a decoupled preload vectored perpendicular to the mid-transverse plane of the disc. The preload is decoupled in the sense that it is independent of the applied test commands and is thus constant throughout all dynamic tests and recovery periods (Fig. 2).

Any neutral zone of a biological joint can cause poor performance in load control. Very low stiffness in the neutral zone creates a situation wherein even a small force error causes the robot to displace to the edge of the neutral zone because the force error cannot converge until the specimen exhibits a tangible stiffness. This condition is difficult to predict and is highly dependant on the specimen, test type and loading rate. Longer duration shear, compression and recovery preload conditions are likely to experience slow but unrecoverable bending rotations in 6DOF force control. In this work the neutral zone was managed by constraining the affected bending axis in position control for long recovery periods and slower shear tests that experienced large rotations to the edge of the neutral zone (Table 3). Together with the constant presence of the preload, this constraint established a reproducible datum from which to begin each test and dynamic tests remained correctly aligned with the anatomical axes.

An ovine functional spinal unit (FSU) was tested to demonstrate this algorithm in a biomechanical context due to its ready availability and similarity to human lumbar spine (Wilke et al., 1997). A fresh-frozen ovine lumbar spine was flensed of all non-ligamentous soft tissue and an FSU was dissected by cutting through the vertebral bodies parallel to the mid-transverse plane of the intervertebral disc (IVD). Wood's Metal (LW4, AMAC Alloys, Australia), due to its increased stiffness over polymethyl methacrylate (PMMA) and dental stone (Kim et al., 2006), was used to pot the FSU in alignment with the hexapod coordinate system. During testing the FSU was submerged in a protease inhibited phosphate buffered saline (PBS) bath kept at 37 °C to simulate a physiologic environment, since the testing environment has been shown to affect results (Costi et al., 2002; Race et al., 2000). Further, a compressive preload directed normal to the disc mid-transverse plane and acting through the specimen centre of rotation (COR) generating a typical 0.2 MPa intradiscal pressure (Sasaki et al., 2001; Wilke et al., 1999; Edwards et al., 2001) was applied to most closely mimic *in vivo* loading conditions. It was concluded that the unconstrained algorithm would converge to rotating about the specimen's COR, however the preload and moment transformations required an initial estimate of the COR which was calculated by the Pearcy and Bogduk (1988) method, which assumes symmetry about the saggital plane and is fixed. Isolated directions were tested via haversine command waveforms, due to the highly anisotropic nature of the IVD (Costi et al., 2008). Force targets were designed to explore the nonlinearity of the specimen without causing damage. The algorithm was demonstrated in each primary axis – compression, flexion/extension, lateral bending, axial rotation, posterior and lateral shear. The limits of the algorithm were tested by increasing the loading rate from a baseline of 0.01 Hz until tracking performance monitored in real-time was subjectively deemed to have substantially deteriorated. 6DOF RMS force errors were calculated and grouped into force and moment axes for each test. The RMS tracking error provides a sense of the overall

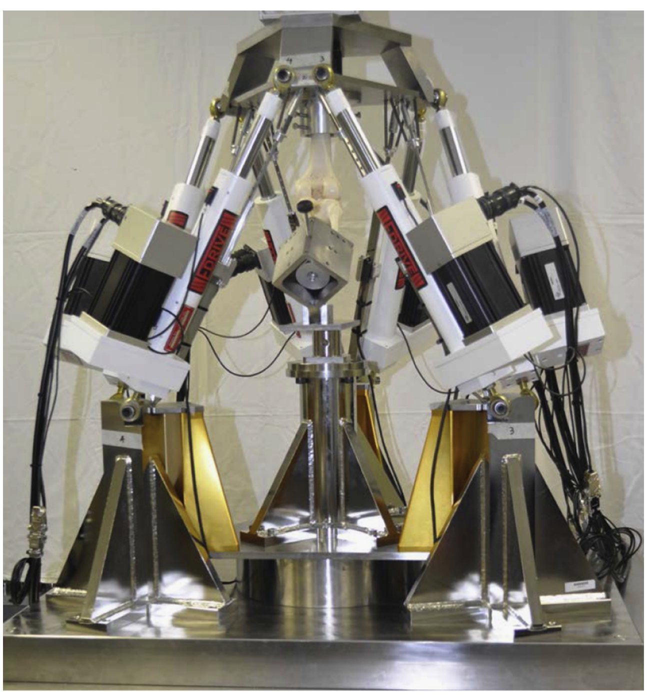

Fig. 1. Hexapod robot. The specimen is fixed to the central pillar and manipulated by the end effector, which is connected to the actuators only through the load cell, decoupling the sensing and loading frames.

Table 1
Hexapod specifications (from Ding et al., 2011).

Axis	Hexapod		Load cell	
	Capacity	Accuracy	Capacity	Accuracy
Axial	20 kN	±0.02 mm	4450 N	±0.4 N
Bending	2 kN m	±0.02°	113 N m	±0.01 N m
Torsion	1.5 kN m	±0.02°	56.5 N m	±0.01 N m
Shear	6 kN	±0.003 mm	2225 N	±0.04 N

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