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A Study of a Gough-Stewart Platform-
based Manipulator for Applications in
Biomechanical Testing

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Abstract

This thesis investigates the development and application of a robotic system for *in-vitro* biomechanical testing to study the mechanisms leading to human joint injury and degeneration in an ethical and safe manner. Six degree of freedom (6-DOF) robotic-based systems, in particular Gough-Stewart platform-based systems, have been increasingly used in applications of biomechanical testing where 6-DOF mobility, large load capacity, and high stiffness and positioning accuracy are required from the testing machine. This study proposes a novel Gough-Stewart platform-based manipulator with ultra-high stiffness and accuracy for use in biomechanical testing and investigates its mechanism and control. Not only restricted to biomechanical testing, the proposed manipulator concept can also be applied to other robotic-based applications, particularly those requiring ultra-high accuracy positioning under large external loads (e.g. machining). Four main features of the proposed manipulator are individually studied in this thesis: namely, stiffness and control of a non-collocated actuator-sensor mechanism, active preload control using actuation redundancy for backlash elimination, adaptive velocity-based load control of human joints for unconstrained testing, and reproducing the *in-vivo* measured kinematics on human cadaveric joints.

Stiffness and Control of the Non-collocated Actuator-Sensor Mechanism

A novel Gough-Stewart platform-based mechanism is proposed with a fully decoupled actuator-sensor arrangement for passively compensating the structural compliance of the manipulator. The stiffness of the robot load frame and the sensing frame are respectively quantified using the robot kinematics error model combined

with finite element analysis (FEA) on the top and bottom assemblies. Numerical results demonstrate that the proposed mechanism improves the stiffness of the robotic testing system in excess of an order of magnitude on the translational axes and two orders of magnitude for rotational axes compared to a traditional actuator-sensor collocated design. Control disturbances arising from actuator-sensor non-collocation is addressed using decoupled control. Experimental results show that the proposed decoupled control algorithm improves the dynamic accuracy of the manipulator by approximately 25% on average.

Active Preload Control Using Actuation Redundancy for Backlash Elimination

This thesis investigates combining the benefits of both active and passive preload control methods, using actuation redundancy to prevent backlash on a general Gough-Stewart platform. Both the mechanical configuration and the dynamics model of the redundant manipulator are investigated for the ease of control. A novel online optimization algorithm combined with a feedback force control scheme is formulated to achieve a real-time method which is robust to both model inaccuracy and load disturbance. Simulation results demonstrate an effective preload efficacy by the redundant arrangement within the workspace of the robot. Simulation results also show that the proposed method can effectively achieve backlash-free positioning of the manipulator under large 6-DOF external loads. Experimental results further prove that the proposed method can eliminate backlash instabilities from control and consequently higher bandwidth control can be achieved by the robot with improved accuracy.

Adaptive Velocity-based Load Control of Human Joint for Unconstrained Testing

A novel adaptive velocity-based load control method is proposed in this thesis to more effectively achieve pure force or moments on human joints under unconstrained testing compared to existing methods. The force/moment control gains are designed to vary adaptively based on the tracking performance of the force/moment to make a compromise between load following and control stability, which makes the proposed method self-adaptive to unknown joint dynamics. Sheep functional spinal units are used to experimentally validate the method on the custom-built Gough-Stewart platform-based manipulator. Experimental results illustrate the efficiency of the

proposed method, which can be further improved when overcoming certain limitations of the system (e.g. load sensor noise, position inaccuracy arising from backlash, etc.)

Reproducing the *In-vivo* Measured Kinematics on Human Cadaveric Joints

This thesis develops a method to scientifically reproduce the general *in-vivo* kinematics measured from a living human on human cadaver joints using the custom-built Gough-Stewart platform-based manipulator. A human wrist is used as a typical example to elaborate the theory of the method and to assess the fidelity of the method. The proposed method uses a 3-D motion capture system to collect the *in-vivo* wrist kinematics from 12 patients undertaking hammering motion. In parallel, CT scans and static motion capture are undertaken on 8 cadaveric human wrist specimens in an effort to define the locations of the coordinate systems. Consequently the *in-vivo* measured wrist kinematics is transformed to the kinematics of the robotic testing system, which is used to reproduce the hammering motion. Experimental results show that the accuracy of the reproduced motion on the cadaveric samples is of similar magnitude to the measurement error of the motion capture system. Experimental results also show that the assumption of fixed wrist joint centre of rotation is valid for motion reproduction.

