CHAPTER 14

CHAPTER 14
Recupera exoskeletons

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Andrik Wöhrlea, Andrik Wöhrlea, Andrik Wöhrlea, A. Kirchner**
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[|], Elsa A. Kirchner^c,
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Bremen, Germany
^bWorking Grou** Martin Mallwitz^{a,e}, Michael Maurus^{a,e}, Shivesh Kumar^a,
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Henning Wiedemann^b, Heiner Pete
Kartik Chari^a, Ibrahim Tijjani^a, and
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^dInstitute of Communication Technology, Dortmund Uni For the development of exoskeletons as an active external support structure of Medical Technology Systems, University of Duisburg-Essen, Duisburg, Germany
^dInstitute of Communication Technology, Dortmund University of Ap ^dInstitute of Communication Technology, Dortmund University of Applied Sciences and Arts,
Dortmund, Germany
14.1 Introduction
The development of exoskeletons as an active external support structure
for the human body h **14.1 Introduction**
The development of exoskeletons as an active external support structure
for the human body has made significant progress in recent decades thanks
to miniaturization and digitalization. The decisive fact **14.1 Introduction**
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for the human body has made significant progress in recent do
to miniaturization and digitalization. The decisive factor fc
and handling is mechanical transparency 14.1.1 Motivation for series-parallel hybrid design
Building a robotic support structure and handling is mechanical transparency [1] for the user, in the sense of
perceived restriction of movement. This applies to the appl and handling is mechanical transparency [1] for the user, in the sense of
perceived restriction of movement. This applies to the application of the
exoskeleton as a power assistance, as an input device for remote control o

perceived restriction of movement. This applies to the application of the exoskeleton as a power assistance, as an input device for remote control or as a robotic rehabilitation device $[2]$.
 14.1.1 Motivation for serie Exoskeleton as a power assistance, as an input device for remote control or
as a robotic rehabilitation device [2].
14.1.1 Motivation for series-parallel hybrid design
Building a robotic support structure around humans, as a robotic rehabilitation device [2].
 14.1.1 Motivation for series-parallel hybrid design

Building a robotic support structure around humans, which is not perceived

as restrictive, places high demands on the ergonom **14.1.1 Motivation for series-parallel hybrid design**
Building a robotic support structure around humans, which is not perceived
as restrictive, places high demands on the ergonomics of the kinematic
setup. Human joints ar **14.1.1 Motivation for series-parallel hybrid design**
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setup. Human joints ar Building a robotic support structure around humans, which is not perceived
as restrictive, places high demands on the ergonomics of the kinematic
setup. Human joints are complex structures in terms of their mobility and
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as restrictive, places high demands on the ergonomics of the kinematic
setup. Human joints are complex structures in terms of their mobility and
can as restrictive, piaces ingli demiants on the eigonomics of the Kinematic
setup. Human joints are complex structures in terms of their mobility and
can often only be approximated with rigid mechanics by combinations of
rota betup. Thunan Joints are complex structures in terms of their moonity and
can often only be approximated with rigid mechanics by combinations of
rotational and linear joints. In addition to the bony skeletal structure, the during motion. The use of parallel kinematics can separate the main pivot ended the main pivot of carrillage, capsules, tendons, ligaments and muscles. In order to adequately represent the shoulder joint, at least three, p tional mechanical joints have to be combined. The joint axes often cannot
be mapped directly, since the construction space is limited by the human
body. Collisions of the mechanics with the human body must be prevented
dur The joint axes often cannot

ce is limited by the human

an body must be prevented

can separate the main pivot

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aining, and Fuction space is limited by the human
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data mining, AI training, and similar technolog uction space is limited by the human
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Biologically Inspired Series-Parallel Hybrid Robots
point of a mechanism from the drive axis, thus making optimum use of the
installation space. At the same time, the movement can be restricted in a
defined way. This is ac Biologically Inspired Series-Parallel Hybrid Robots
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installation space. At the same time, the movement can be restricted in a
defined way. point of a mechanism from the drive axis, thus making optimum use of the installation space. At the same time, the movement can be restricted in a defined way. This is achieved by positively guided movement of numerous lin point of a mechanism from the drive axis, thus making optimum use of the
installation space. At the same time, the movement can be restricted in a
defined way. This is achieved by positively guided movement of numerous
lin point of a incenanism non the drive axis, thus maxing optimum use of the
installation space. At the same time, the movement can be restricted in a
defined way. This is achieved by positively guided movement of numerous
lin Instantion space. The time same time, the movement can be restricted in a
defined way. This is achieved by positively guided movement of numerous
links of the mechanism. The advantages of parallel kinematics include more
f defined way. This is achieved by positively guided movement of numerous
links of the mechanism. The advantages of parallel kinematics include more
freedom for installing the actuators, high stiffness and a good dynamic bemixs of the inechainshit. The advantages of paraner Kinematics include
freedom for installing the actuators, high stiffness and a good dynan
havior, but it increases the number of moving components and the
in modeling and be justified. A combination of serial and parallel kinematics in many cases
leads to very good overall results in terms of motion space, force trans-
mission and installation space. This design philosophy forms the basis o Stroke rehabilitation space. This design philosophy forms the basis of
RECUPERA exoskeletons, as shown in Fig. 14.1.
14.1.2 Application scenarios
The RECUPERA exoskeletons were developed as a training device for
stroke r

The ECUPERA exoskeletons, as shown in Fig. 14.1.
 14.1.2 Application scenarios

The RECUPERA exoskeletons were developed as a

stroke rehabilitation [3] and modified for the purpose
 14.1.2.1 Rehabilitation scenario

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14.1.2 Application scenarios
The RECUPERA exoskeletons were developed as a training device for
stroke rehabilitation [3] and modified for the purpose of teleoperation.
14.1.2.1 Rehabilitation scenario
Exoskeletons and **14.1.2 Application scenarios**
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stroke rehabilitation [3] and modified for the purpose of teleoperation.
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stroke rehabilitation [3] and modified for the purpose of teleoperation.
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Exoskeletons and here especially active exoskele The Testoch Ethni chosenceons were developed as a training device for
stroke rehabilitation [3] and modified for the purpose of teleoperation.
14.1.2.1 Rehabilitation scenario
Exoskeletons and here especially active exos **14.1.2.1 Rehabilitation scenario**
Exoskeletons and here especially active exoskeletons can be used for the
rehabilitation of patients, e.g., after a stroke [4]. Compared to the use of
exoskeletons for the compensation of **14.1.2.1 Rehabilitation scenario**
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rehabilitation of patients, e.g., after a stroke [4]. Compared to the use of
exoskeletons for the compensation of Exoskeletons and here especially active exoskeletons can be used for the
rehabilitation of patients, e.g., after a stroke [4]. Compared to the use of
exoskeletons for the compensation of paralysis, especially after spinal Exosketetons and nete especially active exosketetons can be used for the
rehabilitation of patients, e.g., after a stroke [4]. Compared to the use of
exoskeletons for the compensation of paralysis, especially after spinal exoskeletons for the compensation of paralysis, espedamage, this application is not yet very well establishes
ome studies showing that robot-assisted rehabilitation
[5]. Active exoskeletons are able to introduce forces if
 damage, this application is not yet very well establishe
some studies showing that robot-assisted rehabilitatic
[5]. Active exoskeletons are able to introduce forces is
and thus support them in their movements or make
firs [5]. Active exoskeletons are able to introduce forces into the patient's body
[5]. Active exoskeletons are able to introduce forces into the patient's body
and thus support them in their movements or make them possible in

For the remoted in the remoted to the specific requirements of the patients soury
and thus support them in their movements or make them possible in the
first place. The support adapted to the specific requirements of the **Stand telection** and the remoted the specific requirements of the patient
first place. The support adapted to the specific requirements of the patient
is called assist as needed [6].
14.1.2.2 Teleoperation scenario
Exo **14.1.2.2 Teleoperation scenario**
 14.1.2.2 Teleoperation scenario
 Exoskeletons can also be applied for teleoperation. Teleoperation in general

means the remote control of a robotic system [7,8]. In our case, we und **14.1.2.2 Teleoperation scenario**
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stand teleoperation as the remote c **14.1.2.2 Teleoperation scenario**
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stand teleoperation as the remote co Exoskeletons can also be applied for teleoperation. Teleoperation in general
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stand teleoperation as the remote control of a robotic system equipped Exosketetons can asso be applied for teteoperation. Teteoperation in generation
means the remote control of a robotic system (7,8). In our case, we under-
stand teleoperation as the remote control of a robotic system equip ation of a humanoid of a humanoid of a humanoid of a relation control of a relation system equipped with one or two manipulators. Teleoperation can be a very useful tool when an on-site presence is either too expensive (e stand eccoperation as the remote control of a fobotic system equipped with
one or two manipulators. Teleoperation can be a very useful tool when an
on-site presence is either too expensive (e.g., space exploration missions

(a) Upper-body system

(b) Full-body system

Figure 14.1 The RECUPERA upper-body exoskeleton is a part system of the full-

body exoskeleton mounted on wheelchair.

mapping of the workspaces of the two different systems. A (a) Upper-body system
 Figure 14.1 The RECUPERA upper-body exoskeleton is a part system of the full-

body exoskeleton mounted on wheelchair.

mapping of the workspaces of the two different systems. Active exoskele-

ton Figure 14.1 The RECUPERA upper-body exoskeleton is a part system of the full-
body exoskeleton mounted on wheelchair.
mapping of the workspaces of the two different systems. Active exoskele-
tons also have the advantage o Figure 14.1 The RECOPERA upper-body exoskeletion is a part system of the fun-
body exoskeleton mounted on wheelchair.
mapping of the workspaces of the two different systems. Active exoskele-
tons also have the advantage of mapping of the workspaces of the two different systems. Active exoskeletons also have the advantage of being a haptic interface [9]. This means that it is possible to give force feedback to the operator from forces occurri tons also have the advantage of being a haptic interface [9]. This means that
it is possible to give force feedback to the operator from forces occurring in
the controlled target system and measured at force-torque sensors

Organization

it is possible to give force feedback to the operator from forces occurring in
the controlled target system and measured at force-torque sensors in order
to provide better support, especially for remote manipulation tasks. the controlled target system and measured at force-torque sensors in order
to provide better support, especially for remote manipulation tasks.
Organization
In this chapter, we present the RECUPERA full-body exoskeleton an to provide better support, especially for remote manipulation tasks.

Organization

In this chapter, we present the RECUPERA full-body exoskeleton and the

RECUPERA upper-body exoskeleton subsystem. Section 14.2 describes
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RECUPERA upper-body exoskeleton subsystem. Section 14.2 describes
the mechatronic components and explains the modular concept in terms of
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 In this chapter, we present the RECUPERA full-body exoskeleton and the RECUPERA upper-body exoskeleton subsystem. Section 14.2 describes the mechatronic components and explains the modular concept in terms of mechanical su RECUPERA upper-body exoskeleton subsystem. Section 14.2 describes
the mechatronic components and explains the modular concept in terms of
mechanical sub-mechanisms and decentralized control units. Section 14.3
details the Section 14.5.

308 Biologically Inspired Series-Parallel Hybrid Robots
14.2 Mechatronic system design
The RECUPERA exoskeleton was developed in order to pro Biologically Inspired Series-Parallel Hybrid Robots
 14.2 Mechatronic system design

The RECUPERA exoskeleton was developed in order to provide a support

and training device for stroke patients. In cooperation with a me Biologically Inspired Series-Parallel Hybrid Robots
 14.2 Mechatronic system design

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and training device for stroke patients. In cooperation with a medical de-

vice manufacturer, the general requirement **14.2 Mechatronic system design**
The RECUPERA exoskeleton was developed in order to provide a support
and training device for stroke patients. In cooperation with a medical de-
vice manufacturer, the general requirements f **TA.2 Mechatronic system design**
The RECUPERA exoskeleton was developed in order to provide a suppor
and training device for stroke patients. In cooperation with a medical de
vice manufacturer, the general requirements for EXECUPERA exoskeleton was developed in order to provide a support

training device for stroke patients. In cooperation with a medical de-

Emanufacturer, the general requirements for actuation, range of motion

DM), degree and training device for stroke patients. In cooperation with a medical de-
vice manufacturer, the general requirements for actuation, range of motion
(ROM), degrees of freedom (DOF), safety and application scenario were
de

vice manufacturer, the general requirements for actuation, range of motion (ROM), degrees of freedom (DOF), safety and application scenario were defined. The exoskeleton was designed as a safe, lightweight and modular syst (ROM), degrees of freedom (DOF), safety and application scenario were
defined. The exoskeleton was designed as a safe, lightweight and modular
system in both the mechanical and electrical sense.
Two configurations were bui defined. The exoskeleton was designed
system in both the mechanical and electr
Two configurations were built to be a
cation both in sitting and standing positic
the arm structure and is mounted on a
full-body system with a em in both the mechanical and electrical sense.
Two configurations were built to be able to perform the training appli-
on both in sitting and standing position. The first configuration includes
arm structure and is mounte Two configurations were built to be able to perform the training application both in sitting and standing position. The first configuration includes
the arm structure and is mounted on a wheelchair, while the second is a
f

cation both in sitting and standing position. The first configuration includes
the arm structure and is mounted on a wheelchair, while the second is a
full-body system with active hip, knee, ankle, and spine to support its the arm structure and is mounted on a wheelchair, while the second is a
full-body system with active hip, knee, ankle, and spine to support its own
weight (see Fig. 14.1).
The RECUPERA exoskeleton is also used to remotely full-body system with active hip, knee, ankle, and spine to support its own
weight (see Fig. 14.1).
The RECUPERA exoskeleton is also used to remotely control another
robot. The target system is the humanoid robot RH5 MANUS weight (see Fig. 14.1).
The RECUPERA exoskeleton is also used to re
robot. The target system is the humanoid robot RF
was designed to support a human in assembly tasks.
gripping tasks of objects designed for humans. Th
not The RECUPERA exoskeleton is also used to remotely control another
ot. The target system is the humanoid robot RH5 MANUS [10], which
designed to support a human in assembly tasks. This includes complex
pping tasks of object robot. The target system is the humanoid robot RH5 MANUS [10], which
was designed to support a human in assembly tasks. This includes complex
gripping tasks of objects designed for humans. The requirements change
noticeabl was designed to support a human in assembly tasks. This includes complex
gripping tasks of objects designed for humans. The requirements change
noticeably due to the new application, where an input device for grasping
with

noticeably due to the new application, where an in
with force feedback is needed.
The main changes are the addition of the wrist:
larger torques and forces acting on the human and
possibilities for fine manipulation with t with force feedback is needed.

