Figure 8.14 The first version of the NEUROExos

8.5 CASE STUDY: AN UPPER LIMB POWERED EXOSKELETON

J. C. Perry and J. Rosen

Department of Electrical Engineering, University of Washington, Seattle, Washington, USA

The system described in this case study is the third generation of an upper limb powered exoskeleton. Previous generations included a 1 DoF system (elbow joint, Figures 8.15(a) and (b)) and a 3 DoF system, with 2 DoF at the shoulder joint and 1 DoF at the elbow joint (Figure 8.15(c)). These systems were previously used to develop neural control algorithms for the upper limb (Rosen, Fuchs and arcan, 1999; Rosen *et al.*, 2001). The third exoskeleton generation is a 7 DoF system which is the end result of a research effort reported in part by this case study. The system underwent several design iterations, depicted in Figures 8.15(d), (e) and (f). The final two-arm exoskeleton system is depicted in Figure 8.15(g).

8.5.1 Exoskeleton design

The design and development of a high-performance robotic device is a process with numerous competing factors. The mechanism weight and stiffness exist at opposite ends of the spectrum, the goal being to achieve the highest structural rigidity while maintaining the lowest segmental inertias. Contributing to these underlying requirements are factors such as the operational workspace, desired joint torques, motor placement, link design and cable selection. Since the device will operate in direct contact with humans, additional requirements emerge regarding comfort and safety of operation.

8.5.1.1 Design requirements

Kinematics and dynamics. In order to promote high performance while ensuring safe operation, the requirements must be realized and understood both from their technical as well as their functional

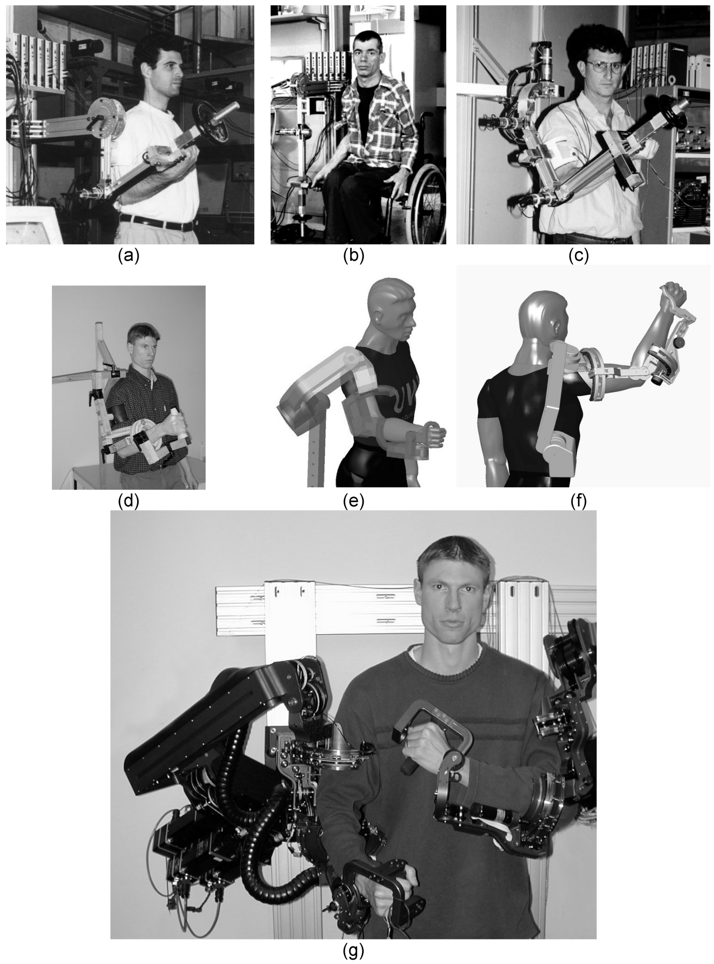


Figure 8.15 The first two prototypes of an upper limb powered exoskeleton. (a) A 1 DoF (elbow joint) powered exoskeleton was developed as a proof of the concept using myosignals as the primary command signals. (b) The 1 DoF exoskeleton system tested with a disabled person suffering from Tay-Sachs. (c) The 3 DoF (two shoulder joints, one elbow joint) powered exoskeleton was developed to study joint dependency during manipulation. (d) A wooden mockup including 7 DoF similar to the final design – note the singular configuration of the shoulder joint due to the joints orientation. (e) A conceptual CAD model of the 7 DoF exoskeleton arm – note how the two exoskeleton shoulder joints were reoriented to position the singular configuration on the periphery of the human arm workspace. (f) A detailed CAD design of the 7 DoF Exoskeleton arm (g) Two 7 DoF Exoskeleton arms