Statement of Originality

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution to Boyin Ding and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Boyin Ding

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Table of Contents

Abstract	I
Statement of Originality	V
Acknowledgement	VII
Table of Contents	IX
List of Figures	XV
List of Tables	XXVII
Chapter 1	1
Introduction	1
1.1 Motivation of this Thesis	1
1.2 Literature Review	3
1.2.1 Biomechanical Testing	3
1.2.1.1 Scope	3
1.2.1.2 Requirements to Implement Biomechanical Testing	4
1.2.2 6-DOF Biomechanical Testing Systems	7
1.2.2.1 Commercial Material Testing Systems	7
1.2.2.2 Custom-built systems	9
1.2.2.3 Serial Robot-based systems	11
1.2.2.4 Parallel Robot-based systems	12
1.2.2.5 Conclusion	17
1.2.3 Compliance Error Compensation	18
1.2.3.1 Active Compensation Based on Control Software Modification ...	18
1.2.3.2 Passive Compensation Based on Physical Decoupling	20

1.2.4 Backlash Error Compensation.....	20
1.2.4.1 General Industrial Solution	21
1.2.4.2 Backlash Model-based Control	22
1.2.4.3 Preload Control.....	23
1.2.5 Pure Force or Moment Control on Human Joints for Unconstrained Testing	24
1.2.5.1 Special Loading Apparatus	24
1.2.5.2 6-DOF Systems with Independent Axes	26
1.2.5.3 Robotic-based Methods.....	27
1.2.6 Reproducing <i>In-vivo</i> Kinematics on Human Joints	28
1.2.7 Conclusion from the Literature Review.....	29
1.3 Contribution of this Thesis.....	31
1.4 Overview of this Thesis.....	33
1.5 Publications and Awards Arising from this Thesis	35
Chapter 2.....	37
Stiffness Analysis and Control of a Stewart Platform-based Mechanism with Decoupled Sensor-actuator Locations	37
2.1 Introduction.....	37
2.2 Background Theory	38
2.2.1 Spatial Description and Transformation	38
2.2.2 Inverse Kinematics	41
2.2.3 Direct Kinematics.....	42
2.2.4 Jacobians (Velocities and Statics).....	42
2.3 Theoretical Analysis.....	43
2.3.1 Mechanism Concept.....	43
2.3.2 Stiffness Analysis.....	45
2.3.2.1 Stiffness Modelling Strategy	45
2.3.2.2 Deformation Errors of Parallel Links	47
2.3.2.3 Deformation Errors of Platform and Framework.....	48
2.3.3 Control Analysis	48
2.3.3.1 Coordinate System Transformation	48
2.3.3.2 Sensor-Actuator Non-collocated Control Problem	50
2.3.3.3 Kinematics-based PID Control.....	50
2.3.3.4 Dynamics-based PD Control	52

2.4 Numerical Simulation on Stiffness	53
2.4.1 Geometrical and Physical Parameters for Simulation	53
2.4.2 FEA Simulation on the Platform Assembly and the Supporting Frame	55
2.4.3 Effective Robotic System Stiffness Vs Load Frame Stiffness	56
2.5 Control Simulation and Experiments	58
2.5.1 Effect of Non-located Sensor-actuator Mechanism	58
2.5.2 Experimental Method (Kinematic-based PID Control)	59
2.5.2.1 Mechanical Design	59
2.5.2.2 Control Hardware Configuration	59
2.5.2.3 Experimental Protocol	60
2.5.3 Results on the Kinematics-based PID Control	61
2.6 Conclusion	63
Chapter 3	65
Active Preload Control of a Redundantly Actuated Stewart Platform for Backlash Prevention	65
3.1 Introduction	65
3.2 Background Theory	66
3.2.1 Inertia Tensor	67
3.2.2 Velocity and Acceleration on a Rigid Body	67
3.2.3 Newton-Euler Equations	68
3.2.4 Backlash-free Condition	69
3.3 Problem Statement	70
3.4 Theoretical Analysis	72
3.4.1 Redundant Manipulator Configuration	72
3.4.2 Inverse Dynamics Equation	73
3.4.3 Preload Optimisation	78
3.4.3.1 Optimisation Problem Formulation	78
3.4.3.2 Optimisation Algorithm	79
3.4.4 Force Control	81
3.4.4.1 Dynamics Model of the Redundant Leg	81
3.4.4.2 Force Control Algorithm	83
3.5 Numerical Simulation	84
3.5.1 Preload Distribution Efficiency of the Redundant Manipulator	84

