Neurorehabilitation of the Upper Extremity

22

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Abstract

Individuals with tetraplegia are largely dependent on the support of caregivers and relatives for basic activities of daily living. Therefore, rehabilitation aims at achieving the greatest amount of autonomy in everyday life by achieving a basic grasping function. The therapeutic approaches are categorised into compensatory and restorative strategies: Compensatory strategies include the provision of an active/passive tenodesis grip, splinting, fitting and adjustment of customised tools to compensate for a lost hand function. Restorative therapeutic approaches are based on principles of motor learning and aim at the restitution of the original function. In cases where substantial neurological recovery occurs, it is highly important to regularly adapt compensatory therapies and to rethink the need for technical aids and assistive devices.

Regular assessments are not only needed for objective evaluation of the individual's neurological and functional recovery over the course of rehabilitation but also to obtain information of the patient's skills, needs and own priorities. A comprehensive assessment helps to match rehabilitative and therapeutic possibilities to individual needs of a patient and to provide an optimised therapy.

Triggered by the rapid technological progress, new techniques and devices have been developed over the last years for enhancement of the treatment of upper extremity impairments, such as non-invasive stimulation or complex robotic devices. It needs to be shown in clinical studies involving a substantial number of participants, if these therapies lead to a superior functional outcome compared to or in combination with traditional treatment options.

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22.1 Introduction

Bilateral loss of hand function as a consequence of an injury of the cervical spinal cord results in a substantial dependency of affected persons on relatives and caregivers. This obviously leads to a tremendous reduction in quality of life and restricts full participation in social and professional activities. It is therefore not surprising that individuals with cervical spinal cord injury (SCI) rate an improvement of a missing grasping function as their highest priority [1, 51].

The overall aim of all neurorehabilitative efforts in persons with tetraplegia is to support an individual in achieving the highest possible level of autonomy and independence. To enhance existing skills, regain lost ones or develop compensatory means, and helping the patient to simplify or to set the grounds for everyday and professional life in the first place are the main goals of occupational therapy in particular in the first phase of rehabilitation after onset of SCI. To achieve these goals, occupational therapists make use of a variety of different treatment methods which are closely linked to the individual's neurological situation. Obviously, the therapeutic focus is put primarily on the enhancement of upper extremity motor functions and manipulation skills. However, also the improvement of sensory function, the normalisation of hypersensibility and the prevention or reduction of nociceptive pain or muscular hypertonus represent important components of the therapeutic spectrum in patients with SCI.

The aim of this chapter is to provide an overall overview of the therapeutic aims, concepts and methods used for neurorehabilitation of upper extremity function according to the level and severity of SCI. Two basic concepts are applied in the rehabilitation of individuals with SCI, namely, restoration and compensation including substitution. In a restorative approach, methods based on the principles of motor learning are used for restitution of the original function. In a compensational approach, technical aids and assistive technology are used for substitution of a permanently lost function. Each person needs to be properly characterised in regard to her or his potential of functional capabilities to define specific therapeutic goals and to set up and regularly adapt an individualised therapy regime. This means that regular assessments not only of the neurological and functional status but also of the needs and priorities of individuals with SCI need to be performed. This chapter will list the most widespread assessments applied in individuals with tetraplegia and reports on their advantages and challenges experienced in their routine application. Also, a selection of promising technology-based restorative therapeutic options such as functional electrical stimulation or complex robotic devices will be discussed with regard to their added value for the rehabilitation outcome.

22.2 Characteristics of Individuals with Cervical Spinal Cord Injury

An analysis of the database of the European Multicenter Study about Spinal Cord Injury (EMSCI) [6] shows that approximately 65 % of the tetraplegic patients with traumatic and ischemic SCI have an initial neurological level of C4 (37.9 %) and C5