aspects. To understand the kinematic and dynamic requirements of an exoskeleton arm for functional use better, a subject study ($n = 6$) analysing the kinematics and the dynamics of the human arm was first performed. In the study, upper limb kinematics were acquired with a motion capture system while subjects performed 24 activities of daily living. Based on previous surveys of the disabled community, the 24 activities were divided among the following four activity categories: general reaching, functional actions, eating and drinking, and hygiene. Utilizing a 7 DoF computational model of the human arm, the equations of motion were used to calculate joint torques from measured kinematics, resulting in a database that may provide a fundamental basis towards the development of assistive technologies for the human arm. Further details of the study may be found in Perry (2006) and Rosen *et al.* (2005).

Results of joint position and joint torque about each axis were condensed to a single set of histograms (Perry, 2006) (see Figure 8.16). While some position distributions appear quite normal in shape, others possess a bimodal or even trimodal form, where the centres of modes correspond to key anthropomorphic configurations. These configurations are positions of the arm that occur commonly throughout daily activities, often where joint velocities remain near zero at the initial or final periods of motion trajectories. In joint torque calculations, velocital and accelerational components were

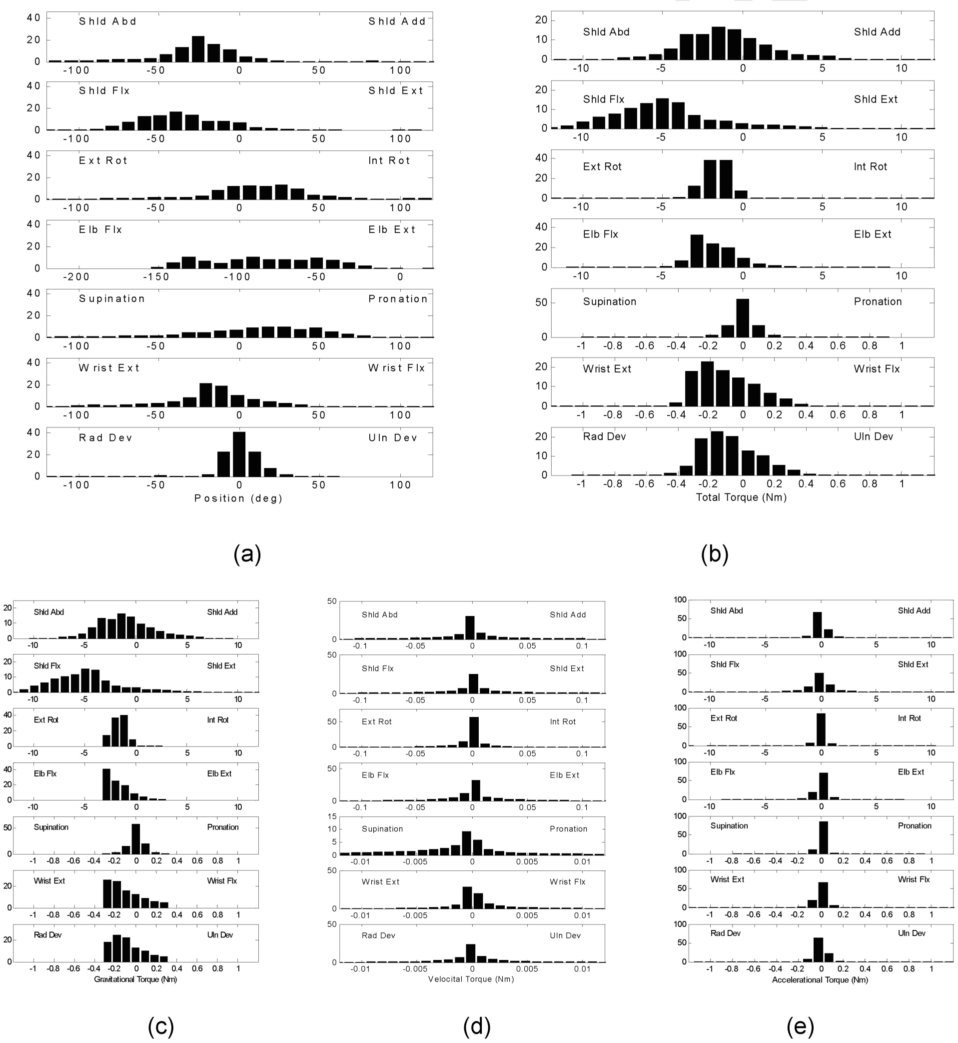


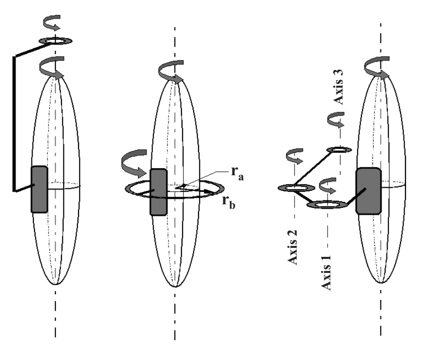
Figure 8.16 (a) Values of position (degrees) and (b) torque (N m) generated during daily activities at each of the 7 DoFs. Torque is expressed in terms of gravitational torque (c), velocital torque (d) and accelerational torque (e)

normally distributed about 0 N m, whereas gravitational component distributions varied with the joint. Additionally, velocital effects were found to contribute only one-hundredth the total joint torque, whereas accelerational components contribute one-tenth of the total torque at the shoulder and elbow, and nearly half of the total torque at the wrist. The results of the study led directly towards the definition of mechanical and functional requirements for the design, and also provided insight regarding dominant aspects of dynamic motion that can be exploited in the implementation of a controller.

Mechanical human machine interfaces (mHMI). The mHMI, known throughout this book as pHRi, are the physical components that mechanically couple the human arm and the exoskeleton structure and enable force transmission between them. With awareness that one intended population of users will possess varying levels of muscular and functional impairment, an emphasis was placed on designing an interface that can easily be attached to the user.