3.5.2 Preload Optimization Simulation	88
3.5.3 Force Control Simulation	96
3.6 Physical Experiment	98
3.6.1 Experiment Method	98
3.6.1.1 Additional Framework Design	98
3.6.1.2 Redundant Leg Assembly Design	99
3.6.1.3 Control Hardware Configuration	103
3.6.1.4 Experimental Protocol	105
3.6.2 Experimental Results	106
3.7 Discussion and Conclusion	119
Chapter 4	121
Adaptive Velocity-based Load Control of Human Joints for Unconstrained Testing—A Robotic-based Method	121
4.1 Introduction	121
4.2 Background Theory	122
4.2.1 Nonlinear Behaviour of Human Joints	122
4.2.2 Velocity-based Force Control	123
4.3 Theoretical Analysis	125
4.3.1 Overall Concept	125
4.3.2 Adaptive Estimation of Force Control Gains	126
4.3.3 Other Improvements in the Algorithm	128
4.3.3.1 Use of Hyperbolic Sine Function in the Feedback Controller	128
4.3.3.2 Feed-forward Control	129
4.3.3.3 Follower Load Preload	130
4.3.3.4 Partially Unconstrained Testing	130
4.4 Physical Experiment	131
4.4.1 Experimental Method	131
4.4.1.1 Ovine FSU Cadaver Preparation and Set-up	131
4.4.1.2 Control Hardware Configuration	132
4.4.1.3 Experimental Protocol	132
4.4.2 Results	134
4.5 Conclusion and Discussion	141
Chapter 5	143

A Scientific Method for Reproducing the <i>In-vivo</i> Measured Kinematics on Human Cadaver Joints Using a Stewart Platform-based Manipulator	143
5.1 Introduction	143
5.2 Background Theory	144
5.2.1 A Review on Wrist Anatomy and Assessment Techniques	144
5.2.2 Transformation Matrix and Anatomical System Definition	145
5.3 Methods	147
5.3.1 Summary	147
5.3.2 <i>In-vivo</i> Data Collection	147
5.3.3 Specimen Preparation and CT Construction	148
5.3.4 Wrist Kinematics Transformation	150
5.3.5 <i>In-vitro</i> Experiment	151
5.4 Results	153
5.4.1 Accuracy of the Reproduced Motion	153
5.4.2 Load Responses at the Wrist COR	155
5.4.3 Carpal Kinematics	156
5.5 Discussion and Conclusion	158
5.5.1 Evaluation of the Motion Reproduction Method	158
5.5.2 Kinematics of the Carpal Bones	161
Chapter 6	163
Robot Control System Design and Typical Applications of the Developed Robotic Testing System in Biomechanics	163
6.1 Introduction	163
6.2 Robot Control System Design	163
6.2.1 Control Hardware and Software Design	163
6.2.2 Functionality and GUI Design	167
6.2.3 Robot Specifications	169
6.3 Typical Applications of the Robotic Testing System in Biomechanics	171
6.3.1 Assessment of Impaction Bone Grafting	171
6.3.1.1 Project Summary	171
6.3.1.2 Results	171
6.3.2 Understanding of 3D Lumbar Intervertebral Disc Internal Strains during Repetitive Loading	173
6.3.2.1 Project Summary	173

6.3.2.2 Results.....	173
6.3.3 Assessment of Primary Stability of Cementless Tibial Tray.....	176
6.3.3.1 Project Summary.....	176
6.3.3.2 Results.....	177
Chapter 7.....	179
Conclusion and Future Work.....	179
7.1 Conclusion.....	179
7.1.1 Stiffness and Control of the Non-located Actuator-Sensor Mechanism.....	179
7.1.2 Active Preload Control Using Actuation Redundancy for Backlash Elimination.....	180
7.1.3 Adaptive Velocity-based Load Control of Human Joint for Unconstrained Testing.....	181
7.1.4 Reproducing the <i>In-vivo</i> Measured Kinematics on Human Cadaveric Joints.....	181
7.2 Future Work.....	182
7.2.1 Non-located Actuator-Sensor Mechanism.....	182
7.2.2 Intelligent Active Preload Control of the Redundantly Actuated Manipulator.....	183
7.2.3 Study the Control of the Manipulator to Simulate More Physiological Joint Motion and Loading.....	183
References.....	185
Appendix A.....	197
Mechanical Drawings of the Additional Frame and Redundant Leg Assembly	197
Appendix B.....	215
Electrical Drawings and Wiring Diagrams of the Robot Control System.....	215
Appendix C.....	221
Matlab Codes.....	221
C.1 Code for Calculating the Stiffness of the Non-Collocated Actuator-Sensor Mechanism.....	221
C.2 Code for Preload Control Simulation.....	227

List of Figures

Figure 1.1. Degrees of freedom of a functional spinal unit (FSU). The human joint is able to rotate and translate in all three planes and therefore has six degrees of freedom. These degrees of freedom can be broken down into three rotations—left and right axial rotation, flexion and extension, and left and right lateral bending—and three translations—anterior and posterior shear, compression and decompression, and left and right lateral shear. (Wilke et al., 1998) 5

Figure 1.2. Instron Biopuls-Spine showing testing of a FSU. A shear table at the bottom is able to achieve anterior-posterior and lateral shear, while a servo actuator box is able to produce compression-decompression, axial rotation, and flexion-extension, and lateral bending. A 6-DOF load-cell is mounted beneath the specimen for measuring the loads at the specimen. (Jones, 2012) 8