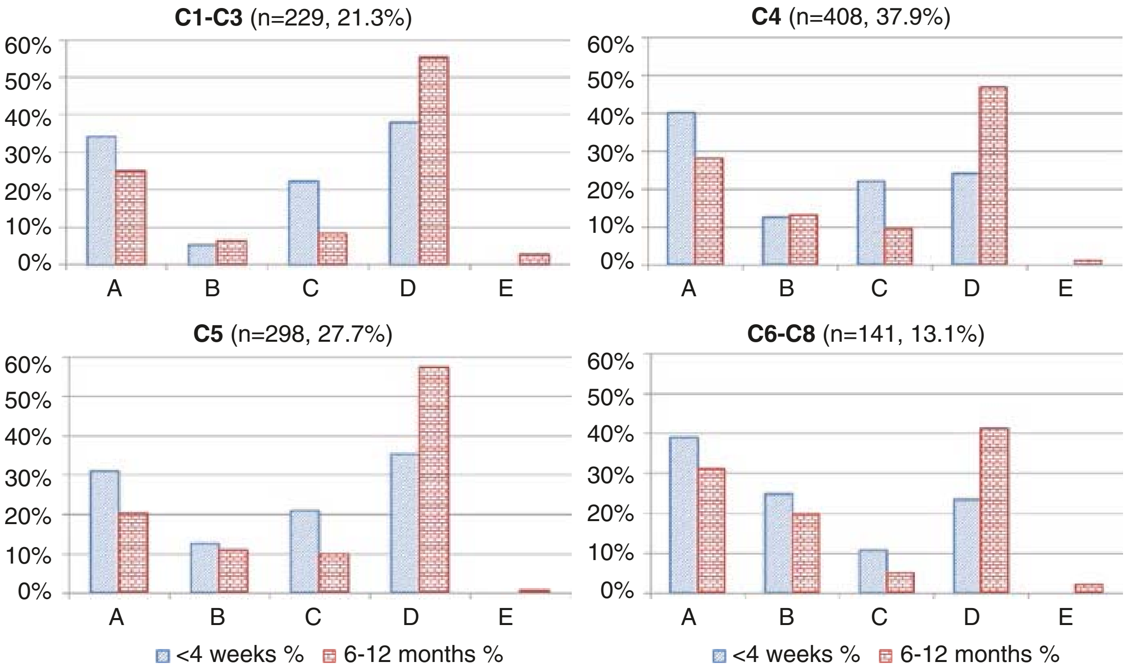

Fig. 22.1 Distribution of the initial (<4 weeks post injury) and chronic (6–12 months post injury) ASIA impairment scale (*AIS*) grades grouped by the initial (<4 weeks post injury) neurological level of injury within a European cohort of traumatic and ischemic SCI (*N*=1,076 patients)

(27.7 %). About 40 % of the patients with tetraplegia initially have a sensorimotor-complete SCI (ASIA impairment scale (AIS) A [21]). In half of the patients with tetraplegia, residual motor functions are preserved below the level of injury (AIS C and D). These individuals have a high potential for recovery of substantial motor functions over the first year after SCI (Fig. 22.1), with the highest amount of neurological recovery within the first 3 months after SCI [6]. In the chronic stage, 50 % of the tetraplegic patients are classified as AIS D meaning that half or more of their key muscles below the neurological level have a muscle grade equal or greater to three (out of five). Most of these patients suffer from a central cord syndrome (CCS) meaning that the strength of the muscles of the lower extremities is higher than those of the arms [48]. Due to the fact that in CCS a combination of upper and lower motor neuron damage occurs, these patients often have a limited potential for neurological recovery of upper extremity function. They might regain independent ambulation, but may not achieve full upper extremity strength [47].

Three-fourth of the initially sensorimotor-complete (AIS A) patients stay complete. However, they recover on average 10 motor points in their upper extremity motor scores independent from the initial cervical level of injury [28, 52]. An initial motor zone of partial preservation of two segments or more is associated with a gain of two or more motor levels 1 year after SCI [34]. Functional recovery of upper extremity function is significantly greater for those individuals regaining two motor levels compared with those recovering only one or no motor level. This is the case in 22 % of the patients with an initial motor level of C4 and in 27 % of the initially C5 patients [28].