The main changes are the addition of the wrists with two active DOF,

larger torques and forces acting on the human and robotic arms, and new

possibilities for fine manipulation with the hu

The main changes are the addition of the wrists with two active DOF,
larger torques and forces acting on the human and robotic arms, and new
possibilities for fine manipulation with the human hand.
14.2.1 Mechanical desig larger torques and forces acting on the human and robotic arms, and new
possibilities for fine manipulation with the human hand.
14.2.1 Mechanical design
In order to adapt the exoskeleton to the needs and movement spaces possibilities for fine manipulation with the human hand.
 14.2.1 Mechanical design

In order to adapt the exoskeleton to the needs and movement spaces of

humans, serial and parallel kinematics were combined and equipped **14.2.1 Mechanical design**
In order to adapt the exoskeleton to the needs and movement spaces of
humans, serial and parallel kinematics were combined and equipped with
the institute's own drives. The system is thus a modul **14.2.1 Mechanical design**
In order to adapt the exoskeleton to the needs and movement spachtumans, serial and parallel kinematics were combined and equippe
the institute's own drives. The system is thus a modular serial-p In order to datapt the enconcretedn to
humans, serial and parallel kinematics
the institute's own drives. The system
brid robot with numerous adaptation
presented below. Fig. 14.2 gives an ove
used actuators, as Table 14.1 the institute's own drives. The system is thus a modular serial-parallel hy-
brid robot with numerous adaptation options, components of which are
presented below. Fig. 14.2 gives an overview about sub-mechanisms and its
us

brid robot with numerous adaptation options, components of which are
presented below. Fig. 14.2 gives an overview about sub-mechanisms and its
used actuators, as Table 14.1 shows the ROM.
14.2.1.1 Actuators
Due to the la presented below. Fig. 14.2 gives an overview about sub-mechanisms and its
used actuators, as Table 14.1 shows the ROM.
14.2.1.1 Actuators
Due to the lack of suitable commercial offers, DFKI has developed its own
drives f used actuators, as Table 14.1 shows the ROM.
 14.2.1.1 Actuators

Due to the lack of suitable commercial offers, DFKI has developed its own

drives for the robotic systems for a torque range of 3 Nm to 500 Nm (in

case o **14.2.1.1 Actuators**
Due to the lack of suitable commercial offers, DFKI has developed its own
drives for the robotic systems for a torque range of 3 Nm to 500 Nm (in
case of rotary drives) or force range of 1 kN to 5 kN (

Figure 14.2 CAD overview of the robotic
green are part of both systems, compone
sively to the full-body exoskeleton.
DFKI rotative drives
The arms and ankles, as depicted in Fig **Figure 14.2** CAD overview of the robotic systems. Components marked in green are part of both systems, components marked in blue belong exclusively to the full-body exoskeleton.
DFKI rotative drives
The arms and ankles, a

Example 14.2 CAD overview of the fobotic systems. Components marked in
green are part of both systems, components marked in blue belong exclu-
sively to the full-body exoskeleton.
DFKI rotative drives
The arms and ankles, green are part of both systems, components manked in blue belong exert
sively to the full-body exoskeleton.
DFKI rotative drives
The arms and ankles, as depicted in Fig. 14.2, are equipped with drives
consisting of a combi DFKI rotative drives
The arms and ankles, as depicted in Fig. 14.2, are equipped with drives
consisting of a combination of a BLDC installation kit from TQ-SYSTEMS
and a HARMONICDRIVE gearbox. This provides a high-power de DFKI rotative drives
The arms and ankles, as depicted in Fig. 14.2, are equipped with drives
consisting of a combination of a BLDC installation kit from TQ-SYSTEMS
and a HARMONICDRIVE gearbox. This provides a high power de DFKI rotative drives
The arms and ankles, as depicted in Fig. 14.2, are equipped with
consisting of a combination of a BLDC installation kit from TQ-SY
and a HARMONICDRIVE gearbox. This provides a high power
and low backla The arms and ankies, as depieted in T
consisting of a combination of a BLDC
and a HARMONICDRIVE gearbox. T
and low backlash (< 1 arcmin) drive uni
position sensors MU from iC-HAUS a
and the detection of the absolute joint and a HARMONICDRIVE gearbox. This provides a high power density
and low backlash (< 1 arcmin) drive unit. Magnetic off-axis high-resolution
position sensors MU from iC-HAUS are used for the rotor commutation
and the detect

and low backlash (\lt 1 arcmin) drive unit. Magnetic off-axis high-resolution
position sensors MU from iC-HAUS are used for the rotor commutation
and the detection of the absolute joint position.
DFKI linear drives
These position sensors MU from iC-HAUS are used for the rotor commutation
and the detection of the absolute joint position.
DFKI linear drives
These drives essentially consist of a combination of a TQ-SYSTEMS BLDC
motor and a ba spindles in combination.

Spin different position.

Spin different position of a TQ-SYSTEMS BLDC

motor and a ball screw. The motor directly drives the nut of the ball screw.

The spindle itself is stationary, which is par DFKI linear drives
These drives essentially consist of a combination of a TQ-SYSTEMS BLDC
motor and a ball screw. The motor directly drives the nut of the ball screw.
The spindle itself is stationary, which is particularly DFKI linear drives
These drives essentially consist of a combination of a TQ-SYSTEMS BLDC
motor and a ball screw. The motor directly drives the nut of the ball screw.
The spindle itself is stationary, which is particularly These drives essentially consist of a combination of a TQ-SYSTEMS BLDC motor and a ball screw. The motor directly drives the nut of the ball screw. The spindle itself is stationary, which is particularly advantageous for motor and a ball screw. The motor directly drives the nut of the Γ The spindle itself is stationary, which is particularly advantageous spindles in combination with high speeds. The commutation as mental measurement is

Overview of range of motion. Table 14.1						
Body part	Motor	Movement	Range			
		Abduction / Adduction	-87° to 40°			
Shoulder	RD 50x8	Ext. Rotation / Int. Rotation	-40° to 75°			
		Flexion / Extension	-170° to 30°			
Elbow	RD 50x8	Flexion	0° to 145°			
Forearm	DY XH540W	Pronation / Supination	-88° to 88°			
DY XH430W Wrist		Palmar Flexion / -43° to 43° Dorsiflexion				
		Radial abduction / Ulnar add.	-20° to 40°			
		Forward / Backward	-0.143 m to 0.122 m			
		Left / Right	-0.153 m to 0.153 m			
Spine	RD 38x8	Up / Down	-0.056 m to 0.057 m			
		Flexion / Extension	-33° to 33.5°			
		Lateral Bending	-33° to 33°			
		Rotation	-87° to 87°			
		Flexion / Extension	-20° to 37°			
Hip	RD 70x10	Adduction / Abduction	-15° to 35°			
		Lateral Rotation / Medial Rot.	-20° to 37°			
Leg	RD 38x12	Up / Down	0.46 m to 0.71 m			
Ankle	RD $50x8$	Dorsi Flexion / Plantar Flexion	-20° to 37°			
		Eversion / Inversion	-15° to 35°			
		Adduction / Abduction	-20° to 37°			

Eversion / Inversion and the 15° to 35°
 Experiment Adduction and Adduction and Adduction and and and and in the wrist. They consist of a BLDC motor

combined with a spur gear and are equipped with their own electronics
 Commercial servos

Commercial servos

DYNAMIXEL-X servo drives from ROBOTIS are used in the forearm for

pronation and supination and in the wrist. They consist of a BLDC motor

combined with a spur gear and are equipped w Commercial servos
DYNAMIXEL-X servo drives from ROBOTIS are used in the forearm for
pronation and supination and in the wrist. They consist of a BLDC motor
combined with a spur gear and are equipped with their own electron Commercial servos
DYNAMIXEL-X servo drives from ROBOTIS are used in the
pronation and supination and in the wrist. They consist of a BI
combined with a spur gear and are equipped with their own
including a position sensor. DYNAMIXEL-X servo drives from ROBOTIS are used
pronation and supination and in the wrist. They consist
combined with a spur gear and are equipped with the
including a position sensor. MKS-DS95 model servo dr
the hand inter pronation and supination and in the wrist. They consist of a BLDC motor
combined with a spur gear and are equipped with their own electronics
including a position sensor. MKS-DS95 model servo drives are installed in
the ha combined with a spur gear and are equipped with their own electronics
including a position sensor. MKS-DS95 model servo drives are installed in
the hand interface and actuate the fingers.
14.2.1.2 Sub-mechanism modules
Dep

including a position sensor. MKS-DS95 model servo drives are installed in
the hand interface and actuate the fingers.
14.2.1.2 Sub-mechanism modules
Depending on the function and range of movement in the overall system,

Recupera exoskeletons 311

Table 14.2 Overview of used actuators with following abbreviations: TQ-

SYSTEMS ROBODRIVE(RD), HARMONICDRIVE (HD), Muliturn (MT), rotative (rot),

linear (lin), ROBOTIS DYNAMIXEL (DY) Recupera exoskeletons 311

SYSTEMS ROBODRIVE(RD), HARMONICDRIVE (HD), Muliturn (MT), rotative (rot),

SYSTEMS ROBODRIVE(RD), HARMONICDRIVE (HD), Muliturn (MT), rotative (rot),

linear (lin), ROBOTIS DYNAMIXEL (DY).

Motor **Table 14.2** Overview of used actuators w
SYSTEMS ROBODRIVE(RD), HARMONICDRIVE (
linear (lin), ROBOTIS DYNAMIXEL (DY).
Motor **Type Gear To** Recupera exoskeletons 311
 Table 14.2 Overview of used actuators with following abbreviations: TQ-

SYSTEMS ROBODRIVE(RD), HARMONICDRIVE (HD), Muliturn (MT), rotative (rot),

linear (lin), ROBOTIS DYNAMIXEL (DY).
 Motor

linear (lin), ROBOTIS DYNAMIXEL (DY). Motor	Type	Gear	Torque	Max Speed	ROM
RD 50x8	rot	HD CPL14A- 50/100:1	18/28 Nm	700/350°/s	MT
RD 70x10	rot	HD CPL25-160:1	92 Nm	$132\degree$ /s	MT
DY XH540W	rot	152.3:1	7.1 Nm	420°/s	MT
DY XH430W	rot	353.5:1	3.4 Nm	180°/s	MT
MKS-DS95	rot	Metal Gear	0.3 Nm	1132°/s	360°
RD 38x12	lin	Ballscrew FBR 8x2	570 N	266 mm/s	130 mm
RD 38x12	lin	Ballscrew FGR 8x2	570 N	266 mm/s	420 mm

RD 38x12 $\begin{array}{|l|l|} \hline \text{Bulscrew FGR} & 570 \text{ N} & 266 \text{ mm/s} & 420 \text{ mm} \\ \hline 8x2 & 266 \text{ mm/s} & 420 \text{ mm} \\ \hline \end{array}$

Shoulder mechanism

The human shoulder joint is a complex structure that allows a very high degree of mobility in s RD 38x12 $\begin{array}{|l|l|} \hline \text{Ballscrew FGR} & 5/0 \text{ N} & 266 \text{ mm/s} & 420 \text{ mm} \ \hline \text{8x2} & \text{8x2} & \text{9x2} & \text{10x} \ \hline \end{array}$

Shoulder mechanism

The human shoulder joint is a complex structure that allows a very high

degree of mobili Shoulder mechanism
The human shoulder joint is a complex structure that allows a very high
degree of mobility in six DOF. The RECUPERA shoulder mechanism sim-
plifies this joint into a ball-and-socket joint that allows ro Shoulder mechanism
The human shoulder joint is a complex structure that allows a very high
degree of mobility in six DOF. The RECUPERA shoulder mechanism sim-
plifies this joint into a ball-and-socket joint that allows rot Shoulder mechanism
The human shoulder joint is a complex structure that allows a very high
degree of mobility in six DOF. The RECUPERA shoulder mechanism sim-
plifies this joint into a ball-and-socket joint that allows rot The human shoulder joint is a complex structure that allows a very high degree of mobility in six DOF. The RECUPERA shoulder mechanism simplifies this joint into a ball-and-socket joint that allows rotation in three axes, The final shoulder joint is a complex structure that allows a very high
degree of mobility in six DOF. The RECUPERA shoulder mechanism sim-
plifies this joint into a ball-and-socket joint that allows rotation in three
axes the second for internal and external rotation and the third areas of the the second
plifies this joint into a ball-and-socket joint that allows rotation in three
axes, as depicted in Fig. 14.3a. This is an almost exact rep pintes this joint into a ban-and-socket joint that allows fotation in three
axes, as depicted in Fig. 14.3a. This is an almost exact replica of the human
shoulder joint, as the connection to the exoskeleton is not rigid an axes, as depicted in Fig. 14.3a. This is an amost exact replica of the infinian
shoulder joint, as the connection to the exoskeleton is not rigid and thus
compensates for missing translational movements. It consists of a s shoulder joint, as the connection to the exoskereon is not right and thus
compensates for missing translational movements. It consists of a serially-
connected chain of joints, the middle joint of which is a parallel-guide compensates for missing translational movements. It consists or a serially-
connected chain of joints, the middle joint of which is a parallel-guided
mechanism. The first joint in the chain allows for abduction and adducti connected chain of Joins, the finder Joint of winter is a paranei-guided mechanism. The first joint in the chain allows for abduction and adduction, the second for internal and external rotation and the third for anteversi rotation. The inst follow in the chain allows for abduction and addition, the second for internal and external rotation and the third for anteversion and retroversion of the arm. All three joints are arranged so that their the second for internal and external fotation and the time for an
and retroversion of the arm. All three joints are arranged so that th
rotation intersect in the shoulder of the user. In order to increase
of movement and t rotation intersect in the shoulder of the
of movement and to avoid a collision v
joint is designed as a planar six-bar doul
allows the drive to be placed outwards
rotation. Two coupling joints are fixed
end-effector rotate The forearm mechanism has been extended by two active DOF in the wrist
sallows the drive to be placed outwards without having the same axis of
rotation. Two coupling joints are fixed to the back structure so that the
end-e allows the drive to be placed outwards without having the same axis of rotation. Two coupling joints are fixed to the back structure so that the end-effector rotates around an ideal point.
Elbow and forearm
The forearm mec

frontation. Two coupling joints are fixed to the back structure so that the end-effector rotates around an ideal point.
Elbow and forearm
The forearm mechanism has been extended by two active DOF in the wrist
and the torqu

Figure 14.3 Sub-mechanism modules.

Figure 14.3 Sub-mechanism modules.

duction gear. The pronation and supination of the forearm is enabled by a

parallel coupling gear inspired by the Harmony exoskeleton [11]. Fig. 14.3b (c) Active Spine with Electronic Box (d) Hip, Knee and Ankle Mechanism
 Figure 14.3 Sub-mechanism modules.

duction gear. The pronation and supination of the forearm is enabled by a

parallel coupling gear inspired by th Figure 14.3 Sub-mechanism modules.

duction gear. The pronation and supination of the forearm is enabled by a

parallel coupling gear inspired by the Harmony exoskeleton [11]. Fig. 14.3b

shows the entire forearm and the d Figure 14.3 Sub-mechanism modules.
duction gear. The pronation and supination of the forearm is enabled by a
parallel coupling gear inspired by the Harmony exoskeleton [11]. Fig. 14.3b
shows the entire forearm and the deta duction gear. The pronation and supination of the forearm is enabled by a
parallel coupling gear inspired by the Harmony exoskeleton [11]. Fig. 14.3b
shows the entire forearm and the detailed kinematics of the forearm is d duction gear. The pronation and supination of the forearm is enabled by a
parallel coupling gear inspired by the Harmony exoskeleton [11]. Fig. 14.3b
shows the entire forearm and the detailed kinematics of the forearm is d duction gear. The pronation and supmation of the forearm is enabled by a
parallel coupling gear inspired by the Harmony exoskeleton [11]. Fig. 14.3b
shows the entire forearm and the detailed kinematics of the forearm is de paraller coupling gear inspired by the Frammony exosketion [11]. Fig. 14.56
shows the entire forearm and the detailed kinematics of the forearm is de-
picted in Fig. 14.6. At the lower lever of the parallelogram, the driv shows the entire forearm and the detailed Kinematos of the forearm is de-
picted in Fig. 14.6. At the lower lever of the parallelogram, the drive turns
the entire mechanism. In the process, the left toothed belt pulley is preced in Fig. 14.0. At the lower lever of the parallelogram, the dive turns
the entire mechanism. In the process, the left toothed belt pulley is also
rotated and the rotation is transmitted to the output by means of a to

Recupera exoskeletons 313
joints of the wrist are arranged as a serial chain. The first joint allows radial
abduction and ulnar adduction, the second palmar flexion and dorsiflex-Recupera exoskeletons 313
joints of the wrist are arranged as a serial chain. The first joint allows radial
abduction and ulnar adduction, the second palmar flexion and dorsiflex-
ion. ion. joints of the wrist are arranged as a
abduction and ulnar adduction, the
ion.
Hand interface
The rehabilitation hand interface ioints of the wrist are arranged as a serial chain. The first joint allows radial
abduction and ulnar adduction, the second palmar flexion and dorsiflex-
ion.
Hand interface
The rehabilitation hand interface is designed as

is joints of the wrist are arranged as a serial chain. The first joint allows radial
abduction and ulnar adduction, the second palmar flexion and dorsiflex-
ion.
Hand interface
The rehabilitation hand interface is designed The mechanism is driven by an MKS-DS95 servo with 0.3 Nm and consideration.
The rehabilitation hand interface is designed as a curve guided coupling
mechanism with one DOF and an end-effector movement range of 90°.
The mec abuted of and uniar addition, the second pannar fickion and dorsinex-
ion.
Hand interface
The rehabilitation hand interface is designed as a curve guided coupling
mechanism with one DOF and an end-effector movement range o Figure 1.1 Hand interface
The rehabilitation hand interface is designed as a curve guided coupling
mechanism with one DOF and an end-effector movement range of 90°.
The mechanism is driven by an MKS-DS95 servo with 0.3 Nm Hand interface
The rehabilitation hand interface is designed
anism with one DOF and an end-6
The mechanism is driven by an MKS-D
apply a maximum gripping force of 5 N.
sensor is connected between the gear and
the gripping Example interface is designed as a curve guided coupling
chanism with one DOF and an end-effector movement range of 90°.