Figure 1.3. AMTI Force-5 showing testing of an artificial hip joint. A torsion table at the bottom is able to achieve axial rotation while a servo actuator box at the side is able to reproduce anterior-posterior shear, compression-decompression, and flexion-extension. Lateral bending can be achieved by assembling a hip/spine kit on the machine. A 6-DOF load-cell is mounted beneath the specimen for measuring the loads at the specimen. (AMTI Inc., 2011) 8

Figure 1.4. Custom-built spine testing system developed by Wilke et al. (1994). Stepper motors were used to produce translations and rotations about all three axes, and a pneumatic system to maintain a preload on the specimen and to also control muscle forces. A 6-DOF load-cell was used to measure the loads at the specimen. .. 10

Figure 1.5. 6-DOF articulated robot (KR 125, KUKA Robots) testing a cadaver knee joint (Zantop et al., 2006). (a) The robotic manipulator can move the knee in 6-DOF, while the universal force moment sensor (UFS) can measure three orthogonal forces and moments. (b) The knee is mounted to the system with the tibia attached to the end-effector of the robot via the UFS while the femur is mounted to the base..... 11

Figure 1.6. Structural concept of a Stewart platform (MathWorks, 2002)..... 13

Figure 1.7. 6-DOF parallel robot (R-2000 Rotopod, Parallel Robotic Systems Corporation) with a spine model mounted via a 6-DOF load-cell. (Goertzen and Kawchuk, 2008)..... 13

Figure 1.8. HexaSpine parallel platform developed by Liem et al. (2007) 14

Figure 1.9. Parallel robotic-based testing system developed by Walker and Dickey (2007). A porcine lumbar spine specimen is mounted within the manipulator and is faced anteriorly. Captions describe the base and top plates, linear actuator, leg potentiometer, UFS load cell, spine mounting cup, aluminium plate fixators, and the intervertebral joint. 15

Figure 1.10. Parallel robotic-based testing system developed by Stokes et al. (2001). 16

Figure 1.11. Robot error compensation methods: a) modification of the manipulator model b) modification of the target trajectory. (Klimchik et al., 2013) 19

Figure 1.12. Zoomed section of the parallel robotic testing system developed by Stokes et al. shown in Fig 1.10, showing the unique top platform assembly design which decouples the upper ends of the actuators and encoders (Stokes et al., 2001) . 20

Figure 1.13. Block diagram showing the configuration of dual loop PID control (Tal, 1998)..... 21

Figure 1.14. Backlash in a two-mass system. T_m , ω_m , and J_m represent the torque, velocity, and inertia of the motor while T_d , ω_l , and J_l represent the torque/force, velocity, and inertia/mass of the load. The transmission system between the motor and load is modelled as a mass-less shaft. θ_s is the twist of the shaft (not explicitly shown in the figure), $\theta_d = \theta_m - \theta_l$ is the displacement angle between the motor angle θ_m

and the load angle θl , and $\theta b = \theta d - \theta s$ is the backlash angle, with the restriction that $-\alpha \leq \theta b \leq \alpha$. k_s , c_s are the elasticity and damping coefficients, respectively, of the shaft, giving the shaft torque T_s . (Nordin and Gutman, 2002) 22

Figure 1.15. Torsion testing rig developed by Latham et al. (1994). 25

Figure 1.16. Unconstrained testing system developed by Hollis et al. (1991). 26

Figure 2.1. Description of a position and an orientation of frame $\{B\}$ with respect to frame $\{A\}$ 39

Figure 2.2. Spatial transformation between multiple frames 40

Figure 2.3. X-Y-Z fixed angles (roll, pitch, yaw angles) 40

Figure 2.4. Schematic showing the kinematics model of a general Stewart platform. 41

Figure 2.5. Left images: Inventor model showing the upper and lower decoupled sensor-actuator locations of the Stewart platform-based manipulator. Right image: Inventor model of the entire Stewart platform-based manipulator. 44

Figure 2.6. Schematic showing the kinematic model of the manipulator 45

Figure 2.7. Schematic showing the lateral section of the manipulator with attached coordinate systems. 49

Figure 2.8. Block diagram showing the kinematics-based control scheme 51

Figure 2.9. Block diagram showing the decoupled PID control algorithm..... 51

Figure 2.10. Loading and boundary conditions on the platform assembly ($\mathbf{tT\theta T} = 0 \ 0 \ 500\text{mm} \ 0 \ 0 \ 0$, $\mathbf{FeTMeT} = 0 \ 0 \ 20,000\text{N} \ 0 \ 0 \ 0$) 55

Figure 2.11. Loading and boundary conditions on the supporting frame ($\mathbf{tT\theta T} = 0 \ 0 \ 500\text{mm} \ 0 \ 0 \ 0$, $\mathbf{FeTMeT} = 0 \ 0 \ 20,000\text{N} \ 0 \ 0 \ 0$) 56