An important factor for the individual prognosis of neurological recovery is the degree of lower motor neuron damage. Although numbers in the literature vary to a large degree, it can be assumed that at least in the high-lesioned patients with a neurological level of injury at or rostral to C4 a substantial degree of denervation in particular of the biceps muscle is present [10, 39]. A thorough neurological examination (reflex testing, neurophysiological nerve conduction recordings) may help to identify the extent of lower motor neuron damage associated to a cervical spinal lesion. The knowledge about the status of innervation of the upper extremity muscles is of utmost importance for selection of the appropriate therapeutic approach (compensation or restoration) and to align patient's expectations for recovery with realistic rehabilitation goals based on clinical experience. Additionally, an agonistic/antagonistic imbalance of innervation may result in a higher risk for joint contractures, if not adequately treated [4].

22.3 Restoration Versus Compensation: The Two Ends of a Therapeutic Continuum

The basic aim of rehabilitation of upper extremity function in subjects with tetraplegia is to provide them with as much autonomy as possible. A strong focus is put on the ability to perform activities of daily living such as dressing/undressing, personal hygiene, eating or performing transfers independent from caregivers. In this context, training is based on two fundamental principles, namely, restoration or compensation.

Assuming that an SCI leads to the loss of skilled motor behaviour, recovery or restoration would depend on the reacquisition of elemental motor patterns by motor learning or, in the absence of reacquisition, adaptation of remaining (compensation) or integration of alternative (substitution) motor elements. The term *recovery* of motor performance is defined as the restoration of elemental motor patterns present prior to central nervous system (CNS) injury [32]. Motor *compensation* is defined as the appearance of new motor patterns resulting from the adaptation of remaining motor elements or *substitution*, meaning that functions are taken over, replaced or substituted by technical aids or assistive devices.

There is still a lack of consensus on the definition of "functional recovery". This term is often used without distinguishing whether the "recovery" is occurring at the body function/structure or the activity level. Thus, there is often no consensus about whether "recovery" is because of true motor recovery or compensation at each of these levels.

The International Classification of Functioning, Disability and Health (ICF [53, 54]), published by the WHO in 2001, provides a standard language and framework for the description of health and health-related states independent from specific diseases. Functioning and disability are viewed as a complex interaction between the health condition of the individual and the contextual factors of the environment as well as personal factors. The ICF is based on a biopsychosocial model and provides a coherent view of different perspectives of health: biological, individual and social. It is structured around the following broad constructs:

- Body functions and structure
- Activities (related to tasks and actions by an individual) and participation (involvement in a life situation)
- Environmental factors

In an attempt to improve knowledge exchange between fundamental researchers, clinical researchers and clinicians, a definition of recovery and compensation at three different levels of the ICF, at which each may occur, has been proposed (Table 22.1).

A way of distinguishing between *recovery* and *compensation* is to look on how the movement is performed (body function/structure level) and on the movement outcome (activity level). At the body function/structure level, the emphasis is on the quality of movement regardless of movement outcome or task accomplishment. Recovery at this level is characterised by the reappearance of pre-injury movement patterns during task accomplishment. True motor recovery at this level, therefore, could be characterised, for example, by a decrease in spasticity or by a reduction in trunk displacement during a reaching or pointing movement. *Adaptive compensation* at this level would be characterised by the appearance of alternative movement

Table 22.1 Definitions of motor recovery and motor compensation at three different ICF levels

Level	Recovery	Compensation
ICF: health condition	*Restoring function in neural tissue that was initially impaired after injury*. May be seen as spontaneous reactivation of spinal axons, interneurons or motor neurons affected by the spinal trauma	*Neural tissue acquires a function that it did not have prior to injury*. May be seen as activation of alternative spinal cord or brain areas normally not observed in able-bodied individuals
ICF: body function/ structure (performance)	*Restoring the ability to perform a movement in the same manner as it was performed before injury*. This may occur through the reappearance of pre-injury movement patterns during task accomplishment (voluntary joint range of motion, temporal and spatial inter-joint coordination, etc.)	*Performing an old movement in a new manner*. May be seen as the appearance of alternative movement patterns (i.e. recruitment of additional or different degrees of freedom, changes in muscle activation patterns such as increased agonist/antagonist coactivation, delays in timing between movements of adjacent joints, etc.) during task accomplishment
ICF: activity (functional)	*Successful task accomplishment using limbs or end effectors typically used by non-disabled individuals*[a]	*Successful task accomplishment using alternative end effectors such as neuroprostheses or robot arms*

