A Musculoskeletal Model-based Assistance-As-Needed Paradigm for Assistive Robotics

Marc G. Carmichael

Submitted in fulfillment of the requirement
for the degree of Doctor of Philosophy

2013

UNIVERSITY OF
TECHNOLOGY SYDNEY

The Faculty of Engineering and Information Technology
Mechatronics and Intelligent Systems Group

www.uts.edu.au

Supervisor	:	Prof. Dikai Liu
Co-Supervisor	:	Prof. Kenneth J. Waldron

Certificate

I, Marc G. Carmichael, declare that this thesis entitled *A Musculoskeletal Model-based Assistance-As-Needed Paradigm for Assistive Robotics* and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed: Production Note:
Signature removed prior to publication.

Date: 07/01/2013

Acknowledgements

This work would not have been possible without the encouragement and support of many, many others around me.

I would firstly like to thank my supervisor Prof. Dikai Liu for the opportunity to work on this topic and the support you provided throughout. Your direction, motivation and the perfect amount of pressure allowed me to accomplish this significant milestone in my life.

To my co-supervisor Prof. Kenneth Waldron, and to Dr. Gabriel Aguirre-Ollinger for all of your advice and expertise. It was an immense help and contributed greatly to the completion of this work.

To all the professors, researchers, engineers and students at the Centre for Autonomous Systems. I am glad to have had the opportunity to work in an environment surrounded by such clever and motivated people. You made my time a whole lot more enjoyable, and your support assured me that everything was going to work out, eventually.

Lastly to my friends, family, and loved ones. This commitment has occupied the majority of my life over the past years. Even with the little time I have been able to give you, I continued to receive encouragement, support and understanding throughout it all. For that I am extremely thankful.

Contents

1 Introduction **1**

1.1 Background and Motivation 2

1.2 Research Question 7

1.3 Scope 9

1.4 Contributions 10

1.5 Thesis Structure 12

2 Related Work **14**

2.1 Assistive Robotics 15

2.1.1 Industry 15

2.1.2 Assisted daily living 16

2.1.3 Rehabilitation 20

2.1.4 Other examples of assistive robots 22

2.2 Control of Physically Assistive Robots 24

2.2.1 Control schemes in assistive robotics 25

2.2.2 Physical assistance paradigms 27

2.2.3 The Assistance-As-Needed (AAN) paradigm 32

2.3 Musculoskeletal Modelling 38

2.3.1 Musculotendon Unit (MTU) model 39

2.3.2 MTU length, velocity and moment-arms 44

2.3.3 Muscular joint torque produced by MTU forces 45

2.3.4 Rigid body kinematics 45

2.3.5 Rigid body dynamics 47

2.3.6 Muscle activation dynamics 48
2.3.7 Musculoskeletal model applications 49
2.3.8 Musculoskeletal models in robotics 50
2.4 Summary 51

3 A Framework for Model-based Robotic AAN 53
3.1 Framework 54
3.1.1 Structure 56
3.2 Strength as the Measure of Capability 58
3.3 Task Model (TM) 60
3.3.1 Limb motion 61
3.3.2 External force 61
3.3.3 Usage 62
3.3.4 Examples 63
3.4 Strength Model (SM) 65
3.4.1 Upper limb musculoskeletal model (MM) 68
3.4.2 Strength calculation assuming uncoupled joints 70
3.5 Framework Applied to Example Tasks 71
3.5.1 Case study 1: drinking task 71
3.5.2 Case study 2: sliding task 77
3.6 Discussion 82
3.6.1 Realism of the SM results 82
3.6.2 Alternatives to muscle-based strength 82
3.6.3 Quasi-static simplification 86
3.6.4 Consideration of physical impairment 88
3.7 Summary 90

4 Musculoskeletal Model-based Strength Estimation 92
4.1 Optimisation Model 93
4.1.1 Considerations 93
4.1.2 Dynamic equation 96