Figure 2.12. Deformations of the platform assembly ($\mathbf{tT\theta T} = 0 \ 0 \ 500\text{mm} \ 0 \ 0 \ 0$, $\mathbf{FeTMeT} = 0 \ 0 \ 20,000\text{N} \ 0 \ 0 \ 0$) 56

Figure 2.13. Deformations of the supporting frame ($\mathbf{tT\theta T} = 0 \ 0 \ 500\text{mm} \ 0 \ 0 \ 0$, $\mathbf{FeTMeT} = 0 \ 0 \ 20,000\text{N} \ 0 \ 0 \ 0$) 56

Figure 2.14. Photograph of the assembled manipulator testing a polymer specimen . 59

Figure 2.15. Schematics showing the control hardware configuration for the robot position control experiment and the communication between the hardware elements 60

Figure 2.16. Photograph showing the high density polymer specimen fixed in the mounting cups..... 61

Figure 2.17. Three moments at specimen COR during testing 62

Figure 2.18. Tracking errors on three translations at specimen COR under kinematics-based control..... 62

Figure 2.19. Tracking errors on three rotations at specimen COR under kinematics-based control..... 62

Figure 3.1. The inertia tensor of an object. Here a vector \mathbf{t}_A locates the differential volume element $d\mathbf{v}$ 67

Figure 3.2. Free-body diagram shows two fixed points (C and B) on a moving rigid body where a frame $\{B\}$ is attached to point B and a global reference frame $\{A\}$ is spatially fixed. 68

Figure 3.3. Backlash dead-zone model where the vertical axis represents the value of the backlash shaft torque T_s , the horizontal axis represents the value of the angle difference between the motor and the load θ_d , and ab represents the maximum backlash angle..... 70

Figure 3.4. Backlash-free condition for a linear actuator 70

Figure 3.5. Schematics showing the preload control method where \mathbf{F}_{ex} and \mathbf{M}_{ex} represents the external forces and moments, \mathbf{p} , $\dot{\mathbf{p}}$, and $\ddot{\mathbf{p}}$ represents the end-effector trajectory, velocity, and acceleration, f_r represents the desired preload on the redundant actuator, and $\boldsymbol{\tau}_r$ and $\boldsymbol{\tau}_c$ represent the control forces for driving the redundant actuator and the original six ballscrews respectively. 71

Figure 3.6. Configuration of the redundant manipulator where BSP represents the ballscrew piston, M1 and M2 represent the upper mass and bottom mass of the mass-

spring-damper system respectively, FS represents the force sensor, and SJ represents the lower spherical joint.	73
Figure 3.7. Free-body diagram of one leg and the moving platform, where a_i represents the fixed joint centre of leg i , p_i represents the moving joint centre of leg i , c_i represents the gravity centre of leg i , o represents the end-effector, q represents the gravity centre of the moving platform, and e represents the point where the external loads are exerted on the moving platform. The end-effector coordinate system frame $\{o\}$ is attached to o , a leg inertia coordinate system frame a_i is attached to a_i and rotates in coincidence with leg i , and a global coordinate system frame $\{O\}$ is fixed for reference. ($i=1:7$).	74
Figure 3.8. Online optimization algorithm at discrete time tk	80
Figure 3.9. Simplified schematic diagram of the redundant actuator	81
Figure 3.10. Block diagram of the redundant actuator dynamics	83
Figure 3.11. Block diagram of position-based force control.	83
Figure 3.12. Preload distribution efficiency on x-axis translation.	85
Figure 3.13. Preload distribution efficiency on y-axis translation.	86
Figure 3.14. Preload distribution efficiency on z-axis translation.	86
Figure 3.15. Preload distribution efficiency on x-axis rotation.	86
Figure 3.16. Preload distribution efficiency on y-axis rotation.	87
Figure 3.17. Preload distribution efficiency on z-axis rotation.	87
Figure 3.18. Control forces on the six legs under $\pm 240\text{N}$ x-axis shear without preload control.	90
Figure 3.19. Optimized control forces and desired preload under $\pm 240\text{N}$ x-axis shear	90
Figure 3.20. Control forces on the six legs under $\pm 240\text{N}$ y-axis shear without preload control.	91