Examedanism is driven by an MKS-DS95 servo with 0.3 Nm and can

ly a maximum gripping force of 5 N. The renabilitation hand interface is designed as a curve guided coupling
mechanism with one DOF and an end-effector movement range of 90°.
The mechanism is driven by an MKS-DS95 servo with 0.3 Nm and can
apply a maximum gr mechanism with one DOF and an end-effector movement range of 90°.
The mechanism is driven by an MKS-DS95 servo with 0.3 Nm and can
apply a maximum gripping force of 5 N. A HONEYWELL FSG15N force
sensor is connected between

The mechanism is driven by an MKS-DS95 servo with 0.5 happly a maximum gripping force of 5 N. A HONEYWELL FSC sensor is connected between the gear and the output and is use the gripping force.
The teleoperation hand interf Iy a maximum gripping force of 5 N. A HONEYWELL FSG15IN force
sor is connected between the gear and the output and is used to control
gripping force.
The teleoperation hand interface (see Fig. 14.3b) was designed to enable sensor is connected between the gear and the output and is used to control
the gripping force.
The teleoperation hand interface (see Fig. 14.3b) was designed to enable
an operator to remotely control a robot, with a focus

the gripping torce.

The teleoperation hand interface (see Fig. 14.3b) was designed to enable

an operator to remotely control a robot, with a focus on grasping tasks. For

this, it features three surfaces with force feedb I ne teleoperation hand interface (see Fig. 14.5b) was designed to enable
an operator to remotely control a robot, with a focus on grasping tasks. For
this, it features three surfaces with force feedback to create the sens an operator to remotely control a robot, with a focus on grasping tasks. For
this, it features three surfaces with force feedback to create the sensation of
grasping an object via a surrogate motion.
The surfaces are mount this, it teatures three surfaces with force feedback to create the sensation of
grasping an object via a surrogate motion.
The surfaces are mounted on linear sliders with a stroke of 20 mm and
are driven by an MKS-DS95 ser grasping an object via a surrogate motion.

The surfaces are mounted on linear sliders with a stroke of 20 mm and

are driven by an MKS-DS95 servo motor each. The resistive force, applied

by the operator's fingers, is mea The surfaces are mounted on linear sliders with a stroke of 20 mm and
are driven by an MKS-DS95 servo motor each. The resistive force, applied
by the operator's fingers, is measured by HONEYWELL FSG15N force sen-
sors. One are driven by an MKS-DS95 servo motor each. The resistive force, appli
by the operator's fingers, is measured by HONEYWELL FSG15N force se
sors. One slider corresponds to the index finger, one to the thumb and to
to middle In a operator's tingers, is measured by HONEYWELL FSG15IN force sen-

I. One slider corresponds to the index finger, one to the thumb and one

middle, ring and little finger. This allocation was chosen since in many

s, th sors. One slider corresponds to the index tinger, one to the thumb and one
to middle, ring and little finger. This allocation was chosen since in many
tasks, the last three fingers are often used together, whereas thumb an to middle, ring and little finger. I his allocation was chosen since in many tasks, the last three fingers are often used together, whereas thumb and in-
dex finger are used more individually. Since the sliders are driven

tasks, the last three tingers are often used together, whereas thumb and in-
dex finger are used more individually. Since the sliders are driven by the
servos via levers, the maximum feedback force is not constant througho servos via levers, the maximum te
the ROM, but varies between 141
In addition to the sliders with
features two buttons, a joystick wi
gency stop. The hand interface is e
rest to assist the operator in keepir
Torso structur In addition to the sliders with gripping surfaces, each hand interface
features two buttons, a joystick with integrated push button and an emer-
gency stop. The hand interface is ergonomically shaped and provides a hand
re

In addition to the sidels with gripping surfaces, cach hand interface
features two buttons, a joystick with integrated push button and an emer-
gency stop. The hand interface is ergonomically shaped and provides a hand
res reatures two buttons, a joystick with integrated push button and an emer-
gency stop. The hand interface is ergonomically shaped and provides a hand
rest to assist the operator in keeping a relaxed hand posture.
Torso stru rest to assist the operator in keeping a relaxed hand posture.
Torso structure
The torso design utilizes the advantages of a parallel kinematic machine
in terms of the force-to-weight ratio and the inherent limitation of t Torso structure
Torso structure
The torso design utilizes the advantages of a parallel kinematic machine
in terms of the force-to-weight ratio and the inherent limitation of the
ROM. The STEWART-GOUGH PLATFORM in Fig. 14.3 Torso structure
The torso design utilizes the advantages of a parallel kinematic machine
in terms of the force-to-weight ratio and the inherent limitation of the
ROM. The STEWART-GOUGH PLATFORM in Fig. 14.3c consists of s The torso design utilizes the advantages of a parallel kinematic machine
in terms of the force-to-weight ratio and the inherent limitation of the
ROM. The STEWART-GOUGH PLATFORM in Fig. 14.3c consists of six
variable lengt Ine torso design utilizes the advantages of a parallel kinematic machine
in terms of the force-to-weight ratio and the inherent limitation of the
ROM. The STEWART–GOUGH PLATFORM in Fig. 14.3c consists of six
variable lengt in terms of the force-to-weight ratio and the inherent limitation of the ROM. The STEWART-GOUGH PLATFORM in Fig. 14.3c consists of six variable length drives operating in parallel. It allows three rotational and three tran

Biologically Inspired Series-Parallel Hybrid Robots
unified as Actuator Control Unit, see Section 14.2.2.1. The movement of
the back assists in standing up and sitting down and increases the reach of
the arms. The electron Biologically Inspired Series-Parallel Hybrid Robots

unified as Actuator Control Unit, see Section 14.2.2.1. The movement of

the back assists in standing up and sitting down and increases the reach of

the arms. The elect Biologically Inspired Series-Parallel Hybrid Robots
unified as Actuator Control Unit, see Section 14.2.2.1. The movement of
the back assists in standing up and sitting down and increases the reach of
the arms. The electron 314 Biologically Inspired Series-Parallel Hybrid Robots
unified as Actuator Control Unit, see Section 14.2.2.1. The movement of
the back assists in standing up and sitting down and increases the reach of
the arms. The elec 314 Biologically Inspired Series-Parallel Hybrid Robots

unified as Actuator Control Unit, see Sectio

the back assists in standing up and sitting dc

the arms. The electronic box is mounted on

nism. An XSENS MT1300 inert unified as Actuator Control Unit, se
the back assists in standing up and si
the arms. The electronic box is mou
nism. An XSENS MT1300 inertial se
of the hip joint connection.
Hip and ankle
The hip and foot are equipped wit in the back assists in standing up and sitting down and increases the reach of
the arms. The electronic box is mounted on the top plate of the mecha-
nism. An XSENS MT1300 inertial sensor is also mounted on the base plate

ical parallel mechanism (ASPM) that acts as a 3 DOF swivel joint. For
the arms. The electronic box is mounted on the top plate of the mecha-
nism. An XSENS MT1300 inertial sensor is also mounted on the base plate
of the hi the arms. The effectome box is mounted on the top plate of the interna-
nism. An XSENS MT1300 inertial sensor is also mounted on the base plate
of the hip joint connection.
Hip and ankle
The hip and foot are equipped with the hip joint connection.

Hip and ankle

The hip and foot are equipped with a specially developed almost spher-

ical parallel mechanism (ASPM) that acts as a 3 DOF swivel joint. For

this purpose, three rotative drives e Fip and ankle
The hip and foot are equipped with a specially developed almost spher-
ical parallel mechanism (ASPM) that acts as a 3 DOF swivel joint. For
this purpose, three rotative drives each drive the end-effector via Hip and ankle
The hip and foot are equipped with a specially developed almost spher-
ical parallel mechanism (ASPM) that acts as a 3 DOF swivel joint. For
this purpose, three rotative drives each drive the end-effector via The hip and diotare equipped with a specially developed almost spherical parallel mechanism (ASPM) that acts as a 3 DOF swivel joint. For this purpose, three rotative drives each drive the end-effector via a spatial quadr 1 ne mp and toot are equipped with a specially developed almost spher-
ical parallel mechanism (ASPM) that acts as a 3 DOF swivel joint. For
this purpose, three rotative drives each drive the end-effector via a spa-
tial q ical parallel mechanism (ASPM) that acts as a 3 DOF swivel joint. For
this purpose, three rotative drives each drive the end-effector via a spa-
tial quadrilateral consisting of a coupling rod with two ball pivots. In the
 this purpose, three rotative drives each drive the end-effector via a spa-
tial quadrilateral consisting of a coupling rod with two ball pivots. In the
end-effector, the quadrilaterals are perpendicular to each other and i tial quadrilateral consisting of a coupling rod with two ball pivots. In the
end-effector, the quadrilaterals are perpendicular to each other and inter-
sect at their centers. In mechanism theory, the ASPM is classified as end-effector, the quadrilaterals are perpendicular to
sect at their centers. In mechanism theory, the ASPN
of type 3-[<u>R</u>-[2-SS]] [12,13]. Mechanical end stop
ators and thus also the overall mechanism. A spec
distribution of type 3-[<u>R</u>-[2-SS]] [12,13]. Me
ators and thus also the overall m
distribution of the tension within
only compression and tension force
A force acting in the direction of
bearing without active torque.
Knee joint
The l distribution of the tension within the mechanism; A special reading is divergaled distribution of the tension within the mechanism; due to the ball heads, only compression and tension forces are transmitted via the couplin

ustribution of the tension within the incentainshit, the to the ban heats,
only compression and tension forces are transmitted via the coupling rods.
A force acting in the direction of the axis of rotation is absorbed by t The legs of the exoskeleton cover approximately valuate to a sphering without active torque.
 Knee joint

The legs of the exoskeleton cover approximately the full human ROM

with 7 DOF fully actuated kinematics. Instead For force acting in the direction of the axis of fotation is absorbed by the
bearing without active torque.
 Knee joint

The legs of the exoskeleton cover approximately the full human ROM

with 7 DOF fully actuated kine **Knee joint**
The legs of the exoskeleton cover approximately the full human ROM
with 7 DOF fully actuated kinematics. Instead of a usual $S-R-S$ architec-
ture, in which a spherical joint is used to actuate the hip and ankl Knee joint
The legs of the exoskeleton cover approximately the full human ROM
with 7 DOF fully actuated kinematics. Instead of a usual S -R-S architec-
ture, in which a spherical joint is used to actuate the hip and ankl The legs of the exoskeleton cover approximately the full human ROM
with 7 DOF fully actuated kinematics. Instead of a usual $S-R-S$ architec-
ture, in which a spherical joint is used to actuate the hip and ankle joint
respe The legs of the exoskeleton cover approximately the full human ROM
with 7 DOF fully actuated kinematics. Instead of a usual $\underline{S-R-S}$ architec-
ture, in which a spherical joint is used to actuate the hip and ankle joint
 with / DOF tully actuated kinematics. Instead of a usual Σ - K - Σ architecture, in which a spherical joint is used to actuate the hip and ankle joint respectively and a rotational joint is used in the knee, the knee ture, in which a spherical joint is used to actuate the hip and ankle joint
respectively and a rotational joint is used in the knee, the knee joint used
here is replaced by a prismatic coupling between the hip and ankle jo respectively and a rotational joint is used in the knee, the knee joint used
here is replaced by a prismatic coupling between the hip and ankle joint.
The resulting <u>S-P-S</u> architecture significantly reduces the bending st here is replaced by a prismatic coupling between the hip and ankle joint.
The resulting <u>S-P-S</u> architecture significantly reduces the bending stresses
occurring in the leg structural components. Furthermore, the legs have The resulting Σ -*P*- Σ architecture significantly reduces the bending stresses
occurring in the leg structural components. Furthermore, the legs have
additional passive kinematics in the area of the knee joints, whic occurring in the leg structural components. Furthermore, the legs have
additional passive kinematics in the area of the knee joints, which unfold
from a certain shortening of the prismatic actuator. This serves to unfold
a additional passive kinematics in the area of the knee joints, which unfold
from a certain shortening of the prismatic actuator. This serves to unfold
an additional support as well as a seat structure in which the wearer of from a certain shortening of the prismatic actuator. I his serves to unfold
an additional support as well as a seat structure in which the wearer of the
exoskeleton can rest without the actuators having to utilize any elec an additional support as well as a seat structure in which the wearer of the
exoskeleton can rest without the actuators having to utilize any electri-
cal power (Fig. 14.3d). The unfolding threshold on the prismatic actuat exoskeleton can rest without the actuators having to utilize any electrical power (Fig. 14.3d). The unfolding threshold on the prismatic actuator was chosen such that the passive kinematics remain closed during a normal wa

Recupera exoskeletons 315
With a total weight of the exoskeleton of 42 kg, an additional weight of up
to approximately 70 kg can be supported by the leg design in an upright
posture Recupera exoskeletons 315
With a total weight of the exoskeleton of 42 kg , an additional weight of up
to approximately 70 kg can be supported by the leg design in an upright
posture. posture. With a total weight of the exoskeleton of 42 k
to approximately 70 kg can be supported by
posture.
14.2.1.3 Safety aspects With a total weight of the exoskeleton of 42 kg, an additional weight of up
to approximately 70 kg can be supported by the leg design in an upright
posture.
14.2.1.3 Safety aspects
Safety in the use of an exoskeleton pla

With a total weight of the exoskeleton of 42 kg, an additional weight of up
to approximately 70 kg can be supported by the leg design in an upright
posture.
14.2.1.3 Safety aspects
Safety in the use of an exoskeleton pla **inc** a total weight of the exosketedor of $+2$ kg, an additional weight of the root approximately 70 kg can be supported by the leg design in an upright posture.
 14.2.1.3 Safety aspects

Safety in the use of an exoske **14.2.1.3 Safety aspects**
14.2.1.3 Safety aspects
Safety in the use of an exoskeleton plays a fundamental role in order not to
endanger the user. For the mechanical design, this essentially means limit-
ing the forces an **14.2.1.3 Safety aspects**
Safety in the use of an exoskeleton plays a fundamental role in order not to
endanger the user. For the mechanical design, this essentially means limit-
ing the forces and ROM of the robot. In ord **14.2.1.3 Safety aspects**
Safety in the use of an exoskeleton plays a fundamental role in order not to
endanger the user. For the mechanical design, this essentially means limit-
ing the forces and ROM of the robot. In ord Factionally as a fundamental role in order not to
safety in the use of an exoskeleton plays a fundamental role in order not to
endanger the user. For the mechanical design, this essentially means limit-
ing the forces and Safety in the use of an exoskeleton plays a fundamental role in order not to endanger the user. For the mechanical design, this essentially means limiting the forces and ROM of the robot. In order to maintain the dynamics endanger the user. For the mechanical design, this essentially means limit-
ing the forces and ROM of the robot. In order to maintain the dynamics
and freedom of movement of the user, a negotiation process is necessary. In ing the torces and KOM of the robot. In order to maintain the dynamics
and freedom of movement of the user, a negotiation process is necessary. In
the RECUPERA exoskeleton, the drives were designed according to these
princ and treedom of movement of the user, a negotia
the RECUPERA exoskeleton, the drives were d
principles and have integrated movement-limit
ditionally, in the joints with high DOF such as
the use of parallel kinematics provid principles and have integrated movement-limiting n
ditionally, in the joints with high DOF such as the t
the use of parallel kinematics provides intrinsic move
human contacts to the exoskeleton are not rigid, bu
cro. The b Intionally, in the Johns with high DOT such as the back, hips and ankles,
the use of parallel kinematics provides intrinsic movement limitation. The
human contacts to the exoskeleton are not rigid, but designed with Vel-
c

the use of parallel Kinelhalacs provides intrinst movement inflation. The
human contacts to the exoskeleton are not rigid, but designed with Vel-
cro. The back connection offers enough freedom to compensate for any
misbeha The back connection offers enough freedom to compensate for any
misbehavior of the robot.
14.2.1.4 Interface with human
The upper-body exoskeleton is connected to the human at three contact
points per arm and at two cont 14.2.1.4 Interface with human