4.1.3 Objective function . . . 100
4.1.4 Optimisation constraints . . . 103
4.1.5 Summary of the optimisation model . . . 104
4.2 Evaluation . . . 106
4.2.1 Strength vs force direction . . . 107
4.2.2 Strength vs limb position . . . 109
4.2.3 Strength vs muscle impairment . . . 114
4.3 Assistance Estimation Considering Impairment . . . 118
4.3.1 Impairment due to stroke . . . 119
4.3.2 Case study 1: drinking task . . . 122
4.3.3 Case study 2: sliding task . . . 124
4.4 Discussion . . . 127
4.4.1 Representation of physical impairment . . . 127
4.4.2 Effect of joint coupling on strength estimation . . . 128
4.4.3 Redundancy . . . 129
4.4.4 Ignored activation dynamics . . . 130
4.5 Summary . . . 131

5 Experimental Validation of Model-based AAN 132

5.1 Exoskeleton Platform . . . 133
5.1.1 Physical interaction with the operator . . . 133
5.1.2 Exoskeleton hardware . . . 135
5.1.3 Control scheme . . . 136
5.2 Experiment . . . 138
5.2.1 Tasks . . . 140
5.2.2 Impairment profiles . . . 141
5.2.3 Assistance calculation . . . 143
5.2.4 Experimental procedure . . . 146
5.2.5 EMG acquisition . . . 146
5.2.6 Virtual load forces . . . 150
5.3 Experimental Results . . . 155

5.3.1 Muscle activity for different tasks 155
5.3.2 Assistance at the hand 157
5.3.3 Assistance at the muscles 158
5.3.4 Assistance targeted for impaired muscles 159
5.4 Summary 163

6 Conclusion 164
6.1 Summary of Contributions 165
6.1.1 A novel model-based AAN framework 165
6.1.2 Optimisation model for calculating strength 165
6.1.3 Analysis of physical impairment 166
6.1.4 Practical validation on a robotic system 166
6.1.5 Development of a robotic exoskeleton 167
6.2 Discussion and Limitations 167
6.2.1 Reliance on the musculoskeletal model 167
6.2.2 Factors other than strength affecting tasks 169
6.2.3 Definition of the subject's impairment 170
6.2.4 Real time computation 171
6.3 Future Work 171
6.3.1 Trials with impaired subjects 171
6.3.2 Strength estimation improvement 172
6.3.3 Fitting the MM to individual subjects 172
6.3.4 Hybrid model-empirical AAN paradigm 174

Appendix 176
A Upper Limb Musculoskeletal Model 176
A.1 Reduction to four degrees of freedom 176
A.2 Upper limb mass and inertia properties 179
A.3 Upper limb impairment consistent with stroke 180
B Strength Capability Calculation with Uncoupled Joint Simplification . . 181
C Water Bottle Inertial Properties 184

D Strength Capability Calculation Considering Joint Coupling 185
  D.1 Optimisation objective function 185
  D.2 Optimisation constraints 186
E Robotic Exoskeleton Platform 188
  E.1 Actuation 188
  E.2 Sensing 188
  E.3 xPC Target computer 189
F EMG Processing 190
  F.1 Matlab code 191

Bibliography **192**

List of Tables

2.1 Intrinsic parameters used for scaling the normalised MTU model. 42

4.1 Upper limb strength at the hand in five different limb positions and in six different directions; comparison between the strength calculated by the SM, and strength data obtained from the literature. 114
4.2 Names of the MTU models in the upper limb MM which have their activation limited to simulate impairment. 115

5.1 MTU impairment profiles used during the experiment. 142
5.2 The subject's strength capability S_P, calculated for each task, and for each impairment profile. 144
5.3 Results for the assistance parameter A that is calculated for each task, and for each impairment profile 145
5.4 Muscle groups measured using EMG and their associated numbering . . 147

A.1 Generalised coordinates in the upper limb musculoskeletal model 177
A.2 MTUs that are *not* utilised in the upper limb musculoskeletal model . . 177
A.3 MTUs that are utilised in the upper limb musculoskeletal model 178
A.4 Mass and inertial properties assigned to the upper limb musculoskeletal model. 179
A.5 MTU impairment profiles based on the study of stroke patients 180
E.1 xPC Target computer specifications 189

List of Figures

1.1 Examples of robotic systems 3
1.2 Age distribution forecast in Australia from 2007 to 2056. 5
1.3 Stroke in Australia, by age and sex 5