To achieve axial rotation of exoskeleton limbs, three primary exoskeletal configurations are conceivable, and are illustrated in Figure 8.17. The first two configurations (Figures 8.17(a) and (b)) involve a single DoF bearing with its axis of rotation aligned collinearly with the approximate anatomical axis of rotation of the segment, while the third configuration (Figure 8.17(c)) involves a first axis that is displaced from the anatomical axis and a minimum of two additional noncollinear axes. In the first two configurations, the exoskeleton joint can be placed at either end of the long axis of the segment (Figure 8.17(a)), or axially between the ends of the segment (Figure 8.17(b)) using a bearing of minimum radius, r^b, greater than the maximum anthropometrical radius, r^a, about the corresponding segment axis. The additional axes of the third configuration are required to correct for noncollinearity of the first axis with respect to the rotating segment.

The configuration in Figure 8.17(a) offers a simple solution that allows for proximal placement of heavy components such as bearings and actuators, reducing inertial effects on power consumption, but the placement is undesirable due to human–machine interferences during shoulder abduction. The configuration in Figure 8.17(c) can avoid the interferences by displacing the joint axis laterally from the segment axis of rotation. However, the two additional joints, adding undesired weight and complexity to the design, are necessary to maintain proper rotation, as was achieved in previous configurations through the use of a single joint. The configuration in Figure 8.17(b) offers an alternative



(a) (b) (c)

Figure 8.17 Three exoskeleton configurations that achieve rotation about the long axis of a limb segment, involving (a) a proximally placed single DoF, (b) a circumferencially placed single DoF and (c) three parallel, noncollinear DoFs single DoF solution where the human–machine interferences associated with configuration 3a can be removed. Full 360° bearings in this arrangement interfere with the torso when the arm is at rest or during motions that place distal arm joints near the body. Alternatively, these interferences can be removed through substitution of the full bearing with a partial bearing where the bearing track is affixed to the proximal exoskeleton link.

Current strength-to-weight limitations of available hardware necessitate nonmobile platforms for immediate upper limb exoskeleton technologies and, consequently, more user-friendly mHMIs. Strength-to-weight ratios of existing materials and electric motors, as well as energy-to-weight ratios of power supplies are not yet at the level necessary to support development of mobile platforms for partial-body upper limb exoskeletons. As a result, a full-body exoskeleton is required to support the existing weight of state-of-the-art power supplies, onboard controllers and other upper limb hardware.