Adapted from Levin et al. [32]

[a]Note that task performance may be successful using compensatory motor strategies and movement patterns

patterns during the accomplishment of a task. *Substitutive compensation* would reflect the use of different effectors to replace lost motor elements. It should be recognised that both adaptive and substitutive compensation may occur in various combinations at the performance level. An example of adaptive compensation is the use of excessive shoulder abduction when the range of active elbow extension is decreased. At the level of the wrist and hand, alternative grasping strategies such as anchoring the fingers on the object to achieve a passive grasp can compensate for the lack of active finger flexion.

Recovery at the activity level requires that the task is performed using the same end effectors and joints in the same movement patterns typically used by able-bodied individuals. In contrast, compensation at this level often takes the form of substitution and would be noted if the patients were able to accomplish the task using assistive devices.

The question of course arises, when to apply a restorative therapy approach and when to move to a compensatory training or vice versa? There is no general answer to these questions, and the separation of compensatory from restorative therapies is often difficult or even impossible. As a general rule, in the first 3 to 6 months after the injury, where the potential for neurological recovery is highest, the focus of rehabilitation specialists is on transferring neurological recovery into functional improvements by application of restorative therapy approaches. However, in parallel in some patients, compensatory movements or substitutive technical aids may be encouraged from the very beginning to maximise functional ability. This is in particular true for patients with severe impairment, poor prognosis and likely low benefit from restorative therapies. Of course, if unexpectedly a patient recovers a substantial amount of sensory or/and motor functions, restorative therapies may be applied at any stage. At the point in time, when only little neurological recovery occurs and the time of admission into the home environment comes close, the more compensatory therapies are in the focus to achieve the highest level of functional ability as a prerequisite for leading an independent life at home.

It is important to emphasise that compensation and recovery are not mutually exclusive. Instead, functional recovery is often dependent upon compensation, and compensatory approaches might enable new possibilities for restorative trainings, e.g. a hand stabilisation orthosis or a grasp neuroprosthesis may allow for retraining shoulder and elbow movements. Because there is no general rule for focusing on compensation or restoration, it is important to know the patient's individual priorities and her or his social environment. Taking them into account is mandatory to agree upon realistic rehabilitative goals and to work with the appropriate therapy methods to achieve them.

22.4 Injury-Level-Dependent Goal Setting

A complete SCI (AIS A) is defined by the absence of motor and sensory functions in the most caudal segments S4/S5 [21]. However, in reality this means that in most of the patients with complete cervical SCI, there is only a limited zone of partial preservation of one or two segments below the neurological and/or motor level of injury.

