

Contents

1	Introduction	1
	References	6
2	State of the Art	7
2.1	Social and Cognitive Human-Robot Interaction	8
2.1.1	Multimodal Communication	9
2.1.2	Expressive Emotion-Based Interaction	9
2.1.3	Social-Cognitive Skills	9
2.2	Physical Human-Robot Interaction	9
2.2.1	Control	10
2.2.2	Human-Friendly Mechanical Design	11
2.2.3	Motion Planning and Obstacle Avoidance	13
2.2.4	Quantifying Human Safety	16
2.3	Robot Safety in Industrial Robotics	18
	References	19
3	Soft-Robotics Control	25
3.1	Robot Dynamics and Modeling	26
3.1.1	Rigid Joint Model	26
3.1.2	Flexible Joint Model	29
3.2	Unified Control for the LWR-III	30
3.2.1	The DLR Lightweight Robot III	30
3.2.2	Control Architecture	31
3.2.3	Implementation in Joint Space	32
3.2.4	Implementation in Cartesian Space	34
3.3	Collision Detection Schemes	35
3.3.1	Energy-Based Detection	36
3.3.2	Direct Derivation Method	37
3.3.3	Derivation from Desired Dynamics	37
3.3.4	Observing Joint Velocity	38
3.3.5	Observing Generalized Momentum	39

3.3.6	Response Behavior of Momentum Observer	42
3.3.7	Comparison of Collision Detection Schemes	42
3.3.8	Practical Remarks	44
3.3.9	Estimating the Contact Wrench	46
3.4	Collision Reaction	47
3.4.1	Reflex like Collision Reaction Schemes	47
3.4.2	Trajectory Scaling	50
3.5	Experiments	56
3.5.1	Energy-Based Collision Detection	56
3.5.2	Balloon Test	57
3.5.3	Human Arm Measurements and Collision Test-Bed	59
3.5.4	Performance Comparison of Reaction Strategies	60
3.5.5	Collisions with the Human Arm and Chest	62
3.5.6	Trajectory Scaling	64
3.6	Summary	65
	References	66
4	Biomechanics and Forensics	69
4.1	Classifying Injury Severity	69
4.1.1	The Abbreviated Injury Scale	70
4.1.2	EuroNCAP	71
4.2	Injury Criteria for the Head	71
4.2.1	Possible Head Injuries and Their Mechanisms	71
4.2.2	The Wayne State Tolerance Curve	73
4.2.3	Rotational Head Acceleration Limits	73
4.2.4	Head Injury Criterion	74
4.2.5	3 ms-Criterion	75
4.2.6	Converting Severity Indices to the Abbreviated Injury Scale	75
4.2.7	GAMBIT	76
4.2.8	Vienna Institute Index	77
4.2.9	Effective Displacement Index	78
4.2.10	Revised Brain Model	78
4.2.11	Maximum Mean Strain Criterion	78
4.2.12	Maximum Power Index	79
4.2.13	The Facial Laceration Criterion	80
4.2.14	Fracture Forces	80
4.3	Injury Criteria for the Neck	82
4.4	Injury Criteria for the Chest	83
4.4.1	Lobdell's Chest Model	83
4.4.2	Force Criterion	84
4.4.3	Acceleration Criterion	84
4.4.4	Compression Criterion	85
4.4.5	Viscous Criterion	86
4.5	Eye Injury	86

References	86
5 Crash-Testing in Robotics	91
5.1 Automobile Crash Testing	93
5.2 Blunt Unconstrained Impacts with the LWR-III	95
5.2.1 Experimental Setup	95
5.2.2 Results for the Head	96
5.2.3 Results for the Neck	98
5.2.4 Results for the Chest	101
5.2.5 Parenthetic Evaluation and Discussion	101
5.2.6 Human-Robot Impacts	105
5.2.7 Influence of Robot Mass and Velocity	107
5.3 Blunt Unconstrained Impacts for General Robots	109
5.3.1 Evaluated Robots	110
5.3.2 Head Injury Criterion and Impact Forces	110
5.4 Constrained Blunt Impacts	114
5.4.1 Types of Blunt Clamping	115
5.4.2 Braking Tests	116
5.4.3 Experimental Results with the LWR-III and KR6	118
5.4.4 Simulations	120
5.5 Constrained Contact with Singularity Forces	124
5.6 Towards a Crash-Testing Protocol	128
5.6.1 Experimental Setup	129
5.6.2 The DLR Crash Report	129
5.6.3 Case Discussions	135
5.7 Summary	143
References	144
6 Sharp and Acute Contact	149
6.1 Soft-Tissue Injury Caused by Sharp Tools	151
6.1.1 Biomechanics of Soft-Tissue Injury	152
6.1.2 The Depth of Vital Organs	153
6.1.3 Braking Distance	155
6.1.4 A Simulation Use-Case with the LWR-III	156
6.2 Experiments	159
6.2.1 Investigated Tools	159
6.2.2 Silicone Block	159
6.2.3 Pig Experiments	160
6.2.4 Human Experiments	168
6.3 Summary	169
References	170