Modelling the human arm. Anthropomorphic joint approximations can be modelled at varying degrees of accuracy and complexity (Kapandji, 1982). The level of complexity needed for a suitable representation greatly depends on the desired tasks to be performed and replicated using the model. Shoulder motion, for example, composed of glenohumeral (GH), acromioclavicular and sternoclavicular articulations, can be represented by the GH joint for a variety of arm activities involving up to 90° of arm elevation. With minimal activity exceeding this range, a simplified model of the shoulder was deemed appropriate for the study. The GH movement can further be simplified to a ball-and-socket joint composed of three orthogonal axes intersecting at the centre of the humeral head, although the true centre of rotation is known to vary with arm orientation (Kapandji, 1982). Rotations about these orthogonal axes may be treated as Euler rotation. The order of flexion–extension and abduction–adduction about the first two axes is arbitrary but should be noted, while the third rotation corresponds to internal–external rotation.

Pronosupination of the forearm has been treated interchangeably in literature as a freedom of the elbow and as a freedom of the wrist. In either case, it should be considered directly adjacent to the forearm, occurring after elbow flexion and before either wrist flexion or deviation, with the axis of rotation running approximately through the 5th metacarpal–phalangeal joint (Kapandji, 1982).

The wrist can be modelled as two orthogonal axes with a fixed offset between them (Kapandji, 1982). The proximal and distal axes of the wrist correspond to wrist flexion–extension and wrist radial–ulnar deviation respectively.

Performance. A widely used quantitative measure to evaluate system performance is bandwidth. Systems having a higher bandwidth are controllable under higher frequency command signals. Limited by the system's lowest natural frequency, the bandwidth is a measure of how successfully tradeoffs between weight and stiffness are made. A target bandwidth of 10 Hz was selected based on the achievable frequency range of the human arm, which resides between 2 and 5 Hz (Kazerooni, 1990). Additional target values for the design include: weight (moving links) of 6.8 kg, maximum static payload of 2.5 kg, maximum angular deflection of 2° per joint and bandwidth of 0–10 Hz. The actual weight was 3.5 kg and 6.3 kg for link 1 and links 2–7 respectively, where links are numbered sequentially between joints and link 1 corresponds to the segment between joints 1 and 2 (Figure 8.17(e)).

Safety Requirements. Paramount to all HMIs is the guarantee of safe operation. Safety precautions have been implemented on three levels, built into the mechanical, electrical and software designs. In the mechanical design, physical stops prevent segments from excessive excursions that could hyperextend or hyperflex individual joints. Electrical brakes that can be added to the actuators allow the system to freeze the exoskeleton arm configuration mechanically in response to an emergency stop (e-stop). The electrical system is equipped with three emergency shutoff switches: an enable button that terminates the motor command signal upon release, a large e-stop button for complete power shutoff by the observer and a similar e-stop foot switch for the user.

Ideally, the above safety measures would go unused as a result of adequate safeguards at the software level. Redundant position sensors, one at either end of the powertrain, monitor both joint motion as well as motor position. Differentiation of position provides knowledge of velocity and acceleration, both of which are incorporated into the control structure to prevent undesirable effects when approaching the joint limits. Redundancy of position sensing also enables software to monitor power transmission integrity. Any slip occurring between the motors and the end-effector will result in a position discrepancy and lead to immediate system shut-down. Software limits are implemented on commanded motor currents, i.e. motor torques.

8.5.1.2 Exoskeleton design

Exoskeletal joint design. Articulation of the exoskeleton is achieved about seven single-axis revolute joints: one for each shoulder abduction–adduction, shoulder flexion–extension, shoulder internal–external rotation, elbow flexion–extension, forearm pronation–supination, wrist flexion–extension and wrist radial–ulnar deviation. The exoskeletal joints are labelled 1 to 7 from proximal to distal in the order shown in Figure 8.18(e).

