

Contents

Acknowledgments	iii
Abstract	v
Kurzfassung	vii
1 Introduction	1
1.1 Motivation	1
1.2 Literature Review	3
1.2.1 Orthopedic and Neurological Rehabilitation	3
1.2.2 Robot-Assisted Therapy	3
1.2.3 Control Strategies	5
1.3 Aims of This Thesis	7
1.4 Contributions	7
1.5 Outline	8
2 Method	11
2.1 Soft Robotic Rehabilitation Devices	11
2.2 Assistive Control Strategy	14
2.3 Key Features	17
3 Modelling	19
3.1 Dynamic Model of Combined Human-Robot Systems	20
3.2 Mass Flow Characteristics of Pneumatic Servo Valves	21
3.3 Torque Characteristics of Soft Pneumatic REC-Actuators	23
3.4 Inverse Quasi-Static Model of Robots based on Estimated Mass Parameters	25
3.4.1 Estimation of Model Mass Parameters	28
3.4.2 Estimation Procedure	30
3.4.3 Implementation	31
3.5 Mathematical Modelling of Human's Extremities	32
3.5.1 Inverse Quasi-Static Human Model based on Standard Mass Distribution of Human Body	33
3.5.2 Improved Inverse Quasi-Static Human Model based on Estimated Mass Parameters	39
3.5.3 Estimation of Dynamic Human Model Parameters based on Function Approximation	43
	ix

3.6	Discussion and Conclusion	46
4	Assistive Control Concepts	49
4.1	Model-based Pressure and Torque Control	51
4.2	Transparency of Soft-Robots and Soft Robotic Rehabilitation Devices	55
4.3	Assistive Control based on Separated Robot and Human Model (ACSM)	58
4.3.1	Controller Design	59
4.3.2	Lyapunov Stability Analysis	63
4.4	Assistive Control based on Separated Robot and Human Model with Forgetting and Remembering (ACSM+)	65
4.4.1	Controller Design	67
4.4.2	Lyapunov Stability Analysis	68
4.5	Adaptive Assistive Control based on Function Approximation with Forgetting (aACFA)	70
4.5.1	Controller Design	72
4.5.2	Lyapunov Stability Analysis	75
4.6	Discussion and Conclusion	76
5	Simulation Study	79
5.1	Verification of Algorithm to Estimate Robot Model Mass Parameters	79
5.2	Verification of Mass Parameter Estimation for a one DoF Combined Human-Robot System	83
5.3	Verification of Assistive Controllers	86
5.3.1	ACSM	89
5.3.2	ACSM+	94
5.3.3	aACFA	100
5.4	Discussion and Conclusion	104
6	Experimental Study	107
6.1	Performance of Model-based Pressure Controller	108
6.2	Transparency of Soft-Robots	110
6.2.1	Transparent Soft-Robots Interacting with Humans	111
6.2.2	Influence of Inverse Quasi-Static Robot Models on Robust Po- sition Control of Soft-Robots	113
6.3	Verification of ACSM with Assistive Knee and Shoulder Movement Therapy Device	115
6.3.1	Prototypes of Soft Robotic Rehabilitation Devices	116
6.3.2	Experimental Procedure for Verification with Healthy Subjects	118
6.3.3	Reaction of Assistive Controller to Different Subject's Behavior	119
6.3.4	Safety Features for Clinical Study	122
6.3.5	Preliminary Results of Clinical Study in Orthopedic Rehabil- itation and Feedback of Patients	125

6.4	Comparison of Controllers with Assistive Elbow Trainer and Healthy Subjects	128
6.4.1	Prototype of Assistive Elbow Trainer	129
6.4.2	Experimental Procedure	130
6.4.3	ACSM	131
6.4.4	ACSM+	134
6.4.5	aACFA	137
6.5	Discussion and Conclusion	139
7	Conclusions and Outlook	145
7.1	Summary of Contributions	145
7.2	Key Findings	146
7.3	Impact of Assistive Controlled Soft Robotic Rehabilitation Devices on Robot-Assisted Therapy	147
7.4	Future Work	149
	Bibliography	151
	List of Figures	161
	List of Tables	167
	List of Abbreviations	169
	List of Publications	171