14.2.1.4 Interface with human

The upper-body exoskeleton is connected to the human at three contact

points per arm and at two contact points in the back. The contacts on

the upper arm, for **14.2.1.4 Interface with human**
The upper-body exoskeleton is connected to the human at three contact
points per arm and at two contact points in the back. The contacts on
the upper arm, forearm and hand interface are equi **14.2.1.4 Interface with human**
The upper-body exoskeleton is connected to the human at three contact
points per arm and at two contact points in the back. The contacts on
the upper arm, forearm and hand interface are equi FR2.1.4 *Intertace with himanian*
The upper-body exoskeleton is connected to the human at three contact
points per arm and at two contact points in the back. The contacts on
the upper arm, forearm and hand interface are eq The upper-body exoskeleton is connected to the human at three contact
points per arm and at two contact points in the back. The contacts on
the upper arm, forearm and hand interface are equipped with 6-axis ATI
NANO25 forc points per arm and at two contact points in the back. The contacts on
the upper arm, forearm and hand interface are equipped with 6-axis ATI
NANO25 force/torque sensors and can thus measure the forces that occur
between th the upper arm, torearm and hand interface are equipped with 6-axis A11
NANO25 force/torque sensors and can thus measure the forces that occur
between the exoskeleton and the human. In the full-body exoskeleton, 6-
axis ATI between the exoskeleton and the human. In the full-body exoskeleta
axis ATI NANO25 sensors are also installed in the contact points c
back and hips. A loop in the foot mechanism enables contact wit
human foot. The hip and ARIS ATT INANO23 Sensors are also instance in the contact points on the
back and hips. A loop in the foot mechanism enables contact with the
human foot. The hip and back contacts are realized by straps with quick-
release

back and inps. *A* loop in the foot inechains in enables contact with the
human foot. The hip and back contacts are realized by straps with quick-
release fasteners, the contact in the upper arm by Velcro fasteners. Fig. 1 munan foot. The mp and back contacts are realized by straps with quick-
release fasteners, the contact in the upper arm by Velcro fasteners. Fig. 14.2
documents the position of the contacts and their sensory equipment.
14 14.2.1.5 Adaption to different human sizes
 14.2.1.5 Adaption to different human sizes
 14.2.1.5 Adaption to different human sizes
 16.1.6 m to 1.9 m. The necessary adaptation options are provided in the

shoulder **14.2.1.5 Adaption to different human sizes**
14.2.1.5 Adaption to different human sizes
The exoskeleton is designed for people with an approximate body height
of 1.6 m to 1.9 m. The necessary adaptation options are prov **14.2.1.5 Adaption to different human sizes**
The exoskeleton is designed for people with an approximate body height
of 1.6 m to 1.9 m. The necessary adaptation options are provided in the
shoulder, arms, back and leg stru The exoskeleton is designed for people with an approximate body height
of 1.6 m to 1.9 m. The necessary adaptation options are provided in the
shoulder, arms, back and leg structures. The upper arm length is adjustable
by The exoskeleton is designed for people with an approximate body height
of 1.6 m to 1.9 m. The necessary adaptation options are provided in the
shoulder, arms, back and leg structures. The upper arm length is adjustable
by of 1.6 m to 1.9 m. The necessary adaptation options are provided in the shoulder, arms, back and leg structures. The upper arm length is adjustable by 55 mm, the forearms have a possible length adaptation of 50 mm, as well

Biologically Inspired Series-Parallel Hybrid Robots
can be adjusted to a defined starting level within a height of 100 mm. But
this takes affect to the possible task space. Biologically Inspired Series-Parallel Hybrid Robots

can be adjusted to a defined starting level within a height of 10

this takes affect to the possible task space.
 14 2 2 Electrical and electronic design Biologically Inspired Series-Parallel Hybrid Robots

14.2.2 Electrical and electronic design

14.2.2 Electrical and electronic design

16 electrical and electronic design

2.1 electrical and electronic design

2.1 electric

Biologically Inspired Series-Parallel Hybrid Robots

can be adjusted to a defined starting level within a height of 100 mm. But

this takes affect to the possible task space.
 14.2.2 Electrical and electronic design

The can be adjusted to a defined starting level within a height of 100 mm. But
this takes affect to the possible task space.
14.2.2 Electrical and electronic design
The electrical and electronic design of both the wheelchair can be adjusted to a defined starting level within a height of 100 mm. But
this takes affect to the possible task space.
14.2.2 Electrical and electronic design
The electrical and electronic design of both the wheelchair **14.2.2 Electrical and electronic design**
 14.2.2 Electrical and electronic design

The electrical and electronic design of both the wheelchair and the full-

body exoskeleton is based on a hybrid centralized-decentraliz **14.2.2 Electrical and electronic design**
The electrical and electronic design of both the wheelchair and the full-
body exoskeleton is based on a hybrid centralized-decentralized control
scheme. Fig. 14.4 shows an overvie **14.2.2 Electrical and electronic design**
The electrical and electronic design of both the wheelchair and the full-
body exoskeleton is based on a hybrid centralized-decentralized control
scheme. Fig. 14.4 shows an overvie The electrical and electronic design of both the wheelchair and the full-
body exoskeleton is based on a hybrid centralized-decentralized control
scheme. Fig. 14.4 shows an overview of all actuators and the underlying
netw The execution and electronic design of both the whetehrian and the tun-
body exoskeleton is based on a hybrid centralized-decentralized control
scheme. Fig. 14.4 shows an overview of all actuators and the underlying
networ body exosketedn is based on a hybrid echitalized-decentralized control
scheme. Fig. 14.4 shows an overview of all actuators and the underlying
network structure (see also Section 14.2.2.1 for details). The control on the
a scheme. Fig. 14.4 shows an overview of an a
network structure (see also Section 14.2.2.1 fo
actuator level is performed in a decentralized
time capabilities to support a multi-level safety
high-level controls are computed actuator level is performed in a decentralized manner and provide
time capabilities to support a multi-level safety strategy. Both the mid
high-level controls are computed in the central processing system
exoskeleton (see me capacines to support a main forer sarety stategy. Dout the first and
high-level controls are computed in the central processing system of the
exoskeleton (see Fig. 14.4 and Section 14.2.2.2). They provide complex
functi

mgn rever comos are computed in the central processing system of the
exoskeleton (see Fig. 14.4 and Section 14.2.2.2). They provide complex
functionality, such as kinematics/dynamics computations and functions to
interact self-designed and have been developed to specifically controllers
 14.2.2.1 Decentralized actuator-level controllers
 14.2.2.1 Decentralized actuator-level controllers

Every actuator is controlled by a dedicated modul 14.2.2.1 Decentralized actuator-level controllers
14.2.2.1 Decentralized actuator-level controllers
Every actuator is controlled by a dedicated modular Actuator Control Unit
(ACU) which is placed close to the corresponding **14.2.2.1 Decentralized actuator-level controllers**
Every actuator is controlled by a dedicated modular Actuator Control Unit
(ACU) which is placed close to the corresponding actuator. The ACUs are
self-designed and have b **14.2.2.1 Decentralized actuator-level controllers**
Every actuator is controlled by a dedicated modular Actuator Control Unit
(ACU) which is placed close to the corresponding actuator. The ACUs are
self-designed and have b Every actuator is controlled by a dedicated modular Actuator Control Unit
(ACU) which is placed close to the corresponding actuator. The ACUs are
self-designed and have been developed to specifically control BLDC mo-
tors. Every actuator is confioned by a dedicated modular Actuator Confior Ome
(ACU) which is placed close to the corresponding actuator. The ACUs are
self-designed and have been developed to specifically control BLDC mo-
tors. A (ACC) winch is placed close to the corresponding actuator. The ACCs are self-designed and have been developed to specifically control BLDC motors. An ACU typically contains three separate subunit PCBs: one PCB for power el sch-ucsigned and nave been developed to specificary control BEDC ino-
tors. An ACU typically contains three separate subunit PCBs: one PCB
for power electronics, one for data acquisition and communication and
one PCB for c on the computing to the computing and communication and communication and one PCB for computing. Multiple different ACU PCB subunits can be combined in order to fulfill specific requirements of each actuator. Table 14.3 sh for power electronics, one for data acquisition and communication and
one PCB for computing. Multiple different ACU PCB subunits can be
combined in order to fulfill specific requirements of each actuator. Ta-
ble 14.3 show one TCD for compluding. Multiple unferent *NCO TCD* subturns can be combined in order to fulfill specific requirements of each actuator. Table 14.3 shows an overview of the configurations used in the RECUPERA exoskeleton. ble 14.3 shows an overview of the configurations used in the RECUPERA
exoskeleton. The control and communication functionality is realized us-
ing a dedicated hardware design in the Xilinx XC6SLX45 Spartan 6 FPGA
on the co Dre 14.5 shows an overview of the comigurations used in the NECOFERA
exoskeleton. The control and communication functionality is realized us-
ing a dedicated hardware design in the Xilinx XC6SLX45 Spartan 6 FPGA
on the com exosketeton. The control and communication functionality is realized us-
ing a dedicated hardware design in the Xilinx XC6SLX45 Spartan 6 FPGA
on the computing PCB subunit. The used controller is implemented as a
cascaded figurated individe design in the Xinitx ACOSEX+5 Spatian 0 11 GA on the computing PCB subunit. The used controller is implemented as a cascaded position-velocity-current PID algorithm (see Section 14.3.3.1). Every ACU is s fuse. Every ACU is supplied with two different voltages. For the motor phases,
a voltage of 48 V is used, while 12 V is used for the computing and com-
munication part. Both voltages and the related currents are continuously
mon The central electronic system of the exoskeleton is located in a backpack munication part. Both voltages and the related currents are continuously monitored by the FPGA. For safety reasons, the FPGA implements a configurab Individually paid. Doll. Voltages and all contained early are conditionally
monitored by the FPGA. For safety reasons, the FPGA implements a con-
figurable, firmware-based fuse. Additionally, each ACU contains a hardware
f

Figure 14.4 The exoskeleton is controlled by two central systems, called

Figure 14.4 The exoskeleton is controlled by two central systems, called
 $\frac{1}{2}$
 $\frac{1}{2}$
 $\frac{1}{2}$
 $\frac{1}{2}$
 $\frac{1}{2}$
 $\frac{1}{2}$
 $\frac{1}{2$ Examed actuator-level control architecture implemented on the FPGA of each

Figure 14.4 The exoskeleton is controlled by two central systems, called

ZynqBrain (ZB), and a network of decentralized Actuator Control Units (**Example 14.4** The exoskeleton is controlled by two central systems, called ZynqBrain (ZB), and a network of decentralized Actuator Control Units (ACU) for motor control. Each motor is controlled locally by an adjacent AC **Figure 14.4** The exoskeleton is controlled by two central systems, called ZynqBrain (ZB), and a network of decentralized Actuator Control Units (ACU) for motor control. Each motor is controlled locally by an adjacent ACU **Figure 14.4** The exoskeleton is controlled by two central systems, called ZynqBrain (ZB), and a network of decentralized Actuator Control Units (ACU) for motor control. Each motor is controlled locally by an adjacent ACU Zynqbram (ZB), and a network of dece
for motor control. Each motor is control
tributed ACUs are connected via an ND
caded actuator-level control architectu
ACU; *u* is the angular position, *u* is the a
rent. The reference caded actuator-level control architecture implemented on the FPGA of each
ACU; *u* is the angular position, *u* is the angular velocity and *i* is the motor cur-
rent. The reference values are provided by the mid-level con

ACU; *a* is the angular position, *a* is the angular velocity and *i* is the motor cur-
rent. The reference values are provided by the mid-level control on the ZBs.
All ACUs continuously send telemetry status data to ZB1 w The main computing system consists of two dedicated Pico-ITX PCBs

(70×100 mm) called *ZynqBrain*. It contains a Xilinx Zynq ZC7030 [16]

Septem an Chin A 7C7030 consists of two dedicated Pico-ITX PCBs

(70×100 mm) called MDLCom network.

and high-level control, software for the user interface, communication and

networking as well as safety features like a wireless emergency switch.

The main computing system consists of two dedicated Pic A High-level control, software for the user interface, communication and
networking as well as safety features like a wireless emergency switch.
The main computing system consists of two dedicated Pico-ITX PCBs
(70×100 mm) and high-level control, software for the user interface, communication and
networking as well as safety features like a wireless emergency switch.
The main computing system consists of two dedicated Pico-ITX PCBs
 $(70 \times 1$ and high-level control, software for the user interface, communication and
networking as well as safety features like a wireless emergency switch.
The main computing system consists of two dedicated Pico-ITX PCBs
 $(70\times10$ networking as well as safety features like a wireless emergency switch.
The main computing system consists of two dedicated Pico-ITX PCBs
(70×100 mm) called ZynqBrain. It contains a Xilinx Zynq ZC7030 [16]
System on Chip. The main computing system consists of two dedicated Pico-ITX PCBs (70×100 mm) called *ZynqBrain*. It contains a Xilinx Zynq ZC7030 [16] System on Chip. A ZC7030 consists of two sections: a Processing System (PS) (which is (70×100 mm) called *ZynqBrain*. It contains a Xilinx Zynq ZC7030 [16]
System on Chip. A ZC7030 consists of two sections: a Processing System
(PS) (which is a dual-core ARM Cortex-A9 CPU running at 1 GHz) and a
Programmabl

Biologically Inspired Series-Parallel Hybrid Robots
 Table 14.3 Configurations of the Actuator Control Units (ACU).

Each ACU consists of zero or more PCBs for Power electronics Data acquisition and communication Computa Biologically Inspired Series-Parallel Hybrid Robots
 Table 14.3 Configurations of the Actuator Control Units (ACU).

Each ACU consists of zero or more PCBs for Power elec-

tronics, Data acquisition and communication, Co Biologically Inspired Series-Parallel Hybrid Robots
 Table 14.3 Configurations of the Actuator Control Units (ACU).

Each ACU consists of zero or more PCBs for **P**ower electronics, **D**ata acquisition and communication, Biologically Inspired Series-Parallel Hybrid Robots
 Table 14.3 Configurations of the Actuator Control Units (ACU).

Each ACU consists of zero or more PCBs for **P**ower electronics, **D**ata acquisition and communication, Biologically Inspired Series-Parallel Hybrid Robots
 Table 14.3 Configurations of the Actuator Control Units (ACU).
 Each ACU consists of zero or more PCBs for Power electronics, Data acquisition and communication, Comp Table 14.3 Configurations of the Actuator Control Units (ACU).
Each ACU consists of zero or more PCBs for **P**ower electronics, **D**ata acquisition and communication, **C**omputation or
Microcontroller. To control a motor, it Table 14.3 Configurations of the Actuator Control Units (ACU).