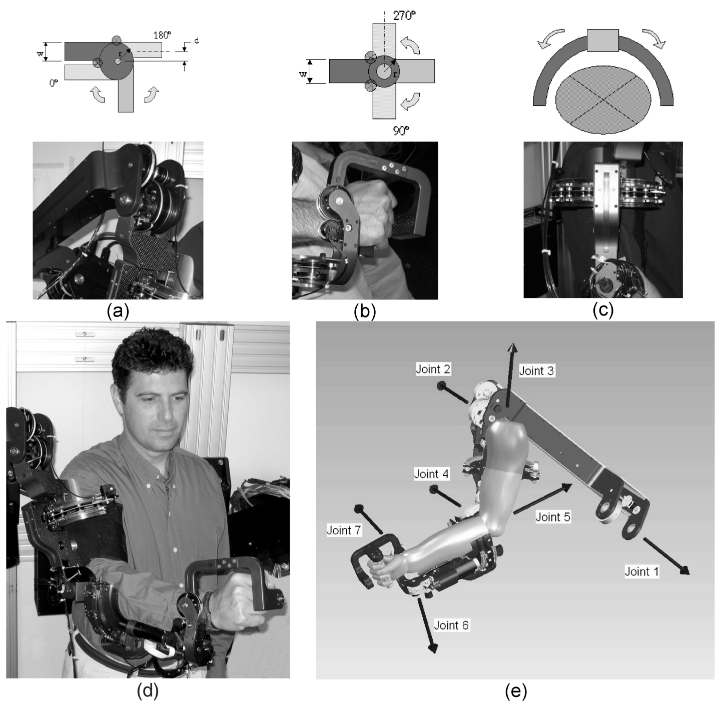


Figure 8.18 The exoskeleton is composed of three joint configurations: (a) 90° joints, (b) 180° joints and (c) axial joints. Together the joints produce an exoskeleton structure that achieves full glenohumeral, elbow and wrist functionality (d). (e) Exoskeletal axes assignment in relation to the human arm. Positive rotations about each joint produce the following motions: (1) combined flexion/abduction, (2) combined flexion/adduction, (3) internal rotation, (4) elbow flexion, (5) forearm pronation, (6) wrist extension and (7) wrist radial deviation

In the design of the current exoskeleton, three joint configurations emerged. The configurations can be classified as one of the following: (a) 90°, (b) 180°, or (c) axial. The distinction pertains to the relative alignment of adjoining links when the joint is approximately centred within its range of motion. While some joints of the body articulate about their mid-RoM when adjoining links are near orthogonal (Figure 8.18(a)), others do so when the links are near parallel (Figure 8.18(b)). A third configuration emerges in axial rotation of both the upper and lower arm segments (Figure 8.18(c)). As shown in Figure 8.18(d), exoskeleton joints 1 and 7 are modelled as 180° joints (Figure 8.18(b)), joints 2, 4 and 6 are 90° joints (Figure 8.18(a)), and joints 3 and 5 are axial joints (Figure 8.18(c)). Joint RoM in 90° and 180° configurations can be increased either by increasing the central radius, r, or decreasing the link width, w (top of figures 8.15 (a) and (b)). Adjusting the link offset distance, d, shifts the joint limits, illustrated with small transparent circles, and effectively tunes the joints mid-RoM.

The shoulder complex is reduced to the glenohumeral (GH) joint articulation (see Section 3.3,) and the GH joint is considered a spherical joint composed of three individual axes intersecting at its centre. The elbow is modelled by a single axis orthogonal to the third shoulder axis. A joint stop prevents the joint from hyperextension. Exoskeletal pronation–supination takes place midway between the elbow and wrist joints as it does in the physiological mechanism. Finally, two intersecting orthogonal axes represent the wrist. Although anthropometrically it would be more accurate to incorporate a slight offset between the flexion–extension and radial–ulnar deviation axes, this offset has been neglected for simplicity. The RoM achievable with the exoskeleton arm is as follows: 180° for shoulder flexion–extension and abduction–adduction, 166° for shoulder internal–external rotation, 150° for elbow flexion–extension and, at the wrist, 120° of flexion-–extension, 60° of radio–ulnar deviation and 155° of pronation–supination. The current exoskeleton mHMI uses a semicircular bearing design to allow users to don the device without strain or discomfort. The semicircular guides are composed of three 60° curved rail–bearing segments (THK, Tokyo Japan).

Singularity placement. A singularity is a device configuration where a degree of freedom is lost or compromised as a result of an alignment of two rotational axes. In the development of a 7 DoF exoskeleton, the existence of singularities will depend on the desired reachable workspace. For devices that require large ranges of motion, for motions greater than or equal to 180° in at least one joint singularities cannot be eliminated. In this case, the challenge is to place the singularity in an unreachable or near unreachable location, such as the edge of the workspace.