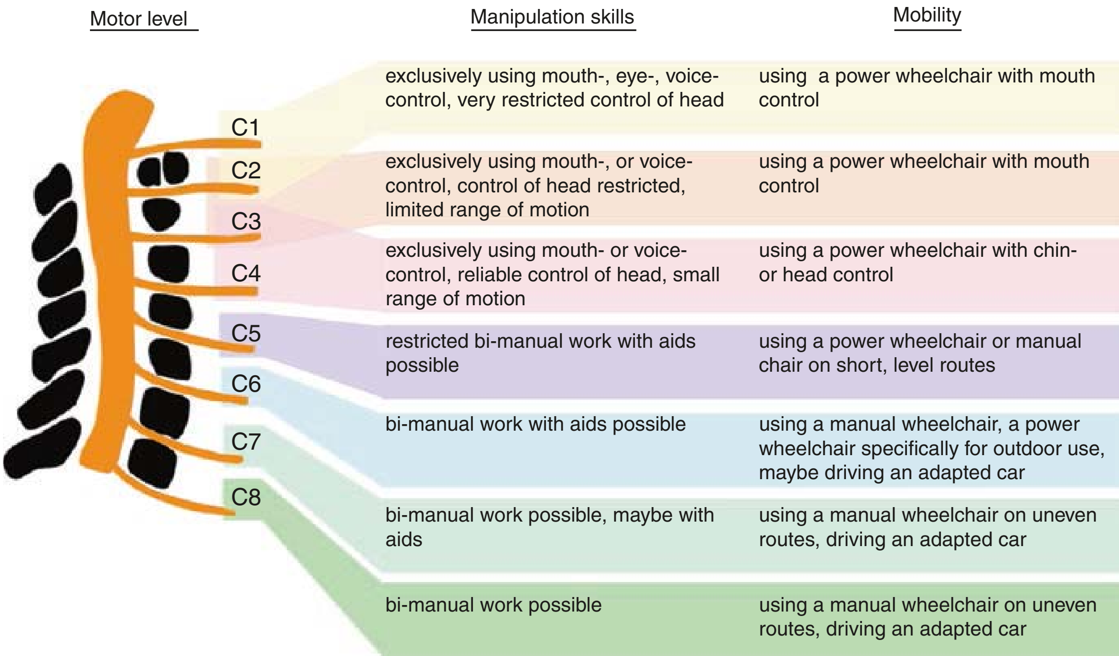

Fig. 22.2 Overview of goals for achievable manipulation skills and level of mobility in respect to the cervical motor level (Adapted from Gerner [11])

For patients with cervical SCI a shift of the motor level of only one segment caudally can result in a tremendous improvement in independence. Taking additional factors like age, pre-injury comorbidities and diseases or cultural background not into account, general rehabilitative goals can be defined in respect to the motor level (Fig. 22.2). The initial setting of goals is important to bundle all rehabilitative efforts and for communication to the patient.

22.4.1 Goal Setting in Complete Tetraplegia

With a motor level between C0 and C4, an individual with tetraplegia is not able to achieve a high level of autonomy and to act independently without technical aids and appliances and personal assistance. In particular, persons with a motor level rostral to C4, who may be dependent on artificial ventilation, need a very high level of support by caregivers. The general rule applies that the higher the neurological level and the severity of the lesion, the more electronic aids are being used to achieve at least a minimal level of autonomy. In cases of minimal residual functions, therapy is strongly focused on the development of individual solutions and the adaptation of different aids and appliances to achieve the highest level of autonomy possible. This includes aids to control a wheelchair for mobility and a computer to get access to information and to communicate to the outside world.

The residual motor functions present in the case of a motor level of C5 are normally sufficient to achieve a certain degree of autonomy in the sense of independence from caregivers for at least most of the day. Substitutional approaches consist of the individual adaption of an electrically powered, electrically assisted or manual wheelchair and the provision of simple aids such as holders for pens, razors, etc.

Compensatory therapy focuses on the development of an active or passive tenodesis grip (Figs. 22.3 and 22.4). Restorative therapies are performed with the aim of strengthening shoulder and upper arm muscles and maintaining the mobility of the joints of the upper extremities.

A full control of the wrist extensor muscles (extensor carpi radialis muscle) enables patients with a motor level of C6 to achieve a higher degree of autonomy than patients with higher SCI. Compared to a patient without active wrist extension, the need for technical aids and appliances is reduced. The major aim of rehabilitation in this patient group is to strengthen the wrist extensors to achieve together with a shortening of the finger flexor muscles a strong grasp. This active tenodesis grip may be used by patients very effectively. With a motor level of C6, a patient is basically able to lead an autonomous life independent of the help of others by using adequate aids and appliances.

Fig. 22.3 Basic principle of the passive tenodesis grip. A supination of the wrist leads to a passive wrist extension and closing of the fingers

Fig. 22.4 Basic principle of the active tenodesis grip, where an active wrist extension results in a passive closing of the fingers

In motor levels at or caudal to C7, there is active control over the triceps brachii muscle, which allows for the active extension of the elbow. In this subpopulation, technical aids and appliances can be reduced to a minimum. Due to the active control of the elbow flexors and extensors, a better fine motor control and a more precise and faster placement of the hand in space are possible. Additionally, a better weight relief for prevention of pressure injuries can be performed by the individual with SCI. In this group of patients, also partial control of hand muscles may be preserved to a certain degree to support hand opening or closing. Like in all other groups, a strong focus of all restorative therapies is strength training of all muscles under voluntary control.