Each ACU consists of zero or more PCBs for **P**ower electronics, **D**ata acquisition and communication, **C**omputation or
 Microcontroller. To control a motor, Tradition ACU PCBs

Each ACU consists of zero or more PCBs for Power electronics, Data acquisition and communication, Computation or

Microcontroller. To control a motor, it senses the motor position

via iC-MU [15] Absol

 $\begin{array}{c|c|c|c|c|c} \n & Hip & P, D, C & RD\ 70x10-160 & A, R \\ \n & Hine & P, D, C & RD\ 38x12-2 & A, R, L \\ \n & A, R, L & RD\ 50x8-100 & 2xA \n \end{array}$
 14.2.2.3 Power management

The DFKI's own Central Power Management Board (CPMB) serves **internal power management**
 14.2.2.3 Power management
 14.2.2.3 Power management
 14.2.2.3 Power m **14.2.2.3 Power management**

The DFKI's own Central Power Management Board (CPMB) serves as

internal power supply and battery management. This allows the entire sys-

tem to be supplied with the required voltages. The ce **14.2.2.3 Power management**
The DFKI's own Central Power Management Board (CPMB) serves as
internal power supply and battery management. This allows the entire sys-
tem to be supplied with the required voltages. The centra **14.2.2.3 Power management**
The DFKI's own Central Power Management Board (CPMB) serves as
internal power supply and battery management. This allows the entire sys-
tem to be supplied with the required voltages. The centra 14.2.2.3 Power management
The DFKI's own Central Power Management Board (CPMB) serves as
internal power supply and battery management. This allows the entire sys-
tem to be supplied with the required voltages. The central The DFKI's own Central Power Management Board (CPMB) serves as
internal power supply and battery management. This allows the entire sys-
tem to be supplied with the required voltages. The central computing unit
is operated internal power supply and battery management. This allows the entire system to be supplied with the required voltages. The central computing unit
is operated with 5 V, the decentralized ACU with 12 V for logic circuit
and tem to be supplied with the required voltages. The central computing unit
is operated with 5 V, the decentralized ACU with 12 V for logic circuit
and 48 V for power electronics. The CPMB can switch between an exter-
nal p is operated with 5 V, the decentralized ACU with 12 V for logic circuit
and 48 V for power electronics. The CPMB can switch between an exter-
nal power supply and a battery, as well as perform its charging function.
Two ad and 48 V for power electronics. The CPMB can switch between an exter-
nal power supply and a battery, as well as perform its charging function.
Two additional voltage converters are located in the elbow and supply the
DYNA nal power supply and a battery, as well as perform its charging function.
Two additional voltage converters are located in the elbow and supply the
DYNAMIXEL-X motors with a 12 V voltage separate from the logic volt-
age, Two additional voltage converters are located
DYNAMIXEL-X motors with a 12 V voltage
age, as well as the model servos in the har
full-body system, the individual assemblies'
be switched on and off with two programm
power c age, as well as the model servos in the harfull-body system, the individual assemblies'
be switched on and off with two programm
power consumption can also be monitored.
can be found in [18].
14.2.2.4 Safety aspects
To e full-body system, the individual assemblies' arms, legs and the back can
be switched on and off with two programmable electrical fuses and their
power consumption can also be monitored. A more detailed description
can be f be switched on and off with two programmable electrical fuses and their
power consumption can also be monitored. A more detailed description
can be found in [18].
14.2.2.4 Safety aspects
To ensure safe operation of the e

Becupera exoskeletons 319
be switched off externally on both systems by means of emergency but-
tons on the arms, hand interface and on the full-body system on the back.
A wireless emergency button operated by an external Recupera exoskeletons 319
the switched off externally on both systems by means of emergency but-
tons on the arms, hand interface and on the full-body system on the back.
A wireless emergency button operated by an external Recupera exoskeletons 319
be switched off externally on both systems by means of emergency but-
tons on the arms, hand interface and on the full-body system on the back.
A wireless emergency button operated by an external Recupera exoskeletons 319
be switched off externally on both systems by means of emergency but-
tons on the arms, hand interface and on the full-body system on the back.
A wireless emergency button operated by an external Recupera exoskeletons 319
be switched off externally on both systems by means of emergency but-
tons on the arms, hand interface and on the full-body system on the back.
A wireless emergency button operated by an external be switched off externally on both systems by means of emergency but-
tons on the arms, hand interface and on the full-body system on the back.
A wireless emergency button operated by an external person and a foot
pedal fo be switched off externally on both systems by means of emergency but-
tons on the arms, hand interface and on the full-body system on the back.
A wireless emergency button operated by an external person and a foot
pedal fo software of externally of boar systems by means of emergency bat-
tons on the arms, hand interface and on the full-body system on the back.
A wireless emergency button operated by an external person and a foot
pedal for th A wireless emergency button operated by an external person and a foot pedal for the user provide the same functionality. Hard and soft limits for position, speed and current are specified at the decentralized ACU level and The wireless emergency button operated by an external person and a root pedal for the user provide the same functionality. Hard and soft limits for position, speed and current are specified at the decentralized ACU level a position, speed and current are specified and are decoupled from the mid and h
limits are exceeded, this also causes the
soft limits are used as a control value li
exceeding the limit is prevented by mo
the software level, limits are exceeded, this also causes the 48 V voltage t
soft limits are used as a control value limit and in the
exceeding the limit is prevented by moving in the o
the software level, as a third element, there are furth
 For this section as a control vante finit and in the case of the position,
exceeding the limit is prevented by moving in the opposite direction. On
the software level, as a third element, there are further setpoint limits

Executing the finit is prevented by filosofy in the opposite direction. On
the software level, as a third element, there are further setpoint limits that
cannot be exceeded.
14.3 Modeling and control
In this section, we **14.3 Modeling and control**
 14.3 Modeling and control

In this section, we present the kinematic and dynamic modeling of the

possible exoskeleton configurations, the control architecture and software

design for variou 14.3 Modeling and control

In this section, we present the kinematic and dynamic modeling c

possible exoskeleton configurations, the control architecture and sof

design for various rehabilitation therapies and teleoperat 14.3 Modeling and control

In this section, we present the kinematic and dynamic modeling of the

possible exoskeleton configurations, the control architecture and software

design for various rehabilitation therapies and

In this section, we present the kinematic and dynamic modeling of the
possible exoskeleton configurations, the control architecture and software
design for various rehabilitation therapies and teleoperation.
14.3.1 Modula possible exoskeleton configurations, the control architecture and software
design for various rehabilitation therapies and teleoperation.
14.3.1 Modular robot description models
In its application, the RECUPERA exoskelet design for various rehabilitation therapies and teleoperation.
 14.3.1 Modular robot description models

In its application, the RECUPERA exoskeleton is not only controlled in

terms of position, but also based on forces 14.3.1 Modular robot description models
In its application, the RECUPERA exoskeleton is not only controlled in
terms of position, but also based on forces and torques. For this purpose,
the dynamic parameters of mass, cent **14.3.1 Modular robot description models**
In its application, the RECUPERA exoskeleton is not only controlled in
terms of position, but also based on forces and torques. For this purpose,
the dynamic parameters of mass, ce In its application, the RECUPERA exoskeleton is not only controlled in
terms of position, but also based on forces and torques. For this purpose,
the dynamic parameters of mass, center of gravity, moments of inertia and
ax In its application, the ECCOLERA exostection is not only controlled in
terms of position, but also based on forces and torques. For this purpose,
the dynamic parameters of mass, center of gravity, moments of inertia and
ax terms or position, but also based on forces and torques. For tims purpose, the dynamic parameters of mass, center of gravity, moments of inertia and axes of rotation as well as their orientations of the individual robot li ince dynamic parameters of mass, center of gravity, moments of mertia and
axes of rotation as well as their orientations of the individual robot links
are required. The values can partly be determined experimentally or can axes of fotation as well as their orientations of the intrividual floot illness
are required. The values can partly be determined experimentally or can
be extracted from the CAD model. This is done with the SW2URDF
tool [1 format. The commissioning of a complex robotic system requires functioning-
The coordinate systems are assigned to the links and joint axes from
gin to end-effector. The SW2URDF tool reads the values calculated
the CAD software, c sub-assemblies. Troubleshooting the entire system is completed in the CAD software, converts them into the Universal Robot Description Format (URDF) and links them to the exported meshes in STL data format.
The commissioni

consumer systems are assigned to the miss and joint axes non
origin to end-effector. The SW2URDF tool reads the values calculated
in the CAD software, converts them into the Universal Robot Descrip-
tion Format.
The commis software, converts them into the Universal Robot Descrip-
ion Format (URDF) and links them to the exported meshes in STL data
format.
The commissioning of a complex robotic system requires functioning
sub-assemblies. Troub in the CrL solivate, converts them into the Chrystal Robot Descrip-
tion Format.
The commissioning of a complex robotic system requires functioning
sub-assemblies. Troubleshooting the entire system is complex and time-
con format.

The commissioning of a complex robotic system requires functioning

sub-assemblies. Troubleshooting the entire system is complex and time-

consuming due to the numerous possible errors on the hardware and

softwa The commissioning of a complex robotic system requires functioning
sub-assemblies. Troubleshooting the entire system is complex and time-
consuming due to the numerous possible errors on the hardware and
software side. It

Figure 14.5 Overview of the exported (left), processed and used models

(right). The PHOBOS-CI used to process the models is explained in Chapter 17.

are maintained using a Continuous Integration (CI) pipeline (see Chap-
 Figure 14.5 Overview of the exported (left), processed and used models (right). The PHOBOS-CI used to process the models is explained in Chapter 17.
are maintained using a Continuous Integration (CI) pipeline (see Chapter Figure 14.5 Overview of the exported (left), processe (right). The PHOBOS-CI used to process the models is exp
are maintained using a Continuous Integration (CI)
ter 17). Using this CI during the commissioning the
held con are maintained using a Continuous Integration (CI) p:
ter 17). Using this CI during the commissioning the
held consistent with each other.
14.3.2 Kinematics and dynamics
RECUPERA exoskeleton is a highly complex series-pa are maintained using a Continuous Integration (CI) pipeline (see Chap-
ter 17). Using this CI during the commissioning the various models are
held consistent with each other.
14.3.2 Kinematics and dynamics
RECUPERA exosk

are maintained using a Continuous Integration (CI) pipeline (see Chap-
ter 17). Using this CI during the commissioning the various models are
held consistent with each other.
14.3.2 Kinematics and dynamics
RECUPERA exosk ter 17). Using this CI during the commissioning the various models are
held consistent with each other.
14.3.2 Kinematics and dynamics
RECUPERA exoskeleton is a highly complex series-parallel hybrid mech-
anism with 34 D **14.3.2 Kinematics and dynamics**
14.3.2 Kinematics and dynamics
RECUPERA exoskeleton is a highly complex series-parallel hybrid mech-
anism with 34 DOF, where 24 DOF are actuated with parallel submecha-
nism modules. Ove **14.3.2 Kinematics and dynamics**
RECUPERA exoskeleton is a highly complex series-parallel hybrid mechanism with 34 DOF, where 24 DOF are actuated with parallel submechanism modules. Overall, the exoskeleton can be seen as 14.5.2 Milematics and dynamics
RECUPERA exoskeleton is a highly complex series-parallel hybrid mech-
anism with 34 DOF, where 24 DOF are actuated with parallel submecha-
nism modules. Overall, the exoskeleton can be seen a anism with 34 DOF, where 24 DOF are actuated w
nism modules. Overall, the exoskeleton can be seen
tion of 5 series-parallel hybrid submechanisms invol
a torso. Hence, the loop closure function (LCF) of
be composed by combi nism modules. Overall, the exoskeleton can be seen as a tree-type composi-
tion of 5 series-parallel hybrid submechanisms involving 2 legs, 2 arms and
a torso. Hence, the loop closure function (LCF) of the overall system c

ion of 5 series-parallel hybrid submechanisms involving 2 legs, 2 arms and
a torso. Hence, the loop closure function (LCF) of the overall system can
be composed by combining the LCF of the 5 individual sub-assemblies.
Anal a torso. Hence, the loop closure function (LCF) of the overall system can
be composed by combining the LCF of the 5 individual sub-assemblies.
Analytical LCF of RECUPERA arm
The RECUPERA exoskeleton arm is a 7 DOF series-p be composed by combining the LCF of the 5 individual sub-assemblies.
Analytical LCF of RECUPERA arm
The RECUPERA exoskeleton arm is a 7 DOF series-parallel hybrid mech-
anism which contains a double parallelogram linkage a Analytical LCF of RECUPERA arm

The RECUPERA exoskeleton arm is a 7 DOF series-parallel hybrid mechanism which contains a double parallelogram linkage at the shoulder joint

and a parallelogram linkage in wrist joint (see The RECUPERA exoskeleton arm is a 7 DOF series-parallel hybrid mechanism which contains a double parallelogram linkage at the shoulder joint and a parallelogram linkage in wrist joint (see Fig. 14.6 for its schematic and The RECUPERA exoskeleton arm is a 7 DOF series-parallel hybrid mechanism which contains a double parallelogram linkage at the shoulder joint and a parallelogram linkage in wrist joint (see Fig. 14.6 for its schematic and and a parallelogram linkage in wrist joint (see Fig. 14.6 for its schematic
and topological graph). The loop closure function of the parallelogram-like
linkages can be composed from the mimic joint definition in URDF [20]

Figure 14.6 Single arm schematic and its topological graph.
\nvector *q* and its relation with *y*, i.e., LCF (*y*), is shown in Eq. (14.1).
\n
$$
\begin{bmatrix}\nq_{100,200} \\
q_{200,222} \\
q_{222,223} \\
q_{223,300} \\
q_{223,203} \\
q_{300,400} \\
q_{501,522} \\
q_{511,522} \\
q_{511,512} \\
q_{511,512} \\
q_{500,500} \\
q_{500,511} \\
q_{511,512} \\
q_{510,500} \\
q_{500,700} \\
q_{500,700} \\
q_{500,800}\n\end{bmatrix}\n=\n\begin{bmatrix}\n1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0\n\end{bmatrix}\n\begin{bmatrix}\nq_{100,200} \\
q_{200,232} \\
q_{300,400} \\
q_{400,500} \\
q_{500,600} \\
q_{500,700} \\
q_{600,700} \\
q_{700,800}\n\end{bmatrix}\n+\n\begin{bmatrix}\n0 \\
q_{100,200} \\
q_{200,232} \\
q_{300,400} \\
q_{400,500} \\
q_{500,600} \\
q_{500,700} \\
q_{600,700} \\
q_{700,800}\n\end{bmatrix}
$$
\n(14.1)

Biologically Inspired Series-Parallel Hybrid Robots
 **Numerical LCF of RECUPERA leg

The RECUPERA exoskeleton legs are each 7** Biologically Inspired Series-Parallel Hybrid Robots
 Numerical LCF of RECUPERA leg