Figure 3.21. Optimized control forces and desired preload under $\pm 240\text{N}$ y-axis shear	91
Figure 3.22. Control forces on the six legs under $\pm 1500\text{N}$ z-axis loading without preload control.....	92
Figure 3.23. Optimized control forces and desired preload under $\pm 1500\text{N}$ z-axis loading	92
Figure 3.24. Control forces on the six legs under $\pm 60\text{Nm}$ x-axis bending without preload control.....	93
Figure 3.25. Optimized control forces and desired preload under $\pm 60\text{Nm}$ x-axis bending	93
Figure 3.26. Control forces on the six legs under $\pm 60\text{Nm}$ y-axis bending without preload control.....	94
Figure 3.27. Optimized control forces and desired preload under $\pm 60\text{Nm}$ y-axis bending	94
Figure 3.28. Control forces on the six legs under $\pm 40\text{Nm}$ z-axis torsion without preload control.....	95
Figure 3.29. Optimized control forces and desired preload under $\pm 40\text{Nm}$ z-axis torsion	95
Figure 3.30. Simulated force control performance on the redundant leg.....	97
Figure 3.31. Inventor model of the additional framework for mounting the redundant leg	99
Figure 3.32. Deformations of the additional framework under extreme loading conditions.....	100
Figure 3.33. Inventor model of redundantly actuated manipulator	101
Figure 3.34. Photograph of the NET motor bike shock absorber.....	102

Figure 3.35. Measured static response of the shock absorber (tested under displacement control with a haversine waveform of a -35mm amplitude at 0.01Hz for three cycles). Note the hysteresis. 102

Figure 3.36. Assembly of the redundantly actuated manipulator—experimental rig 103

Figure 3.37. Schematics showing the control hardware configuration for the preload control experiment and the communication between the hardware elements..... 104

Figure 3.38. Comparison between dead mass preload (left figures) and active preload control using the redundant leg (right figures). The robot was commanded to shear the specimen by 1mm along x-axis using a have-sine waveform at 0.02Hz for three cycles. (Fig. 3.38 continues on next page) 107

Figure 3.38. Comparison between dead mass preload (left figures) and active preload control using the redundant leg (right figures). The robot was commanded to shear the specimen by 1mm along x-axis using a haver-sine waveform at 0.02Hz for three cycles..... 108

Figure 3.39. Comparison between dead mass preload (left figures) and active preload control using the redundant leg (right figures). The robot was commanded to shear the specimen by 1mm along y-axis using a haver-sine waveform at 0.02Hz for three cycles. (Fig. 3.39 continues on next page) 109

Figure 3.39. Comparison between dead mass preload (left figures) and active preload control using the redundant leg (right figures). The robot was commanded to shear the specimen by 1mm along y-axis using a haver-sine waveform at 0.02Hz for three cycles..... 110

Figure 3.40. Comparison between dead mass preload (left figures) and active preload control using the redundant leg (right figures). The robot was commanded to compress the specimen by 0.4mm along z-axis using a haver-sine waveform at 0.02Hz for three cycles. (Fig. 3.40 continues on next page)..... 111

Figure 3.40. Comparison between dead mass preload (left figures) and active preload control using the redundant leg (right figures). The robot was commanded to

compress the specimen by 0.4mm along z-axis using a haver-sine waveform at 0.02Hz for three cycles.....	112
Figure 3.41. Comparison between dead mass preload (left figures) and active preload control using the redundant leg (right figures). The robot was commanded to bend the specimen by 6 degree about x-axis using a haver-sine waveform at 0.01Hz for three cycles. (Fig. 3.41 continues on next page)	113
Figure 3.41. Comparison between dead mass preload (left figures) and active preload control using the redundant leg (right figures). The robot was commanded to bend the specimen by 6 degree about x-axis using a haver-sine waveform at 0.01Hz for three cycles.	114
Figure 3.42. Comparison between dead mass preload (left figures) and active preload control using the redundant leg (right figures). The robot was commanded to bend the specimen by 6 degree about y-axis using a haver-sine waveform at 0.01Hz for three cycles. (Fig. 3.42 continues on next page)	115
Figure 3.42. Comparison between dead mass preload (left figures) and active preload control using the redundant leg (right figures). The robot was commanded to bend the specimen by 6 degree about y-axis using a haver-sine waveform at 0.01Hz for three cycles.	116
Figure 3.43. Comparison between dead mass preload (left figures) and active preload control using the redundant leg (right figures). The robot was commanded to twist the specimen by 6 degree about z-axis using a haver-sine waveform at 0.02Hz for three cycles. (Fig. 3.43 continues on next page)	117
Figure 3.43. Comparison between dead mass preload (left figures) and active preload control using the redundant leg (right figures). The robot was commanded to twist the specimen by 6 degree about z-axis using a haver-sine waveform at 0.02Hz for three cycles.	118
Figure 4.1. Idealized representation of the load-displacement behaviour of a lumbar FSU. In the NZ, large changes in displacement can occur with little or no change in applied load. In the EZ, large changes in load can be produced by small changes in applied displacement. (Gilbertson et al., 2000).....	123