2.1 Physically assistive robotic systems for industrial applications 16
2.2 Walking assist devices from Honda 17
2.3 Exoskeletons for replacing lost functionality due to impairment 18
2.4 Lower limb exoskeletons for paraplegics 19
2.5 The InMotion Arm Robot by Interaction Motion Technologies 21
2.6 Rehabilitation devices available from Hocoma 21
2.7 Other examples of assistive robotic systems for various applications . . . 23
2.8 Distinction between the control scheme and the assistance paradigm of an assistive robot 24
2.9 Physically assistive robotic systems that use force reflection paradigms . 29
2.10 Robots which scale up or down operator motions 31
2.11 Generalisation of performance-based Assistance-As-Needed 34
2.12 Typical Hill-type musculotendon unit (MTU) model 40
2.13 Normalised muscle force-length-velocity, and tendon force-strain curves . 42

3.1 Generalisation of Assistance-As-Needed, represented as the gap between the requirements of a task and the capability of a human to perform it . 55
3.2 The model-based AAN framework. 56

3.3 The frequency distribution of Activities of Daily Living (ADLs) performed in every day life. 60
3.4 Example of the Task Model (TM). 62
3.5 Example of applying the TM to a task where the operator is required to carry an object of known mass. 63
3.6 Example of applying the TM to a sandblasting task. 64
3.7 Example of applying the TM to a rehabilitation exercise. 65
3.8 Example of the Strength Model (SM) 66
3.9 Overview of calculating operator strength capability using the SM. 68
3.10 Upper limb musculoskeletal model 69
3.11 Subject performing the drinking task 72
3.12 Locations of the targets in the drinking task. 73
3.13 Example of the upper limb motion captured during the drinking task. . . 74
3.14 The subject's calculated strength capability for the drinking task 76
3.15 Gap between the task's strength requirement and the subject's calculated strength during the drinking task movement 77
3.16 Locations of the targets in the table sliding task. 78
3.17 The upper limb motion captured during the sliding task. 79
3.18 The subject's calculated strength capability during the sliding task. . . . 80
3.19 Gap between the task's strength requirement and the subject's calculated strength during the sliding task 81
3.20 Linear acceleration of the hand measured during the drinking task . . . 86
3.21 Angular acceleration of the hand measured during the drinking task . . 87
3.22 Comparison of the strength measured in the paretic versus the non-paretic upper limbs of stroke patients with hemiparesis. 89

4.1 Example of the Strength Model (SM) 94
4.2 Procedure for calculating the operator's strength capability using the optimisation model within the SM framework. 105

4.3 The six different directions for which the strength at the hand is calculated using the SM, and compared to strength measurements obtained from the literature. 108
4.4 Strength at the hand in six orthogonal directions 109
4.5 The five upper limb positions for which the strength at the hand is calculated using the SM, and compared to strength measurements obtained from the literature. 110
4.6 Upper limb strength capability versus limb position, calculated with the SM and compared to strength measurements from the literature 112
4.7 Visualisation of the SM results using a polar plot 116
4.8 The effect of muscular impairment on strength at the hand. 117
4.9 Measured strength comparison between the paretic and non-paretic upper limbs of stroke patients with hemiparesis. 120
4.10 Strength impairment profiles with various impairment severity. 121
4.11 Upper limb motion recorded during the drinking task. 122
4.12 Results for the drinking task. 123
4.13 Upper limb motion recorded during the sliding task. 125
4.14 Results for the sliding task. 126
4.15 Differences in the strength results calculated with and without considering joint coupling. 129

5.1 The exoskeleton platform developed to evaluate the model-based AAN paradigm 134
5.2 Difference between external-force and internal-force exoskeleton systems 135
5.3 Robot motion trajectory created using an admittance control scheme. . 136
5.4 PD controller used to track the motion trajectory created from the admittance control scheme. 137
5.5 The combination of force measurements before they are fed to the admittance control scheme. 138
5.6 The subject's upper limb position during the experiment. 140
5.7 The six tasks performed by the subject in the experiment. 141