The RECUPERA exoskeleton legs are each 7 DOFs with a 3 DOF ASPM

representing the hip and ankle modules, and a 1 DOF prismatic joint tha Biologically Inspired Series-Parallel Hybrid Robots
Rumerical LCF of RECUPERA leg
The RECUPERA exoskeleton legs are each 7 DOFs with a 3 DOF ASPM
representing the hip and ankle modules, and a 1 DOF prismatic joint that
m Biologically Inspired Series-Parallel Hybrid Robots
 Numerical LCF of RECUPERA leg
 The RECUPERA exoskeleton legs are each 7 DOFs with a 3 DOF ASPM

representing the hip and ankle modules, and a 1 DOF prismatic joint t Biologically Inspired Series-Parallel Hybrid Robots
 Numerical LCF of RECUPERA leg
 The RECUPERA exoskeleton legs are each 7 DOFs with a 3 DOF ASPM

representing the hip and ankle modules, and a 1 DOF prismatic joint t Numerical LCF of RECUPERA leg
The RECUPERA exoskeleton legs are each 7 DOFs with a 3 DOF ASPM
representing the hip and ankle modules, and a 1 DOF prismatic joint that
mimics the knee. A comprehensive kinematic analysis of Numerical LCF of RECUPERA leg
The RECUPERA exoskeleton legs are each 7 DOFs with a 3 DOF ASPI
representing the hip and ankle modules, and a 1 DOF prismatic joint th
mimics the knee. A comprehensive kinematic analysis of AC The RECUPERA exoskeleton legs are each 7 DOFs with a 3 DOF ASPM
representing the hip and ankle modules, and a 1 DOF prismatic joint that
mimics the knee. A comprehensive kinematic analysis of ACTIVE ANKLE
is provided in [1 Epresenting the inp and ankie modules, and a 1 DOP prismatic joint that
mimics the knee. A comprehensive kinematic analysis of ACTIVE ANKLE
is provided in [13,21,22]. Since, it is not possible to get rotative inverse
kinem

achieved in [13,21,22]. Since, it is not possible to get folative inverse
kinematics of the ASPM in a fully analytical fashion, the LCF of the ASPM
modules in hip and ankle joints are resolved numerically.
Hybrid numerica fined in hip and ankle joints are resolved numerically.
Hybrid numerical-analytical LCF of overall RECUPERA system
Since, it is straight-forward to solve the inverse kinematics of STEWART-
GOUGH PLATFORM, the overall LCF Hybrid numerical-analytical LCF of overall RECUPERA system
Since, it is straight-forward to solve the inverse kinematics of STEWART-
GOUGH PLATFORM, the overall LCF of the RECUPERA system can be
achieved in a hybrid numer Hybrid numerical-analytical LCF of overall RECUPERA system
Since, it is straight-forward to solve the inverse kinematics of STEWART-
GOUGH PLATFORM, the overall LCF of the RECUPERA system can be
achieved in a hybrid numer Since, it is straight-forward to solve the inverse kinematics
GOUGH PLATFORM, the overall LCF of the RECUPERA
achieved in a hybrid numerical-analytical manner using th
fined in [23], where the arms (γ_2, γ_3) and torso ng Eq. (14.1) for left and right arms) and the leg
are solved numerically. The overall LCF of the RE-
ition, velocity, and acceleration levels are given by
(14.4), respectively.
 γ_1^T γ_2^T γ_3^T $\gamma_{4,num}^T$ $\gamma_{$

$$
\gamma = \left[\begin{array}{cc} \gamma_1^T & \gamma_2^T & \gamma_3^T & \gamma_{4,\text{num}}^T & \gamma_{5,\text{num}}^T \end{array} \right]^T \tag{14.2}
$$

submechanisms (
$$
\gamma_4
$$
, γ_5) are solved numerically. The overall LCF of the RE-
CUPERA system at position, velocity, and acceleration levels are given by
Eqs. (14.2), (14.3), and (14.4), respectively.
\n
$$
\gamma = \begin{bmatrix} \gamma_1^T & \gamma_2^T & \gamma_3^T & \gamma_{4,\text{num}}^T & \gamma_{5,\text{num}}^T \end{bmatrix}^T \qquad (14.2)
$$
\n
$$
\mathbf{G} = \begin{bmatrix} \mathbf{G}_1 & 0 & 0 & 0 & 0 \\ 0 & \mathbf{G}_2 & 0 & 0 & 0 \\ 0 & 0 & \mathbf{G}_3 & 0 & 0 \\ 0 & 0 & 0 & \mathbf{G}_{4,\text{num}} & 0 \\ 0 & 0 & 0 & 0 & \mathbf{G}_{5,\text{num}} \end{bmatrix} \qquad (14.3)
$$
\n**Bynamics**\nOnce the LCF of the overall system is available, the equations of motion of the explicitly constrained series-parallel hybrid system can be derived in both forward and inverse managers. The inverse dynamic model is solved in

Dynamics

 $g = \begin{bmatrix} 0 & 0 & 0 & G_{4,num} & 0 \\ 0 & 0 & 0 & 0 & G_{5,num} \end{bmatrix}$
 $g = \begin{bmatrix} g_1^T & g_2^T & g_3^T & g_{4,num}^T & g_{5,num}^T \end{bmatrix}^T$ (14.4)

Dynamics

Once the LCF of the overall system is available, the equations of motion

of the explicitly co **b** $\mathbf{g} = \begin{bmatrix} 0 & 0 & 0 & 0 & \mathbf{G}_{5, num} \end{bmatrix}$
 bynamics

Once the LCF of the overall system is available, the equations of motion

of the explicitly constrained series-parallel hybrid system can be derived in

both fo **g** = $\begin{bmatrix} g_1^T & g_2^T & g_3^T & g_{4,num}^T & g_{5,num}^T \end{bmatrix}^T$ (

Dynamics

Once the LCF of the overall system is available, the equations of more the explicitly constrained series-parallel hybrid system can be derive both for Dynamics

Once the LCF of the overall system is available, the

of the explicitly constrained series-parallel hybrid system

both forward and inverse manners. The inverse dyna

real time to enable torque control
 14.3.3.1 Once the LCF of the overall system is available
of the explicitly constrained series-parallel hybric
both forward and inverse manners. The inverse d
real time to enable torque control of the system.
14.3.3.1 Exoskeleton c of the explicitly constrained series-parallel hybrid system can be derived in
both forward and inverse manners. The inverse dynamic model is solved in
real time to enable torque control of the system.
14.3.3.1 Exoskeleton

is implemented on FPGAs, each driving a single actuator using a cascaded position, a velocity, and a current control loop. Each of the control according a single actuator using a cascaded position, a velocity, and a curren real time to enable torque control of the system.
 14.3.3. Exoskeleton control
 14.3.3.1 First level control

As described in Sec. 14.2.2, the first level control architecture for each joint

is implemented on FPGAs, e Recupera exoskeletons 323

can be directly selected for control. In Fig. 14.4, we can see the actuator

level control architecture. With the help of motor current measurements, it

is possible to use torque control for the Recupera exoskeletons 323

can be directly selected for control. In Fig. 14.4, we can see the actuator

level control architecture. With the help of motor current measurements, it

is possible to use torque control for the Recupera exoskeletons 323

is possible to use torque control. In Fig. 14.4, we can see the actuator

level control architecture. With the help of motor current measurements, it

is possible to use torque control for the mo Recupera exoskeletons 323

can be directly selected for control. In Fig. 14.4, we can see the actuator

level control architecture. With the help of motor current measurements, it

is possible to use torque control for the Recupera exoskeletons 323

can be directly selected for control. In Fig. 14.4, we can see the actuator

level control architecture. With the help of motor current measurements, it

is possible to use torque control for the can be directly selected for control. In Fig. 14.4, we can see the actuator
level control architecture. With the help of motor current measurements, it
is possible to use torque control for the motors. Further, the actuato can be directly selected for control. In Fig. 14.4, we can see the actuator
level control architecture. With the help of motor current measurements, it
is possible to use torque control for the motors. Further, the actuato can be directly selected for control. In Fig. 14.4, we can see the actuator
level control architecture. With the help of motor current measurements, it
is possible to use torque control for the motors. Further, the actuato rever control architecture. With the neip or motor current measurements, it
is possible to use torque control for the motors. Further, the actuator level
modularity enables the implementation of decoupled safety checks at modularity enables the implementation of deco
mid level controllers. Position, velocity and curre
value and in case of a sensor failure the controlle
This low-level architecture meets the requirement
of therapy concepts an mid lever controllers. I osition, velocity and current are inflicted to a maximal
value and in case of a sensor failure the controller is stopped automatically.
This low-level architecture meets the requirements for the im

value and in case of a sensor failing the controller is stopped attomatically.
This low-level architecture meets the requirements for the implementation
of therapy concepts and teleoperation and is a solid foundation for b This low-lever attricecture metes the requirements for the implementation
of therapy concepts and teleoperation and is a solid foundation for both
kinematic and dynamic control implemented in the mid-level architecture.
1 the weight of the system is compensated with the help of an inverse dy-**14.3.3.2 Mid-level control**
 14.3.3.2 Mid-level control

The mid-level control architecture implements the kinematic and dynamic

model of the system and associated control approaches for rehabilitation

therapies and **14.3.3.2 Mid-level control**
The mid-level control architecture implements the kinematic and dynamic
model of the system and associated control approaches for rehabilitation
therapies and teleoperation. In the (1) *Gravity* The mid-level control architecture implements the kinematic and dynamic
model of the system and associated control approaches for rehabilitation
therapies and teleoperation. In the (1) *Gravity Compensation* (GC) mode,
the The mia-level control architecture implements the kinematic and aynamic
model of the system and associated control approaches for rehabilitation
therapies and teleoperation. In the (1) *Gravity Compensation* (GC) mode,
the model or the system and associated control approaches for renabilitation
therapies and teleoperation. In the (1) *Gravity Compensation* (GC) mode,
the weight of the system is compensated with the help of an inverse dy-
nam therapies and teleoperation. In the (1) Gravity Compensation (GC) mode,
the weight of the system is compensated with the help of an inverse dy-
namic model of the exoskeleton arms. GC mode can also be used to take
into acc the weight of the system is compensated with the help of an inverse dy-
namic model of the exoskeleton arms. GC mode can also be used to take
into account the dynamics of the human arms. The input to this model
is the actu namic model of the exoskeleton arms. GC mode can also be used to take
into account the dynamics of the human arms. The input to this model
is the actuator positions read from the position encoders (see Table 14.3).
The out into account the dynamics of the numan arms. The input to this model
is the actuator positions read from the position encoders (see Table 14.3).
The output is the reference torque values, which are then converted into
mot is the actuator positions read from the position encoders (see Table 14.5).
The output is the reference torque values, which are then converted into
motor current and sent to the current controller implemented in the ACU.
 The output is the reference torque values, which are then converted into
motor current and sent to the current controller implemented in the ACU.
The GC mode is used to implement a transparent behavior of the system
and re motor current and sent to the current controller implemented in the ACO.
The GC mode is used to implement a transparent behavior of the system
and represents the *basic operation mode* of the system, on which most of the
o The GC mode is used to implement a transparent behavior of the system
and represents the *basic operation mode* of the system, on which most of the
other modes are based on. Wrenches measured at the force-torque sensors
of and represents the *basic operation moae* of the system, on which most of the other modes are based on. Wrenches measured at the force-torque sensors of the exoskeleton arms can optionally be applied to assist human contro other modes are based on. Wrenches measured at the force-torque sensors
of the exoskeleton arms can optionally be applied to assist human control
of the exoskeleton. To support repetitive movement therapies for stroke
pati or the exoskeleton arms can optionally be applied to assist numan control
of the exoskeleton. To support repetitive movement therapies for stroke
patients, (2) Teach & Replay (TR) mode can be used. This mode has two
phases or the exoskeleton. To support repetitive movement therapies for stroke
patients, (2) Teach & Replay (TR) mode can be used. This mode has two
phases: First, gravity compensation for the affected arm is enabled so that
a th patients, (\angle) *leach* \leftrightarrow *Replay* (TK) mode can be used. This mode has two phases: First, gravity compensation for the affected arm is enabled so that a therapist can easily move the arm. The equipped touch sensor on phases: First, gravity compensation for the affected arm is enabled so that
a therapist can easily move the arm. The equipped touch sensor on the
forearm (see Fig. 14.3b) recognizes the intention of the therapist to teach
 a therapist can easily move the arm. The equipped touch sensor on the forearm (see Fig. 14.3b) recognizes the intention of the therapist to teach a movement and stores the trajectory (position and velocity readings from th forearm (see Fig. 14.3b) recognizes the intention of the therapist to teach
a movement and stores the trajectory (position and velocity readings from
the involved ACUs) in the system's storage device. Secondly, the traject a movement and stores the trajectory (position and velocity readings from
the involved ACUs) in the system's storage device. Secondly, the trajectory
can be replayed according to a trigger by the patient or therapist. Durthe involved ACOs) in the systems storage device. Secondly, the trajectory
can be replayed according to a trigger by the patient or therapist. Dur-
ing the replay, the exoskeleton executes the trajectory movement in the
ca can be replayed according to a trigger by the patient or therapist. During the replay, the exoskeleton executes the trajectory movement in the cascaded position-velocity control mode in the ACU. Additionally, mirror therap

**of the unhealthy arm. Further, sitting and standing features for the lower
part of the full-body exoskeleton are implemented at this level. As a new
feature for telemanipulation, a robotic arm or the arms of a dual armed** Biologically Inspired Series-Parallel Hybrid Robots
of the unhealthy arm. Further, sitting and standing features for the lower
part of the full-body exoskeleton are implemented at this level. As a new
feature for telemanip Feature for the unhealthy arm. Further, sitting and standing features for the lower
part of the full-body exoskeleton are implemented at this level. As a new
feature for telemanipulation, a robotic arm or the arms of a dua Biologically Inspired Series-Parallel Hybrid Robots
of the unhealthy arm. Further, sitting and standing features for the lower
part of the full-body exoskeleton are implemented at this level. As a new
feature for telemanip Biologically Inspired Series-Parallel Hybrid Robots

of the unhealthy arm. Further, sitting and standing features for the lower

part of the full-body exoskeleton are implemented at this level. As a new

feature for telema of the unhealthy arm. Further, sitting and standing features for the lower
part of the full-body exoskeleton are implemented at this level. As a new
feature for telemanipulation, a robotic arm or the arms of a dual armed
r of the unhealthy arm. Further, sitting and standing features for the lower
part of the full-body exoskeleton are implemented at this level. As a new
feature for telemanipulation, a robotic arm or the arms of a dual armed
r or the unhealthy arm. Further, sitting and standing reatures for the lower
part of the full-body exoskeleton are implemented at this level. As a new
feature for telemanipulation, a robotic arm or the arms of a dual armed
r part of the full-body exoskeleton are implemented at this level. As a new
feature for telemanipulation, a robotic arm or the arms of a dual armed
robot can be controlled using the (4) *Teleoperation* (TO) mode. The map-
pi feature for telemanipulation, a robotic arm or the arms of a dual armed
robot can be controlled using the (4) *Teleoperation* (TO) mode. The map-
ping between source system (exoskeleton) and target system (e.g., RH5
MANUS) robot can be controlled using the (4) *Ieleoperation* (1O) mode. The map-
ping between source system (exoskeleton) and target system (e.g., RH5
MANUS) is done by a Cartesian mapping of the poses of selected end-
effectors ping between source system (exoskeleton) and target system (e.g., KH5
MANUS) is done by a Cartesian mapping of the poses of selected end-
effectors and can be scaled in Cartesian space. For that, a predefined pose
mapping MANUS) is done by a Cartesian mapping of the poses of selected end-
effectors and can be scaled in Cartesian space. For that, a predefined pose
mapping between end-effector frames is needed by adding additional links
to th effectors and can be scaled in Cartesian space. For that, a predefimapping between end-effector frames is needed by adding additito the end-effectors in the URDF with a correcting transforma
force feedback, the force-torqu to the end-effectors in the URDF with a corre
force feedback, the force-torque sensor wrenche
mapped to and applied at the corresponding frai
Wrenches can also be scaled and capped before tl
oskeleton. Additionally, the th Force recuback, the force-torque sensor wrenches at the target system are
mapped to and applied at the corresponding frames of the source system.
Wrenches can also be scaled and capped before they are applied to the ex-
os

mapped to and applied at the corresponding maints of the solitec system.
Wrenches can also be scaled and capped before they are applied to the ex-
oskeleton. Additionally, the three trigger buttons on the left and right ha is with the start and capped before they are applied to the examples of the same of the parameter
faces can be mapped to gripper joints.
 14.3.3.3 High level control
 A web-based GUI is provided for high level control **14.3.3.3 High level control**
 14.3.3.3 High level control
 14.3.3.3 High level control
 A web-based GUI is provided for high level control of the exoskeleton

and can be accessed using a mobile phone, tablet or PC. **14.3.3.3 High level control**
 A web-based GUI is provided for high level control of the exoskeleton

and can be accessed using a mobile phone, tablet or PC. The web server

is hosted on ZynqBrain2 and based on the Pyth **14.3.3.3 High level control**
A web-based GUI is provided for high level control of the exoskeleton
and can be accessed using a mobile phone, tablet or PC. The web server
is hosted on ZynqBrain2 and based on the Python Fla erator of the exoskeleton
and can be accessed using a mobile phone, tablet or PC. The web server
is hosted on ZynqBrain2 and based on the Python Flask framework [24].
The GUI allows the user/therapist to select the operati A web-based GOI is provided tor high level control of the exoskeleton
and can be accessed using a mobile phone, tablet or PC. The web server
is hosted on ZynqBrain2 and based on the Python Flask framework [24].
The GUI all and can be accessed using a mobile phone, tablet or PC. The web server
is hosted on ZynqBrain2 and based on the Python Flask framework [24].
The GUI allows the user/therapist to select the operation mode of the ex-
oskelet is nosted on ZynqBrainz and based on the Python Flask framework [24].
The GUI allows the user/therapist to select the operation mode of the ex-
oskeleton, which can be either one of the different therapy modes (GC, M,
or T 1 ne GOI allows the user/therapist to select the operation mode of the ex-
oskeleton, which can be either one of the different therapy modes (GC, M,
or TR) or the TO mode. It is also possible to manage different patient/op oskeleton, which can be either one of the different therapy modes (GC, M,
or TR) or the TO mode. It is also possible to manage different patient/op-
erator profiles storing specific information like ID or recorded movement or 1 K) or the 1O mode. It is also possible to manage different patient/op-
erator profiles storing specific information like ID or recorded movements.
As the exoskeleton can be adjusted to the user, shoulder width, upper erator profiles storing specific information like ID or recorded movements.
As the exoskeleton can be adjusted to the user, shoulder width, upper arm
length, forearm length and hand size values can be entered in the GUI to As the exoskeleton can be adjusted to the user, shoulder width, upper arm
length, forearm length and hand size values can be entered in the GUI to
automatically create the corresponding user-specific URDF files with the
ad iength, torearm length and nand size values can be entered in the GOI to
automatically create the corresponding user-specific URDF files with the
adjusted segment lengths and inertia using PHOBOS. Moreover, it allows
the o automatically create the corresponding user-specific UKDF files with the adjusted segment lengths and inertia using PHOBOS. Moreover, it allows the operator to use the exoskeleton in different settings: single arm, dual ar adjusted segment lengths and inertia using PHOBOS. Moreover, it allow
the operator to use the exoskeleton in different settings: single arm, du
arm, full body, etc. Both left and right sided users can be supported. F
the T arm, full body, etc. Both left and right sided us
the TO mode, force feedback can be manually
force feedback changes the poses of the exoskele
in return changes the mapped end effector poses
it is also possible to disable The high- and mid-level control is implemented using the Robot Con-
struction Kiri (Rock Robot Control), so that the operator can have
force feedback without changing the target system.
14.3.3.4 **Software design**
The highstructure in the manner of the consected mand interacts, when
in return changes the mapped end effector poses of the teleoperated robot,
it is also possible to disable position control, so that the operator can have
force