For the exoskeleton arm, singularities occur when joints 1 and 3 or joints 3 and 5 align. To minimize the potential for this occurrence, the axis of joint 1 was positioned such that singularities with joint 3 take place only at locations that are anthropometrically hard to reach. To allow some user-specific flexibility in the design, the singular position is movable in 15° increments. For the placement shown in Figure 8.19, the singularity can be reached through simultaneous extension and abduction by 47.5 and 53.6° respectively (Figure 8.19(c)). Similarly, the same singularity can be reached through flexion and adduction of the upper arm by 132.5 and 53.6° respectively (Figure 8.19(d)). The singularity between joints 3 and 5 naturally occurs only in the full elbow extension (Figure 8.19(e)), i.e. on the edge of the forearm workspace. With each of these singularity vectors at or near the edge of the human workspace, the median of the workspace is free of singularities.

Another aspect to consider when placing singularities is mechanical isotropy. For optimal ease of movement in any direction, singular axes should be placed orthogonal to directions where isotropy is of the highest importance. For the singularity placement shown, isotropy will be maximized in 42.5° of shoulder flexion and 26.4° of shoulder abduction, values that lie in the median of shoulder RoM from the ADL study.

Power actuation and transmission. To date, the transmission of power from one location to another is achieved through a variety of means such as shafts, cables, fluid lines and geartrains. Each method

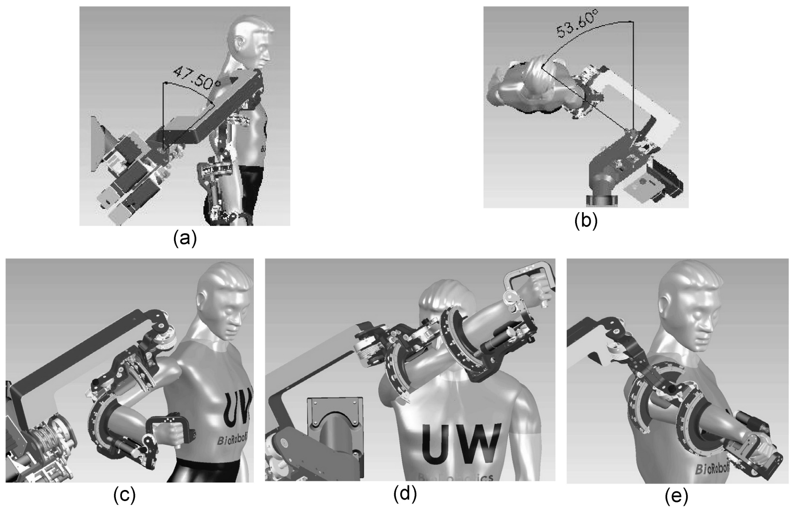


Figure 8.19 Mechanical singularities between axes 1 and 3 occur around the shoulder internal–external rotation axis in configurations (c) and (d). A singularity between axes 3 and 5 also occurs in the full elbow extension (e)

has specific applications where its characteristics are best suited. In the field of wearable robotics, weight is a critical factor that frequently must be sacrificed for the sake of strength or rigidity. However, development of a rigid structure that lacks adequate bandwidth is as ineffective a tool as one that is lightweight but lacks structural rigidity. To achieve both rigidity and bandwidth, critical decisions were made regarding transmission type and placement of actuators.

Cable-drive systems. Cable-drive or tendon-driven systems have been in use on larger-scale devices long before their introduction into the world of biorobotics and microsurgery. In robotic haptics and wearable robotics applications (Salisbury *et al.*, 1988), cable drives are used due to their ability to transmit loads over long distances from an actuator located on a stationary base without the friction or backlash inherent to gears. The low friction associated with cable drives make them back-drivable – a characteristic that is essential for applications in haptics. Moreover, the absence of backlash is achieved through the structural continuity of the cable, enabling a direct link between the driving shaft and the shaft or link being driven. For these reasons, a cable-driven design was selected.

Selection and placement of actuators. As the heaviest components in the design, placement of the motors was a crucial decision. Motors for joints 1 to 4 were mounted on the stationary base, achieving a 60 % reduction in overall weight of the moving parts. The remaining three motors, whose torque requirements are substantially less, were positioned on the forearm. As each motor carries the weight and inertia of the more distally placed motors, the importance of high power-to-weight ratios increases from shoulder to wrist. Shoulder and elbow joints are each driven by a high-torque and low power-to-weight motor (6.2 N m, 2.2 N m/kg), while wrist joints are driven by a lower-torque and high power-to-weight motor (1.0 N m, 4.2 N m/kg). Motors are rare earth (RE) brushed motors (Maxon Motor, Switzerland).