5.8 Muscles of interest during the experiment. 142
5.9 Example of surface EMG electrode placement. 147
5.10 EMG signal processing sequence. 148
5.11 An example EMG signal at each stage of the filtering process. 149
5.12 Hand positions during the experiment to analyse the suitability of using virtual forces to mimic physical loads. 150
5.13 The three experiment variations implemented during the experiment to analyse the suitability of using virtual forces to mimic physical loads. . . 151
5.14 The experiment validating the use of virtual external loads; results for all muscles. 153
5.15 The experiment validating the use of virtual external loads; results for biceps and anterior deltoid muscles. 154
5.16 Measured EMG for each task at different levels of robotic assistance. . . 156
5.17 The assistance measured at the subject's hand versus the desired assistance to be provided 157
5.18 The assistance at the subject's muscles calculated by the change in EMG, versus the desired assistance to be provided. 158
5.19 Correlation between the assistance provided for a specific impaired muscle, and the EMG measured for each muscle without assistance, for each of the experimental tasks performed 160
5.20 Comparison between the assistance provided by the AAN paradigm with muscle m impaired, and EMG for that same muscle measured with no assistance provided 162

Nomenclature

Formatting Style

Formatting	Description
$[\cdots]^T$	Vector or matrix transpose
$\lVert \cdots \rVert$	Vector norm
$\lvert \cdot \rvert$	Scalar absolute value

Subscript and Numbering

Symbol	Description
k	Number of degrees of freedom in the musculoskeletal system
m	Number of MTU models in the musculoskeletal system
$\mathbb{N}_1$	Set of natural numbers $\{1, 2, 3, 4, \ldots\}$

Symbol Usage

Symbol	Description	Units
α	Muscle fibre pennation angle	rad
α_0	Muscle fibre pennation angle at optimal length L_0^m	rad
ε^t	Tendon strain	-
σ	Standard deviation	-
$\boldsymbol{\theta}$	Robot measured joint position vector	rad
$\dot{\boldsymbol{\theta}}$	Robot measured joint velocity vector	rad/s
$\boldsymbol{\theta}_r$	Robot reference joint position vector	rad
$\dot{\boldsymbol{\theta}}_r$	Robot reference joint velocity vector	rad/s
a	MTU activation	-
$\mathbf{a}$	MTU activation column vector	-
A	Robot assistance parameter	-
b	Robot admittance gain	$\mathrm{m.s^{-1}/N}$
$\mathbf{C}$	Coriolis and centripetal effects	N.m
f_A^m	Active force component in muscle fiber	N
f_P^m	Passive force component in muscle fiber	N
f^t	Tendon force	N
f^M	MTU force	N
$\mathbf{f}$	MTU force column vector	N
$\mathbf{f}^A$	MTU active force column vector	N
$\mathbf{f}^P$	MTU passive force column vector	N
$\tilde{f}_A^m(\cdot)$	Normalised MTU fiber active force-length function	-
$\tilde{f}_P^m(\cdot)$	Normalised MTU fiber passive force-length function	-
$\tilde{f}_V^m(\cdot)$	Normalised MTU fiber force-velocity function	-
$\tilde{f}^t(\cdot)$	Normalised MTU tendon force-strain function	-

F_0^m	Maximum isometric muscle fiber force	N
F^E	Scalar magnitude of external force	N
$\mathbf{F}_H$	Measured force vector between robot and human operator	N
$\mathbf{F}_E$	Measured force vector between robot and the task	N
$\mathbf{H}$	Mass matrix of the musculoskeletal dynamic system	kg.m^2
$\mathbf{J}$	Robot kinematic Jacobian matrix	-
$\mathbf{J}_v$	Musculoskeletal kinematic Jacobian matrix	-
$\mathbf{K}_A$	Activation-to-force gain matrix	N
K_D	Derivative gain in robot PD controller	-
K_P	Proportional gain in robot PD controller	-
$\mathbf{K}_\tau$	Activation-to-torque gain matrix	N.m
$\mathbf{K}_{\tau i}$	The i-th row of matrix $\mathbf{K}_\tau$	N.m
l^M	MTU length	m
$\dot{l}^M$	MTU velocity	m/s
$\mathbf{l}$	MTU length column vector	m
$\dot{\mathbf{l}}$	MTU velocity column vector	m/s
l^m	MTU fiber length	m
$\tilde{l}^m$	Normalised MTU fiber length	-
$\dot{l}^m$	MTU fiber velocity	m/s
$\dot{\tilde{l}}^m$	Normalised MTU fiber velocity	-
l^t	Tendon length	m
L_0^m	MTU fiber optimal length (coinciding with F_0^m)	m
L_s^t	MTU tendon slack length	m
$\mathbf{L}$	MTU Jacobian matrix	-
$\mathbf{M}$	Mass matrix of the robot dynamic system	kg.m^2
q	Generalised coordinate position	rad