7	Reactive Pre-collision Strategies	171
7.1	Reaction Strategy with Task Preservation	172
7.1.1	Proximity Disturbance Signals	173
7.1.2	Experiment	174
7.2	Reaction Strategy without Task Preservation	175
7.2.1	Algorithm Design	176
7.2.2	Implementation	182
7.2.3	Simulations	186
7.2.4	Experiments	188
7.3	Summary	193
	References	193
8	Towards the Robotic Co-worker	195
8.1	Functional Modes	197
8.2	Interaction Concept	199
8.2.1	Proximity and Task Partition	200
8.2.2	Interaction Layer	200
8.2.3	Absolute Task Preserving Reaction	201
8.2.4	Task Relaxing Reaction	203
8.2.5	Dealing with Physical Collisions	203
8.2.6	Safety Architecture	203
8.3	Interactive Bin Picking	206
8.3.1	Vision Concept	207
8.3.2	Soft-Robotics Control for Grasping	210
8.3.3	Autonomous Task Execution	210
8.3.4	Evaluation of Grasping Success	211
8.3.5	Extension to Interactive Bin-Picking	212
8.4	Summary	214
	References	214
9	Competitive Robotics	217
9.1	Preliminaries	219
9.2	Safety of the Human	221
9.2.1	Physical Interaction in Humanoid Robot Soccer	221
9.2.2	Physical Interaction in Human Soccer	222
9.2.3	Tripping and Getting Tripped Up	222
9.2.4	Trunk and Head Impacts	224
9.2.5	Limb Impacts	225
9.2.6	Being Hit by the Ball	227
9.2.7	Secondary Impacts	227
9.2.8	Further Aspects	228
9.2.9	Injuries from Blunt Impacts with Soft-Tissue	228
9.2.10	Analysis of Elbow Checks	230
9.3	Robot Joint Protection	232
9.3.1	Joint Stiffness and Kicking Force	233

9.3.2	Kicking a Soccer Ball with the VS-Joint	234
9.4	Robot Performance Improvement	238
9.4.1	Kicking in RoboCup	239
9.4.2	Required Joint Velocity	239
9.4.3	Kicking a Ball with an Elastic Joint	240
9.4.4	Optimal Control for Kicking with an Elastic Joint	245
9.5	Summary	248
	References	249
10	Intrinsic Joint Compliance	253
10.1	Intrinsically Compliant Actuation	254
10.2	Design Considerations	255
10.3	Joint Design, Modeling, Identification, and Control	258
10.3.1	Joint Design	259
10.3.2	Torque Characteristics Layout	260
10.3.3	Model of the QA-Joint	262
10.3.4	Joint Identification	264
10.3.5	State Feedback Controller	266
10.4	Basic Optimal Control Theory	267
10.4.1	Optimal Control of Dynamic Systems	267
10.4.2	Singular Control Problems	269
10.4.3	The Maximum Principle of Pontryagin	269
10.4.4	Bounded State Variables	270
10.5	Shooting Methods for Solving MPBVPs	271
10.5.1	Single-Shooting	271
10.5.2	Multiple-Shooting	272
10.6	The Nelder-Mead Simplex-Downhill Algorithm	273
10.7	Performance Increase through Joint Compliance	275
10.7.1	Maximization of Link Velocity	276
10.7.2	Optimal Control for Linear Cases	277
10.7.3	Constrained Deflection	280
10.7.4	Stiffness Adjustment	287
10.7.5	Performance Analysis for the QA-Joint	290
10.8	Compliance as a Cornerstone of Safety?	298
10.8.1	Sharp Contact	299
10.8.2	Blunt Contact	300
10.9	Blunt Impact Dynamics	302
10.9.1	Head Injury Criterion: Simulation	302
10.9.2	Frontal Impact Force	303
10.9.3	Maximum HIC for Compliant Joints	304
10.9.4	Head Injury Criterion: Experiments	307
10.9.5	Joint Protection and Control Performance	308
10.10	Collision Detection for VSA	309
10.10.1	Generalized Link Side Momentum Observer	309
10.10.2	Generalized Joint Momentum Observer	309

10.10.3 Collision Detection and Reaction for the QA-Joint	311
10.10.4 Experimental Collision Detection Performance	312
10.11 Summary	313
References	314
11 Considerations for New Robot Standards	317
11.1 Limitations of Existing Safety Standards	319
11.2 Possible Injuries in Robotics: A Synopsis	321
11.3 Extended Abbreviated Injury Scale	323
11.4 Standard Impacts	325
11.4.1 Standard Impact Phases	325
11.4.2 Standard Dummy Impact Tests	326
11.4.3 Crash-Test Dummies for Robot-Human Impacts	329
11.4.4 Possible Extensions	329
11.5 Impact of the Monograph and Next Steps	330
11.6 Summary	333
References	334
12 Conclusion and Outlook	337
12.1 Conclusion	337
12.2 Outlook	342
References	343
A Braking Tests	345
B Maximum Link Velocity for n_c Motor Cycles	348