Two-stage pulley reduction. Pulley arrangements can be used to create speed reductions in cable transmissions. Neglecting frictional losses, power throughout the transmission remains constant while tradeoffs between torque and angular velocity can be made. At the motor, the required torque is low while angular velocity is high, whereas at the joint, the torque is high and angular velocity is low. Lower torque corresponds to lower cable tension in stage 1, resulting in less strain and, therefore, less stretch per unit length of cable. Minimizing the length of stage 2 and routing the cable in stage 1 through the majority of the exoskeleton structure maximizes the overall transmission stiffness. Two-stage pulley reductions have been implemented in joints 1 to 4, whereas reductions at the wrist are composed of a single-stage pulley reduction following a single-stage planetary gear reduction. Total reductions for each joint are approximately as follows: 10:1 (joints 1–3), 15:1 (joint 4), 30:1 (joints 5–7).

Cable selection. Steel cables, also referred to as wire rope, are available in a variety of strengths, constructions and coatings. Although cable strength generally increases with diameter, the effective minimum bend radius is decreased. Cable compliance, cost and construction stretch generally increases with strand count. A 7×19 cable, composed of 133 individual strands, offers moderate strength and flexibility and is recommended for use with pulleys as small as 25 times the cable diameter (SAVA Industries, Riverdale). Applications requiring high-strength cables and small-diameter pulleys, less than 1/25th the cable diameter, should utilize a higher-count cable construction. The exoskeleton has been developed with both 7×19 and 7×49 cable constructions.

8.5.1.3 System integration

The system is controlled by two PCs (the servo PC and virtual reality (VR) PC). The servo PC is responsible for maintaining low-level servo control. The VR PC runs VR applications and projects a visual view of the virtual environment into the VR goggles (Figure 8.20). The VR PC maintains the current state of the VR environment and calculates via the inherent physics engine the force feedback that needs to be rendered and applied by the exoskeleton arms. The UDP protocol is used as the communication protocol between the servo PC and the VR PC. The servo PC acquires the joint positions of the exoskeleton, which is physically coupled with the human arm, as well as the interaction forces and torques between the operator and the exoskeleton device. Based on the required force feedback that is calculated by the VR PC, the servo PC provides servo command to the actuators

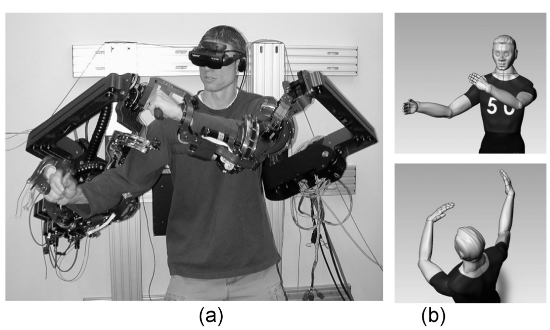


Figure 8.20 The exoskeleton system operating in a VR environment mode: (a) a user wearing the arm and a head-mounted display for viewing a virtual environment and (b) the virtual environment representation as seen through the head-mounted display

to generate the appropriate joint torques that simulate physical interaction with the virtual object. The current joint position is transmitted by the servo PC to the VR PC for keeping the VR environment up to date.

Three multiaxis force/torque sensors are located at the exoskeleton mHMI (upper arm, forearm and hand) measuring the interaction between the human arm and the exoskeleton system. Redundant position sensing capabilities were also incorporated into the mechanism (encoders located on the servo DC motors and potentiometers located on the joints themselves). Analogue to-digital converters (ADCs) as well as encoder counters are used to acquire all the analogue and digital signals. A digital-to analogue converter (DAC) is used to control the DC motor through their linear amplifiers.

8.5.2 Conclusions and discussion

The integration of a human and wearable robot into a single system offers remarkable opportunities for creating a new generation of assistive technology and human–computer interface that may benefit members of both healthy and disabled populations. The same device with different control algorithms may be used in four fundamental modes of operation, although existing devices, see below, are typically limited to one or two. The exoskeleton system developed in this research effort has been designed to operate under the following four modalities:

1. Physiotherapy. The patient wearing an exoskeleton performs task-based occupational or physical therapy in an active or passive mode (Fasoli *et al.*, 2003; Hogan *et al.*, 1992; Krebs *et al.*, 2002).
2. Assistive device (human amplifier). The operator feels scaled-down loads while interacting with objects in the environment, most of the load being carried by the exoskeleton (Kazerooni, 1996).
3. Haptic device. The subject physically interacts with virtual objects while the forces generated through the interactions are fed back to the user through the exoskeleton, conveying shape, stiffness, texture or other characteristics of the virtual objects (Frisoli *et al.*, 2005).
4. Master device. Replacing the virtual environment with a real robot, the operator uses the exoskeleton to control a robotic system in a teleoperation (master–slave) mode, where the exoskeleton reflects back to the user the forces generated as the slave robot interacts with the environment (Jau, 1988).