$\dot{q}$	Generalised coordinate velocity	rad/s
$\ddot{q}$	Generalised coordinate acceleration	rad/s^2
$\mathbf{q}$	Generalised coordinate position column vector	rad
$\dot{\mathbf{q}}$	Generalised coordinate velocity column vector	rad/s
$\ddot{\mathbf{q}}$	Generalised coordinate acceleration column vector	rad/s^2
r_i	The i-th element of vector $\mathbf{r}$	m
$\mathbf{r}$	External force moment-arm column vector	m
s	MTU activation upper bound	-
$\mathbf{s}$	MTU activation upper bound column vector	-
S_P	Strength capability of a human operator	N
$S_P^{\max}$	Strength upper bound used to limit S_P	N
S_T	Strength requirement of a task	N
τ^M	Muscular joint torque	N.m
$\boldsymbol{\tau}^M$	Muscular joint torque column vector	N.m
$\boldsymbol{\tau}^A$	Active muscular joint torque column vector	N.m
τ_i^P	The i-th element of vector $\boldsymbol{\tau}^P$	N.m
$\boldsymbol{\tau}^P$	Passive muscular joint torque column vector	N.m
τ_i^B	The i-th element of vector $\boldsymbol{\tau}^B$	N.m
$\boldsymbol{\tau}^B$	Dynamic and gravity load torque column vector	N.m
$\boldsymbol{\tau}^G$	Gravity load torque column vector	N.m
$\boldsymbol{\tau}^E$	External load torque column vector	N.m
$\mathbf{u}$	Unit vector representing external force direction	-
V_0^m	MTU fiber maximum contractile velocity	m/s

Abbreviations

AAN	Assistance As Needed
ADL	Activities of Daily Living
CV	Coefficient of Variation
EMG	Electromyography
IAD	Intelligent Assist Device
MM	Musculoskeletal Model
MSD	Musculoskeletal Disorder
MTU	Musculo-Tendon Unit
MVC	Maximum Voluntary Contraction
SM	Strength Model
TM	Task Model

Abstract

A Musculoskeletal Model-based Assistance-As-Needed Paradigm for Assistive Robotics

Robotic systems which operate collaboratively with their human operators to provide assistance are becoming reality, and many different paradigms for administering this assistance have been developed. A promising paradigm is Assistance-As-Needed, which aims to provide physical assistance specific to the individual requirements of the operator. This requires that the needs of the operator be determined, which is challenging as they depend on both the task being performed, and the capability of the operator to perform it. Current solutions use performance-based methods which critique the operator from observations obtained during tasks, and then adapt assistance based on how they performed. This approach has shown success in applications such as robotic rehabilitation. However, empirical performance-based methods have inherent limitations, primarily due to the numerous observations required before the operator's assistance needs can be determined. The ideal Assistance-As-Needed paradigm should be able to determine the operator's assistance requirements without prior observations, and with respect to arbitrary tasks.

This thesis presents a novel Assistance-As-Needed paradigm using models to estimate the assistance needs of the human operator. An optimisation model is developed which utilises a publicly available musculoskeletal model representing the human upper limb to estimate their strength, which is compared to the strength required by the task being performed to gauge their assistance requirements. An advantage of this model-based approach is it allows effects on the operator's assistance requirements due to task and physiological factors to be predicted. Furthermore, it avoids many of the limitations faced by empirical performance-based approaches since it does not require empirical observations. The model-based paradigm is demonstrated and evaluated in a number of simulated tasks involving the upper limb. Calculated upper limb strength is analysed with respect to factors such as the limb position, the direction of force at the hand, and muscular impairment. The calculated strength is shown to predict behaviours similar to those described in the literature. Experimental evaluation is performed by implementing the paradigm on a specially developed robotic exoskeleton to govern the assistance it provides a subject in a number of experimental tasks. The model-based Assistance-As-Needed paradigm is shown to successfully govern assistance towards specific muscles when needed in the tasks performed. Means of improving the paradigm, including methods for fitting the model to the subject, and the inclusion of additional physiological factors in the calculation of their assistance requirements is discussed.