Figure 4.2. Block diagram showing the velocity-based force control scheme where subscript d and r represent the desired value and the real value respectively and superscript t and j represent the value in robot task space and the value in robot joint space respectively.....	124
Figure 4.3. Block diagram showing the improved velocity-based force control scheme where subscript d and r represent the desired value and the real value respectively and superscript s represent the value at the specimen COR.....	125
Figure 4.4. Flow chart showing the force control gain optimization algorithm on one DOF at discrete time t_j	127
Figure 4.5. Nonlinear feedback control function consisting of an adaptive force control gain, a hyperbolic sine function, and a saturation.....	129
Figure 4.6. Left figure showing the inferior vertebra of the FSU potted into the lower fixable bath cup and the right figure showing the overall experiment set-up on the Stewart platform-based machine.....	131
Figure 4.7. Control hardware configuration for the unconstrained testing experiment	132
Figure 4.8. Results under compression (F_z) testing with the remaining 5-DOF fully unconstrained.....	135
Figure 4.9. Results under posterior shear testing (F_x) with the remaining 5-DOF partially unconstrained	136
Figure 4.10. Results under lateral shear testing (F_y) with the remaining 5-DOF partially unconstrained	137
Figure 4.11. Results under flexion testing (M_x) with the remaining 5-DOF fully unconstrained.....	138
Figure 4.12. Results under lateral bending testing (M_y) with the remaining 5-DOF fully unconstrained.....	139
Figure 4.13. Results under axial rotation testing (M_z) with the remaining 5-DOF fully unconstrained.....	140

Figure 5.1. Bones of the human wrist joint (Phillips and Schmidt, 2013) 144

Figure 5.2. A. Input wrist angles for the hammering motion (50% of the average of the angles measured in vivo). B. Time history of input wrist angles, including the initial positioning phase, the 3 repetitions and the pauses between them. Note the pronation-supination angle is kept as a constant. RUD, PS and FE are short for radio- ulnar deviation, pronation-supination and flexion and extension respectively. 148

Figure 5.3. A. Prepared cadaveric specimen with bone pins inserted and reflective markers coupled to the bone pins. B. Reconstructed CT scan including bone pins and reflective markers. 149

Figure 5.4. A. Preparation and fixation of the wrist prior to mounting in the robotic testing system. B. Specimen mounted in the Stewart platform-based testing system ready for *in-vitro* testing. 151

Figure 5.5. Wrist FE angle during flexion-extension motion: Input value (red solid), *in-vitro* mean value (blue solid), and *in-vitro* mean value \pm SD (black dash)..... 154

Figure 5.6. Wrist RUD angle during radio-ulnar deviation motion: Input value (red solid), *in-vitro* mean value (blue solid), and *in-vitro* mean value \pm SD (black dash). 154

Figure 5.7. Wrist FE and RUD angles during hammering motion: Input/*In-vivo* mean value (red solid), *in-vitro* mean value (blue solid), and *in-vitro* mean value \pm SD (black dash)..... 155

Figure 5.8. 6-DOF load responses at the wrist COR during hammering motion. Each of the six subplots shows the mean value (thicker line) and the mean value \pm SD (thinner lines) along each of the 6-DOF at the normalised time (0% to 100% percentage of the hammering motion)..... 156

Figure 5.9. Ratios of carpal FE to wrist FE angle, for A. 0 to 15° of flexion and for B. 0 to 15° of extension. Ratios of carpal RUD to wrist RUD angle, for C. 0 to 20° of ulnar deviation and for D. 0 to 20° of radial deviation. Average (bar) and SD (line) are shown for all specimens. The numbers on the bars are the R-square between the experimental curve and the linear fit to it. No value indicates that the amplitude of

bone rotation was negligible (e.g. $<2^\circ$). SCA: scaphoid, LUN: lunate, TRI: triquetrum, CAP: capitate, MET: 3rd metacarpal.	159
Figure 5.10. Ratios of carpal FE to wrist FE angle during hammering for A. 0 to 7.1° of flexion and for B. 0 to 11.1° of extension. Ratios of carpal RUD to wrist RUD angle during hammering, for C. 0 to 13.6° of ulnar deviation and for D. 0 to 4.8° of radial deviation. Average (bar) and SD (line) are shown for all specimens. The numbers on the bars are the R-square between the experimental curve and the linear fit to it. No value indicates that the amplitude of bone rotation was negligible (e.g. $<2^\circ$). SCA: scaphoid, LUN: lunate, TRI: triquetrum, CAP: capitate, MET: 3rd metacarpal.	160
Figure 6.1. Schematic showing the control system architecture (for six legs only). It shows the four platforms on which control loops are running (including rates).....	164
Figure 6.2. Comparison of the load-cell noise energy level in dB (Fz channel only) in power spectrum. Sample frequency: 50Hz, FFT points: 512, FFT method: Welch, Window type: Hann, Overlap: 0.75.....	166
Figure 6.3. Screenshot showing the main body of the custom GUI.....	168
Figure 6.4. Mean (95% confidence interval) stiffness expressed as a fraction of the intact tibia (normalised) for each direction of loading. Significant differences compared to the intact group are denoted by *.	172
Figure 6.5. Displacements on the disc after various cycles of repetitive loading	174
Figure 6.6. Maximum shear strains (%) on the disc after various cycles of repetitive loading.....	175
Figure 6.7. Anterior lift off of the tibial tray during the stance phase of gait (0-60%)	178
Figure A.1. Assembly of the additional framework for mounting the redundant leg which consists of three individual pieces	198
Figure A.2. Drawing showing the dimensions of the front frame piece	199
Figure A.3. Drawing showing the dimensions of the back frame piece	200