In return enanges the mapped end encetor poses of the teleoperated robot,
it is also possible to disable position control, so that the operator can have
force feedback without changing the target system.
14.3.3.4 Software

Example at the table at the top right corner. The components required for each mode are
 Example at the top right corner. The components required for each mode are
 Example at the top right corner. The components req **Example Processing Web Server and States of Component Network Manager

Figure 14.7 Software architecture overview: A Component Network Manager

configures, connects and starts the subset of components (V) required for a
** Eigure 14.7 Software architecture overvier

configures, connects and starts the subse

specific mode. The corresponding directe

the table at the top right corner. The comp

also represented by colors. A web server a

used configures, connects and starts the subset of components (V) required for a
specific mode. The corresponding directed connections (E) are described in
the table at the top right corner. The components required for each mod specific mode. The corresponding directed connections (E) are described in
the table at the top right corner. The components required for each mode are
also represented by colors. A web server application hosted on ZynqBra

the table at the top right corner. The components required for each mode are
also represented by colors. A web server application hosted on ZynqBrain 2 is
used as user interface.
implementation called omniORB. Rock tasks, also represented by colors. A web server application hosted on ZynqBrain 2 is
used as user interface.
implementation called omniORB. Rock tasks, similar to ROS (Robot
Operating System) nodes, encapsulate different function implementation called omniORB. Rock tasks, similar to ROS (Robot
Operating System) nodes, encapsulate different functionalities, run inde-
pendently and provide input and output for other tasks (see Fig. 14.7).
Each task c implementation called omniORB. Rock tasks, similar to ROS (Robot
Operating System) nodes, encapsulate different functionalities, run inde-
pendently and provide input and output for other tasks (see Fig. 14.7).
Each task c implementation called omniORB. Rock tasks, similar to ROS (Robot
Operating System) nodes, encapsulate different functionalities, run inde-
pendently and provide input and output for other tasks (see Fig. 14.7).
Each task c Operating System) nodes, encapsulate different functionalities, run inde-
pendently and provide input and output for other tasks (see Fig. 14.7).
Each task can be configured individually. This enables a very flexible way
t pendently and provide input and output for other tasks (see Fig. 14.7).
Each task can be configured individually. This enables a very flexible way
to adjust the system and to distribute computational demanding compo-
nents Each task can be configured individually. This enables a very flexible way
to adjust the system and to distribute computational demanding compo-
nents among the two ZynqBrains. Additionally, a web server is running on
the to adjust the system and to distribute computa
nents among the two ZynqBrains. Additionally,
the second ZynqBrain, providing access to the
GUI written in JavaScript (see Section 14.3.3.3)
tionalities can be triggered by bi the second ZynqBrain, providing access to the p
GUI written in JavaScript (see Section 14.3.3.3). I
tionalities can be triggered by biosignals like elect
or electromyogram (EMG), which can be proces
bedded processors [3,17 The experimental results of the rehabilitation processors (EEG)
or electromyogram (EMG), which can be processed directly on the em-
bedded processors [3,17].
14.4 Results and discussion
This section presents the experime

or electromyogram (EMG), which can be processed directly on the em-
bedded processors [3,17].
 14.4 Results and discussion

This section presents the experimental results of the rehabilitation therapy

modes and the tel **14.4 Results and discussion**

This section presents the experimental results of the rehabilitation therapy

modes and the teleoperation implemented in the wheelchair configuration.

The rehabilitation modes were also tes **14.4 Results and discussion**
This section presents the experimental results of the rehabilitation therapy
modes and the teleoperation implemented in the wheelchair configuration.
The rehabilitation modes were also tested **14.4 Results and discussion**
This section presents the experimental results of the rehabilitation therapy
modes and the teleoperation implemented in the wheelchair configuration.
The rehabilitation modes were also tested **14.4 Results and discussion**
This section presents the experimental results of the rehabilitation therapy
modes and the teleoperation implemented in the wheelchair configuration.
The rehabilitation modes were also tested This section presents the experimental results
modes and the teleoperation implemented in th
The rehabilitation modes were also tested in c
individuals, see [26]. Since the upper body desi
figurations, the results are equa

Biologically Inspired Series-Parallel Hybrid Robots
 14.4.1 Gravity compensations mode

Transparency of the exoskeleton to the user requires a good gravity Biologically Inspired Series-Parallel Hybrid Robots
 Transparency of the exoskeleton to the user requires a good gravity com-

pensation model, which is also needed for a good usability for the therapist.

In our experim Biologically Inspired Series-Parallel Hybrid Robots
 14.4.1 Gravity compensations mode

Transparency of the exoskeleton to the user requires a good gravity com-

pensation model, which is also needed for a good usability Biologically Inspired Series-Parallel Hybrid Robots
 14.4.1 Gravity compensations mode

Transparency of the exoskeleton to the user requires a good gravity com-

pensation model, which is also needed for a good usability Biologically Inspired Series-Parallel Hybrid Robots
 14.4.1 Gravity compensations mode

Transparency of the exoskeleton to the user requires a good gravity com-

pensation model, which is also needed for a good usability **14.4.1 Gravity compensations mode**
Transparency of the exoskeleton to the user requires a good gravity com-
pensation model, which is also needed for a good usability for the therapist.
In our experiments, described in [**14.4.1 Gravity compensations mode**
Transparency of the exoskeleton to the user requires a good gravity com-
pensation model, which is also needed for a good usability for the therapist.
In our experiments, described in [Transparency of the exoskeleton to the user requires a good gravity com-
pensation model, which is also needed for a good usability for the therapist.
In our experiments, described in [22], the norm of mean absolute error
 Franchoff of the since the since of a good stability for the therapist.
In our experiments, described in [22], the norm of mean absolute error
(MAE) in joint space of four different balanced poses was between 0.12
Nm & 0.2 In our experiments, described in [22], the norm of mean absolute error (MAE) in joint space of four different balanced poses was between 0.12 Nm & 0.26 Nm, which demonstrates the good quality of the model. In the experimen m our enperature, accented in $[-1]$, the Herm of mean accented error (MAE) in joint space of four different balanced poses was between 0.12 Nm & 0.26 Nm, which demonstrates the good quality of the model. In the experiment (FILE) in joint space of four ametent bandled poses that between 0112 Nm & 0.26 Nm, which demonstrates the good quality of the model. In the experiments, the exoskeleton user was able to move its arms freely within the lim Finity of the exist of the exoskeleton user was able to move its arms freely within the limits of the system, as depicted in Fig. 14.8a. When using the gravity compensation mode, it is also possible to include the weight o needed. Example is being used for compensation.

arms into the model for compensation.

mode is being used for the get-in helper

tor or patient to easily enter the exoskele

a minute on average for healthy users if

needed.
 14. mode is being used for the get-in helper mode, er
tor or patient to easily enter the exoskeleton. Thi
a minute on average for healthy users if no adjus
needed.
14.4.2.1 Teach and replay
The teach and replay mode gives a tor or patient to easily enter the exoskeleton. This can be done in less than

a minute on average for healthy users if no adjustments to the system are
 14.4.2. Rehabilitation
 14.4.2.1 Teach and replay

The teach and

movements and later replay
 14.4.2. Rehabilitation
 14.4.2.1 Teach and replay
 16.4.2.1 Teach and replay

The teach and replay mode gives a therapist the possibility to pre-train

movements and later replay these as **14.4.2 Rehabilitation**
14.4.2.1 Teach and replay
The teach and replay mode gives a therapist the possibility to pre-train
movements and later replay these as a sequence or individually. The patient
can benefit from a se **14.4.2 Rehabilitation**
 14.4.2.1 Teach and replay

The teach and replay mode gives a therapist the possibility to pre-train

movements and later replay these as a sequence or individually. The patient

can benefit from **14.4.2 Rehabilitation**
 14.4.2.1 Teach and replay

The teach and replay mode gives a therapist the possibility to pre-train

movements and later replay these as a sequence or individually. The patient

can benefit from **14.4.2.1 Teach and replay**
The teach and replay mode gives a therapis
movements and later replay these as a sequenc
can benefit from a self-intended movement st
trained movement can be triggered via resid
with surface EMG The teach and feplay mode gives a theraphy
movements and later replay these as a sequence
can benefit from a self-intended movement strained movement can be triggered via resid
with surface EMG and thus give the patien
pac can benefit from a self-intended movement start, since the replay of a pre-
trained movement can be triggered via residual muscle activity measured
with surface EMG and thus give the patient the possibility to train self-

trained movement can be triggered via residual muscle activity measured
with surface EMG and thus give the patient the possibility to train self-
paced, shown in Fig. 14.8b.
14.4.2.2 Mirror mode
The mirror mode mimics a with surface EMG and thus give the patient the possibility to train self-
paced, shown in Fig. 14.8b.
14.4.2.2 Mirror mode
The mirror mode mimics a mirror therapy by directly transferring move-
ments from the healthy ar paced, shown in Fig. 14.8b.
 14.4.2.2 Mirror mode

The mirror mode mimics a mirror therapy by directly transferring move-

ments from the healthy arm to the affected one. In this mode, the non-

affected arm controls or **14.4.2.2 Mirror mode**
The mirror mode mimics a mirror therapy by directly transferring move-
ments from the healthy arm to the affected one. In this mode, the non-
affected arm controls or moves the exoskeleton in the gra **14.4.2.2 Mirror mode**
The mirror mode mimics a mirror therapy by directly
ments from the healthy arm to the affected one. In th
affected arm controls or moves the exoskeleton in the gra
mode. All movements are mirrored to The infrior mode infinites a finitior therapy by diffecty transferring inove-
ments from the healthy arm to the affected one. In this mode, the non-
affected arm controls or moves the exoskeleton in the gravity compensatio affected arm controls or moves the exoskeleton in the gravity compensation
mode. All movements are mirrored to the affected side which is running in
the position control mode (see Fig. 14.8c). With this mode, the patient i

mode. All movements are mirrored to the affected side which is running in
the position control mode (see Fig. 14.8c). With this mode, the patient is
able to do self-determined training.
14.4.2.3 Gravity compensation with the position control mode (see Fig. 14.8c). With this mode, the patient is
able to do self-determined training.
14.4.2.3 Gravity compensation with human arm model
As an addition to the pure gravity compensation mode, the The same and the of odes the determined training.
 14.4.2.3 Gravity compensation with human arm model

As an addition to the pure gravity compensation mode, the weight of the

arm of the user can be modeled as well. In t

(a) Gravity Compensation Mode: base mode for mechanical transparency.

(b) Teach and Replay Mode: recorded movements are replayed.

(c) Mirror Mode: all movements are mirrored from the right to the left side.

Figure 14.8 Selected modes of exoskeleton use.

any constraints like in the other modes where the movements are prairied or mirrored from the no Figure 14.8 Selected modes of exoskelet
any constraints like in the other mode
trained or mirrored from the non-affect
14.4.3 Teleoperation
In teleoperation
In teleoperation

Figure 14.8 Selected modes of exoskeleton use.

any constraints like in the other modes where the movements are pre-

trained or mirrored from the non-affected side.
 14.4.3 Teleoperation

In teleoperation mode, we are a any constraints like in the other modes where the movements are pre-
trained or mirrored from the non-affected side.
14.4.3 Teleoperation
In teleoperation mode, we are able to remotely control both the arms of
our humano any constraints like in the other modes where the movements are pre-
trained or mirrored from the non-affected side.
 14.4.3 Teleoperation

In teleoperation mode, we are able to remotely control both the arms of

our hum **14.4.3 Teleoperation**
 14.4.3 Teleoperation

In teleoperation mode, we are able to remotely control both the arms of

our humanoid robot RH5 MANUS. The elbow and wrist poses of the

exoskeleton were mapped to RH5 MANUS, **14.4.3 Teleoperation**
In teleoperation mode, we are able to remotely control both the arms of
our humanoid robot RH5 MANUS. The elbow and wrist poses of the
exoskeleton were mapped to RH5 MANUS, while wrenches measured
at **14.4.3 Teleoperation**
In teleoperation mode, we are able to remotely control both the arms of
our humanoid robot RH5 MANUS. The elbow and wrist poses of the
exoskeleton were mapped to RH5 MANUS, while wrenches measured
at In teleoperation mode, we are able to remotely control both the arms of
our humanoid robot RH5 MANUS. The elbow and wrist poses of the
exoskeleton were mapped to RH5 MANUS, while wrenches measured
at the force-torque sens In teleoperation mode, we are able to femolely control both the arms of
our humanoid robot RH5 MANUS. The elbow and wrist poses of the
exoskeleton were mapped to RH5 MANUS, while wrenches measured
at the force-torque senso our humanoid robot RH5 MANUS. The elbow and wrist poses of the exoskeleton were mapped to RH5 MANUS, while wrenches measured at the force-torque sensors in the wrists of the humanoid were applied at corresponding links of In further exists, we were also able to grasp an object like a box or a soft with both hands at the software applied corresponding links of the exoskeleton. Using the trigger buttons at the dinterfaces, the fingers of the at the force-torque sensors in the wrists of the humanoid were applied
at corresponding links of the exoskeleton. Using the trigger buttons at the
hand interfaces, the fingers of the two-finger and four-finger grippers cou at corresponding miks of the exoskeretor. Osing the tigger buttons at hand interfaces, the fingers of the two-finger and four-finger grippers co be controlled independently. With this setup, it was possible to grasp a pick

Figure 14.9 Exoskeleton teleoperating RH5 MANUS.
In all our teleoperation tests, Cartesian workspace scaling has proven to
be a helpful tool, especially for robots with different workspaces than the
exoskeleton. Workspace Figure 14.9 Exoskeleton teleoperating RH5 MANUS.