The aim of this case study was to describe the development of a 7 DoF upper limb exoskeleton that is based on anthropometric data as well as on the kinematics and dynamics of the arm in activities of daily living. In contrast to previous exoskeleton devices where internal–external rotation joints and pronosupination joints fully enclosed the arm (Frisoli *et al.*, 2005; Kiguchi, Tanaka and Fukuda, 2004; Repperger, Remis and Merrill, 1990), the current exoskeleton design uses open mHMIs for both upper and lower arm segments. This feature greatly reduces challenges associated with donning and doffing by impaired users, a task that can be difficult and even uncomfortable with closed bearing configurations.

Although some studies report that joints, particularly at the shoulder, can achieve ranges of motion exceeding 180°, most joints can only reach such excursions with contributions from neighbouring joints. Despite the GH joint appearance of providing more than 180° of motion about all three axes, this is due largely to scapular motion. As a result, joints capable of providing 180° of motion, or less, using the three configurations described previously are sufficient to develop an arm exoskeleton with full GH, elbow and wrist joint functionality.

Due to the unique placement of the shoulder singularity in this device, pure shoulder flexion is achieved through a combination of rotations about the first two joints of the shoulder (exoskeleton joints 1 and 2). Additionally, this unique placement moves the region of highest shoulder joint isotropy into the area of the workspace most often utilized during functional tasks. This combined effect of placing the singularity in the periphery of the workspace while maintaining high isotropy in the central workspace leads to a device configuration that is highly suited for exoskeleton applications.

As a final remark, it is worth noting several aspects of transmission integrity with regard to cable-driven systems. Depending on the length of the transmission, even small changes in cable length may result in excessively high or excessively low cable tensions, both sources of undesirable effects. For this reason, care must be taken at all cable termination sites to ensure constant cable lengths, as cables wraps around either reduction pulleys, drive pulleys or capstans. The tension that results, and therefore the amount of length change allowable, will vary with the length of cable in the particular stage. Cable runs that are long can endure higher amounts of cable stretch without undergoing significant increases in tension. This, combined with large gear reductions, can result in significant lateral travel of cables as they wrap around motor capstans. The nearest idler pulley should be located sufficiently far from the capstan to maintain proper alignment (less than $\approx 2.5^\circ$ offset) between the cable and helical grooves in the capstan.

The research effort described in this case study represents not only a contribution towards the advancement of haptics and human–computer interfaces but also towards a more general understanding of the human upper limb. The exoskeleton is a unique but versatile high-performance two-way interface, designed, fabricated and integrated to the highest industry standards, and will support further research along a number of academic pathways towards a deeper understanding of the human body, the neuromuscular system and the optimal modalities for neuromuscular rehabilitation.

8.6 CASE STUDY: SOFT EXOSKELETON FOR USE IN PHYSIOTHERAPY AND TRAINING

N. G. Tsagarakis[1], D. G. Caldwell[1] and S. Kousidou[2]

[1]*Italian Institute of Technology, Genova, Italy*
[2]*Centre of Robotics and Automation, University of Salford, Salford, UK*

Full or partial loss of function in the shoulder, elbow or wrist is an increasingly common ailment associated with a wide range of injuries, disease processes and other conditions including sports injuries, occupational injuries, spinal cord injuries (SCIs) and strokes. These impairments can be of varying degrees of severity. Hemiplegia, the most common impairment resulting from a stroke, leaves the survivor with a stronger unimpaired arm and a weaker impaired one. Impairments such as muscle weakness, loss of range of motion, reduced reaction times and disorderly movement organization create deficits in motor control that affect patients' ability to live independently (Parker, Wade and hangton, 1986).

In most such cases intensive and repetitive physiotherapy may be necessary to modify neural organization and recover functional motor skills (Carr and Shepherd, 1987). However:

1. upper-limb disability rates low on the priority list for urgent medical assistance because it is seldom considered life-threatening. Therefore, physiotherapy tends to follow only days or even weeks after admission.
2. Treatment for these conditions typically relies to some extent on manipulative physiotherapy procedures, which by their very nature are highly labour intensive, requiring intensive one-to-one attention from highly skilled medical personnel.