Figure A.4. Drawing showing the dimensions of the top frame piece	201
Figure A.5. Assembly of the redundant leg design	202
Figure A.6. Drawing showing the thread on the ballcrew-actuator shock-absorber connector	203
Figure A.7. Drawing showing ballcrew-actuator shock-absorber connector	204
Figure A.8. Drawing showing the assembly of the ballscrew-actuator shock-absorber connector	205
Figure A.9. Drawing showing the limit bolt for fixing the shock absorber to the connector	206
Figure A.10. Drawing showing the shock absorber body	207
Figure A.11. Drawing showing the shock-absorber load-cell connector	208
Figure A.12. Drawing showing the F214 load-cell body	209
Figure A.13. Drawing showing the load-cell rod-eye connector	210
Figure A.14. Drawing showing the spacer tube for the rod eye.....	211
Figure A.15. Drawing showing the limit bolt acting as the shaft of the rod eye.....	212
Figure A.16. Drawing showing the should for supporting the rod eye shaft	213
Figure A.17. Drawing showing the plate which couples the redundant leg to the top of the robot.....	214
Figure B.1. The wiring diagram of the PCB boards (1)	216
Figure B.2. The wiring diagram of the PCB boards (2)	217
Figure B.3. Wiring diagram on RIO0 (FPGA board 1).....	218
Figure B.4. Wiring diagram on RIO1 (FPGA board 2).....	219
Figure B.5. Electrical drawing of the custom isolation device.....	220

List of Tables

Table 1.1. Main specifications of Instron Biopuls-Spine and AMTI Force-5. *Accuracy here represents the tracking performance of the machine in each axis during a dynamic condition. These values are typical for testing at a 1Hz repetition rate while running the ISO waveforms.....	9
Table 1.2. Specifications of KUKA Robots KR 125 and KR 1000 TITAN. (KUKA Robots, 2013)	12
Table 1.3. Specifications of R-2000 Rotopod. (Parallel Robotic Systems Corporation, 2013).....	14
Table 1.4. Load capacity of HexaSpine parallel platform (Forces in N and Torques in Nm).....	15
Table 1.5. Specifications of the parallel robotic-based testing system developed by Stoke et al. (2001)	16
Table 1.6. A comparison between 6-DOF biomechanical testing systems	17
Table 2.1. Coordinates of A_i with respect to $\{O\}$	54
Table 2.2. Coordinates of P_i with respect to $\{O_p\}$	54
Table 2.3. Coordinates of B_i with respect to $\{O\}$	54
Table 2.4. Coordinates of E_i with respect to $\{O_p\}$	54
Table 2.5. Physical properties of the parts	54

Table 2.6. Effective robotic system stiffness versus the load frame stiffness (unit: N/mm and Nm/°)	57
Table 2.7. RMS errors on six axes under SISO and decoupled SISO control.....	63
Table 3.1. Geometrical parameters of the additional leg and the robot.....	85
Table 3.2. Geometrical and physical parameters for preload optimization simulation	88
Table 3.3. Model parameters for force control simulation	96
Table 3.4. Control parameters for physical experiment (same as the simulation parameter if not listed).....	105
Table 3.5. A comparison between the RMS tracking errors of the robot under dead mass preload and under active preload control	118
Table 4.1. Command waveform along each of the 6-DOF for the unconstrained testing	133
Table 4.2. Physical and control parameters for implementing the unconstrained testing experiment	134
Table 4.3. RMS load errors on all six axes under unconstrained testing along each of the 6-DOF	141
Table 5.1. Definition of anatomical coordinate systems for the forearm and hand ..	146
Table 5.2. RMS errors between commands and measured wrist angles over time, repetitions and subjects. FE: flexion and extension, RUD: radio-ulnar deviation, HAM: hammering motion.....	154
Table 6.1. Specifications of the robotic testing system (6 legs). Displacement accuracy measured when the robot tracks a pure sinusoidal motion waveform with ± 1 mm or ± 1 degree amplitude.....	170
Table 6.2. Results from the verification test on the robotic testing system implemented by a NATA accredited test facility	170