In all our teleoperation tests, Cartesian workspace scaling has proven to

be a helpful tool, especially for robots with different workspaces than the

exoskeleton. Workspa Figure 14.9 Exoskeleton teleoperating RH5 MANUS.
In all our teleoperation tests, Cartesian workspace scaling has proven to
be a helpful tool, especially for robots with different workspaces than the
exoskeleton. Workspace In all our teleoperation tests, Cartesian workspace scaling has pro
be a helpful tool, especially for robots with different workspaces the
exoskeleton. Workspace scaling can also be used to scale down the h
movement and th In all our teleoperation tests, Cartesian workspace scaling has proven to
be a helpful tool, especially for robots with different workspaces than the
exoskeleton. Workspace scaling can also be used to scale down the human
 be a helptul tool, especially for robots with different workspaces than the
exoskeleton. Workspace scaling can also be used to scale down the human
movement and therefore enable a very precise pose control. Also, the scali

exoskeleton. Workspace scaling can also be used to scale down the human
movement and therefore enable a very precise pose control. Also, the scaling
can be chosen according to the current task.
14.4.4 Comparison with simi movement and therefore enable a very precise pose control. Also, the scaling
can be chosen according to the current task.
14.4.4 Comparison with similar exoskeleton systems
A classification of the exoskeleton can be done **14.4.4 Comparison with similar exoskeleton systems**
A classification of the exoskeleton can be done by featuring active DOF,
ROM, mobility, number of tracked limbs and weight. A comparison with
similar upper body exoskele 14.4.4 Comparison with similar exosteleton systems
A classification of the exoskeleton can be done by featuring active DOF,
ROM, mobility, number of tracked limbs and weight. A comparison with
similar upper body exoskeleto A classification of the exoskeleton can be done by featuring active DOF,
ROM, mobility, number of tracked limbs and weight. A comparison with
similar upper body exoskeleton systems in Table 14.4 shows that the RE-
CUPERA u ROM, mobility, number of tracked limbs and weight. A comparison with
similar upper body exoskeleton systems in Table 14.4 shows that the RE-
CUPERA upper body exoskeleton has the best lightweight design. The
RECUPERA exosk similar upper body exoskeleton systems in Table 14.4 shows that the RE-
CUPERA upper body exoskeleton has the best lightweight design. The
RECUPERA exoskeleton is a mobile system mounted to a commercially
available wheelch CUPERA upper body exoskeleton has the best lightweight design. The
RECUPERA exoskeleton is a mobile system mounted to a commercially
available wheelchair. It has a high amount of active DOFs with a low
weight. The total we RECUPERA exoskeleton is a mobile system mounted to a commercially
available wheelchair. It has a high amount of active DOFs with a low
weight. The total weight of an arm after enhancing the system to active
7DOF is 7.14 kg available wheelchair. It has a high amount of active DOFs with a low
weight. The total weight of an arm after enhancing the system to active
7DOF is 7.14 kg. This also includes an active hand interface for teleoper-
ation. weight. The total weight of an arm after enhancing the system to active
7 DOF is 7.14 kg. This also includes an active hand interface for teleoper-
ation. By modifying the arms, the ROM of the elbows and forearms was
signi 7 DOF is 7.14 kg. This also includes an active hand interface for teleoperation. By modifying the arms, the ROM of the elbows and forearms was significantly increased. Although it does not cover the complete human workspac ation. By modifying the arms, the ROM of the elbows and forearms was
significantly increased. Although it does not cover the complete human
workspace, it supports most activities of daily living tasks. The alternative
incl significantly increased. Although it does not cover the complete human
workspace, it supports most activities of daily living tasks. The alternative
inclusion of an active shoulder girdle would have increased shoulder ROM
 ing.

Table 14.4 Comparison of updated RECUPERA upper-body system to other upper-body exoskeletons and the range of motion of activities of daily living.								
Device	RECUPERA	ANYexo $[27]$	Harmony $[11]$	SUEFUL-6 [28]	ADL [11, 29, 30]			
Weight (kg)	14.3	12.98	31.2					
DOF	14	7	14	6				
Bilateral	yes	no	yes	no				
Torso harness	yes	no	yes	no				
Gripper	yes	no	no	no				
Wheelchair	yes	no	no	yes				
Abd./Adduction \circ (Nm)	87/40(28)	170/0(40)	170/60(34)	$\overline{}$	131/54			
Ex./Int. rot. $\rm ^{\circ}$ (Nm)	40/75(18)	105/105(40)	79/80(34)	0/90(35)	76/62			
Flex./Ext. \circ (Nm)	170/30(28)	170/50(40)	160/45(34)	0/90(9)	131/51			
Elbow flex. $\rm ^{\circ}$ (Nm)	145(18)	145(40)	150(13)	120(9)	148			
Pro/supinat. \circ (Nm)	176(7.1)	$\overline{}$	172(1.25)	140(4)	167			
Wrist Abd./Add. \circ (Nm)	20/40(3.4)			20/30	30/40			
Wrist Flex./Ext. \circ (Nm)	43/43(3.4)			60/50	60/60			

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Table 14.4 Comparison of updated RECUPERA upper-body system to other
upper-body exoskeletons and the range of motion of activities of daily living.
Device RECUPERA ANYexo Harmony SUEFUL-6 ADL Recupera exoskeletons 329
 Table 14.4 Comparison of updated RECUPERA upper-body system to other

upper-body exoskeletons and the range of motion of activities of daily living.

Device RECUPERA ANYexo Harmony SUEFUL-6 ADL

Wrist Flex./Ext. $\left| \frac{43}{43.43(3.4)} \right|$ - $\left| \frac{60}{50} \right|$ 60/60
 $\frac{60}{60}$
 14.5 Conclusion and outlook

The RECUPERA exoskeletons are two modular, lightweight, safe and ergonomically adaptable robotic systems tha Wrist Flex./Ext. $|43/43(3.4)|$ -
 $^{\circ}$ (Nm) $^{\circ}$ - $|60/50|$ $|60/60|$
 14.5 Conclusion and outlook

The RECUPERA exoskeletons are two modular, lightweight, safe and ergonomically adaptable robotic systems that serve **14.5 Conclusion and outlook**
The RECUPERA exoskeletons are two modular, lightweight, safe and ergonomically adaptable robotic systems that serve to capture and guide human movement. The upper-body part system attached to **14.5 Conclusion and outlook**
The RECUPERA exoskeletons are two modular, lightweight, safe and ergonomically adaptable robotic systems that serve to capture and guide human movement. The upper-body part system attached to **14.5 Conclusion and outlook**
The RECUPERA exoskeletons are two modular, lightweight, safe and ergonomically adaptable robotic systems that serve to capture and guide human movement. The upper-body part system attached to The RECUPERA exoskeletons are two modular, lightweight, safe and ergonomically adaptable robotic systems that serve to capture and guide human movement. The upper-body part system attached to a wheelchair, as a partial var I he KECUPERA exoskeletons are two modular, lightweight, sate and er-
gonomically adaptable robotic systems that serve to capture and guide hu-
man movement. The upper-body part system attached to a wheelchair, as a
partia gonomically adaptable robotic systems that serve to capture and guide hu-
man movement. The upper-body part system attached to a wheelchair, as a
partial variant of the full-body system, reduces complexity and transfers it man movement. The upper-body part system attached to a wheelchair, as a
partial variant of the full-body system, reduces complexity and transfers its
own weight to the floor via the wheelchair. However, the full-body syste partial variant of the full-body system, reduces complexity and transfers its
own weight to the floor via the wheelchair. However, the full-body system
supports its own weight and enables a wider range of movement due to a own weight to the floor via the wheelchair. However, the full-body system
supports its own weight and enables a wider range of movement due to an
active back. The active legs enable a sitting posture through an extendable
 supports its own weight and enables a wider range of movement due to an
active back. The active legs enable a sitting posture through an extendable
seat mechanism. Both systems can be used for rehabilitation applications
a active back. The active legs enable a sitting posture through an extendable
seat mechanism. Both systems can be used for rehabilitation applications
and for teleoperation. Since the systems are designed as rigid exoskeleto seat mechanism. Both systems can be used for rehabilitation applicand for teleoperation. Since the systems are designed as rigid exoskel
the range of motion and system dynamics must be optimally suited fc
chanical transpar

Biologically Inspired Series-Parallel Hybrid Robots
The RECUPERA exoskeleton was used in two application scenarios.
Ing gravity compensation mode as a basic function, the exoskeleton is
supporting and allows free movement Biologically Inspired Series-Parallel Hybrid Robots

The RECUPERA exoskeleton was used in two application scenarios.

Using gravity compensation mode as a basic function, the exoskeleton is

self-supporting and allows free Sologically Inspired Series-Parallel Hybrid Robots
The RECUPERA exoskeleton was used in two application scenarios.
Using gravity compensation mode as a basic function, the exoskeleton is
self-supporting and allows free mov Biologically Inspired Series-Parallel Hybrid Robots

The RECUPERA exoskeleton was used in two application scenarios.

Using gravity compensation mode as a basic function, the exoskeleton is

self-supporting and allows free Biologically Inspired Series-Parallel Hybrid Robots

The RECUPERA exoskeleton was used in two application scenarios.

Using gravity compensation mode as a basic function, the exoskeleton is

self-supporting and allows free The RECUPERA exoskeleton was used in two application scenarios.
Using gravity compensation mode as a basic function, the exoskeleton is
self-supporting and allows free movement of the user. The humanoid robot
RH5 MANUS was The RECUPERA exoskeleton was used in two application scenarios.
Using gravity compensation mode as a basic function, the exoskeleton is
self-supporting and allows free movement of the user. The humanoid robot
RH5 MANUS was The Tector Ener chosicated was dised in two application scenarios.
Using gravity compensation mode as a basic function, the exoskeleton is
self-supporting and allows free movement of the user. The humanoid robot
RH5 MANUS Esing gravity compensation mote as a basic ranction, the chosicated is
self-supporting and allows free movement of the user. The humanoid robot
RH5 MANUS was remotely controlled. Through the exoskeleton a hap-
tic impressi Sear supporting and allows itee inovelinent of the discribit rise in an hap-
RH5 MANUS was remotely controlled. Through the exoskeleton a hap-
tic impression of the object manipulation was given using force feedback.
Addit For the minitory was tentotely controlled. Through the exostected a nap-
tic impression of the object manipulation was given using force feedback.
Additionally, Cartesian workspace scaling enables a precise remote con-
tro are impression of the expect manipulation was given asing force recubated.
Additionally, Cartesian workspace scaling enables a precise remote control. When manipulating an object similar to a ring using a dual arm power
gr matatonal, cartesian workspace sealing entotes a precise tentote control. When manipulating an object similar to a ring using a dual arm power grasp, this introduced a kinematic closed loop of both the arms, which were now from When mamputating an object similar to a ring using a tidal arm power
grasp, this introduced a kinematic closed loop of both the arms, which were
now connected through the object. Due to latencies introduced by the two grasp, this intoclated a kinematic en
now connected through the object.
systems, the interaction forces of th
fore with the other arm could not l
and the system was rocking up. Ad
mode for the wrists at mid-level confect. For example and ough the object. But to therefore, mistodated by the two
ems, the interaction forces of the two arms with the object and there-
e with the other arm could not be compensated by the human operator
the system by seems, the interaction forces of the two arms with the object and these fore with the other arm could not be compensated by the human operator and the system was rocking up. Additional tests with activated compliance mo ore with the other and too the compensated by the heliand operator
and the system was rocking up. Additional tests with activated compliance
mode for the wrists at mid-level control of RH5 MANUS reduced this ef-
fect. Furt

restriction different modes were supporting rehabilitation different model for the wrists at mid-level control of RH5 MANUS reduced this effect. Further research needs to be done in this direction to enable dual arm power The assist-as-needed technique in this direction to enable dual arm
wer grasping.
As a rehabilitation application, mirror therapy and EMG triggered Teach
Replay mode as well as the arm weight compensation model were tested proven to proven to proven the above discussed Teach Ac Replay and EMG triggered Teach

See Replay mode as well as the arm weight compensation model were tested

with patients. It was observed that depending on the severit

ing the patient to actively and the movements (actively and EMG triggered Teach

& Replay mode as well as the arm weight compensation model were tested

with patients. It was observed that depending on the severity of the Example above as well as the arm weight compensation model were tested
with patients. It was observed that depending on the severity of the patient's
restriction different modes were supporting rehabilitation therapy best. the particular state and as the entire work distribution the exosteleton different modes were supporting rehabilitation therapy best.
The assist-as-needed technique in assistive robotic rehabilitation has proven to promote mate the above that depending on the several of the patients
restriction different modes were supporting rehabilitation therapy best.
The assist-as-needed technique in assistive robotic rehabilitation has
proven to promote The assist-as-needed technique in assistive robotic rehabilitation has
proven to promote motor recovery and induce neuroplasticity by encourag-
ing the patient to actively participate in the movements [31]. This is in star The assist as needed deemique in assistive footal femalmiation has
proven to promote motor recovery and induce neuroplasticity by encourag-
ing the patient to actively participate in the movements [31]. This is in stark
co the particular ability participate in the movements [31]. This is in stark
contrast to the above discussed Teach & Replay and Mirror modes, where
the exoskeleton does the entire work. To deviate from this and give the
pati the particle will be above discussed Teach & Replay and Mirror modes, where the exoskeleton does the entire work. To deviate from this and give the patient full control of initiating and executing these movements up to th the exoskeleton does the entire work. To deviate from this and give th
patient full control of initiating and executing these movements up to thei
current capabilities, this technique will be integrated into the exoskeleto Experience the task is technique will be integrated into the exoskeleton
tent full control of initiating and executing these movements up to their
rent capabilities, this technique will be integrated into the exoskeleton
i putern ran control of mustaring and exceding these movements applies to the current capabilities, this technique will be integrated into the exoskeleton design in the near future. In essence, this technique encourages the

tearient capabridies, this technique will be integrated into the chosactednic design in the near future. In essence, this technique encourages the patient to carry out movements depending upon their muscular ability and as design in the lear tatate. In essence, ans teeninque encountges are pattent
to carry out movements depending upon their muscular ability and assis-
tance will be provided only when they are deviating significantly from the be carry our invention depending apon their intseduar ability and assistance will be provided only when they are deviating significantly from the desired trajectory to guide them towards the target.
To this end, the task i signal experiments have been conducted at DFKI in this regard
their this end, the task is divided into three categories – initial calibration,
online estimation of muscle torques and assistive control. In the calibra-
tion To this end, the task is divided into three categories – initial calibration,
online estimation of muscle torques and assistive control. In the calibra-
tion phase, Maximum Voluntary Isometric Contraction would be used to
 regression model and for multiple joints using a two-layer artificial neural embedded and assistive control. In the calibration phase, Maximum Voluntary Isometric Contraction would be used to generate a preliminary estimat

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network model, for which further improvements and validations are still

needed. The results will be published in the near future.

Furthermore to ensure that the patient is provided with a free Recupera exoskeletons 331

network model, for which further improvements and validations are still

needed. The results will be published in the near future.

Furthermore, to ensure that the patient is provided with a free

Furthermore, to ensure that the patients and validations are still
feed. The results will be published in the near future.
Furthermore, to ensure that the patient is provided with a free zone
and the desired trajectory, a Recupera exoskeletons 331

are twork model, for which further improvements and validations are still

are ded. The results will be published in the near future.

Furthermore, to ensure that the patient is provided with a f Recupera exoskeletons 331
network model, for which further improvements and validations are still
needed. The results will be published in the near future.
Furthermore, to ensure that the patient is provided with a free zo network model, for which further improvements and validations are still
needed. The results will be published in the near future.
Furthermore, to ensure that the patient is provided with a free zone
around the desired traj network model, for which further improvements and validations are still
needed. The results will be published in the near future.
Furthermore, to ensure that the patient is provided with a free zone
around the desired traj round the desired trajectory, a tunnel-based torque controller is planned

o be implemented. As the performance of the controller depends on the

ccuracy of the inverse dynamic model, it forms a major bottleneck and its

u e implemented. As the performance of the controller depends on the
racy of the inverse dynamic model, it forms a major bottleneck and its
ity needs to be further investigated in the future.
erences
E Just, Ö. Özen, P. Bö Facty of the inverse dynamic model, it forms a major bottleneck and its
ity needs to be further investigated in the future.
ETENCES
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Rauter, E

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- ecuracy of the inverse dynamic model, it forms a major bottleneck and its

uality needs to be further investigated in the future.
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 erences

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Rauter, Exoskeleton transparency: feed-forward compensation vs. disturbance ob **ET Just, Ö. Özen, P. Bösch, H. Bobrovsky, Nauter, Exoskeleton transparency: feed-forval Rauter, Exoskeleton transparency: feed-forval Sale (12) (2)
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