In patients with a motor level of C8, more hand and finger movements are present, meaning that no compensatory approaches such as the development of a tenodesis grip need to be applied. Here, mostly restorative therapies are in the focus to increase strength and improve coordination.

Apparently, the segmental innervation is not restricted to the key muscles mentioned so far but also includes other muscles, which also substantially contribute to a better functional status resulting in a higher level of autonomy and in the ability to lead a more independent and self-determined life.

22.4.2 Goal Setting in Incomplete Tetraplegia

In patients with incomplete tetraplegia, the setting of goals dependent on the lesion level is impossible on a general level due to the heterogeneity of this patient population. The sensory and motor impairments of the upper extremity in incomplete lesions normally differ to such a large degree that a highly individualised goal setting is necessary resulting in a variety of different treatments. Restorative therapies concentrate on strength training of muscles under full or partial voluntary control, maintaining the passive and active range of movement, reduction of spasticity and improvement of coordination. The latter aims at practising the physiological motion sequence in a repetitive manner and translate this into activities of daily living. The methods are basically the same than those used for therapy of individuals with complete cervical SCI. A combination of restorative and compensatory approaches might be used to achieve a maximum of independence.

22.5 Compensatory and Substitutional Therapeutic Strategies

In the absence of the possibility for reacquisition of pre-injury motor behaviours in very severely impaired individuals or at the chronic stage of injury, adaptation of remaining (compensation) or integration of alternative (substitution) motor elements are considered as the primary therapeutic approach. The main common compensatory strategies in persons with cervical SCI are the establishment of a passive or active tenodesis grip [14] and provision of dedicated tools and adaptation of the environment to enhance independence in everyday activities.

22.5.1 Passive and Active Tenodesis Grip

A tenodesis grip represents a passive hand grasp mechanism effected by wrist extension. It is caused by the anatomical constraints of the finger muscles in particular of the finger flexors, which as two joint muscles cross the wrist joint and develop a passive tension during wrist extension. This passive tension might be sufficient to accomplish a functional grasping task, if the fingers and the thumb are in a certain alignment to each other. If the wrist is put in flexion position, the fingers will straighten and release a grasped object.

The tenodesis grip can be either passive or active. In the passive condition, wrist extensor muscles have a strength below grade 3, and closing of the hand is only possible passively by supination of the hand and thereby making use of gravity to extend the wrist (Fig. 22.3). Hand opening is achieved by pronation and passive wrist flexion. A prerequisite for an active tenodesis grip is a strength grade of the extensor carpi radialis muscle of at least 3, which is then capable of actively extending the wrist (Fig. 22.4).

Due to high importance, measures for the development of a tenodesis grip are initiated very early in the rehabilitation process of patients who are likely to recover a strong wrist extension. A major component of the therapeutic approach is appropriate splinting of the fingers and wrist to achieve a shortening of the finger and thumb flexor muscles [26]. In order to achieve an optimal outcome, care must be taken to avoid shortening of extensor muscles resulting in extended fingers unable to grasp anything as well as the shortening of the collateral tendons of the hand and finger joints, which results in a non-physiological hand and finger posture. The shortening of muscles is in contrast to contractures of joints reversible by the consequent application of stretching procedures.

Although widely used, there is still no consensus about the general effectiveness of splinting and the superiority of different splinting methods. However, it seems that in the chronic phase splinting might not have the expected effect [15].

In the chronic stage, a tenodesis grip can be surgically installed by the use of tendon transfers in combination with arthrodesis and/or tenodesis procedures [17]. As an example, an active tenodesis grip might be achieved by the transfer of a strong brachioradialis muscle to the distal tendons of the weak carpi radialis muscle together with a tenodesis for synchronisation of all finger flexor tendons (Zancolli lasso procedure). Depending on the number of strong active muscles distal to the elbow, also a higher level of dexterity of finger and hand movements might be achieved.

22.5.2 Assistive Devices and Adaptation of the Environment

Even with an active tenodesis grip, the fingers are closing only passively resulting in a low grasp force [18]. To enable patients to cope with the challenges of daily

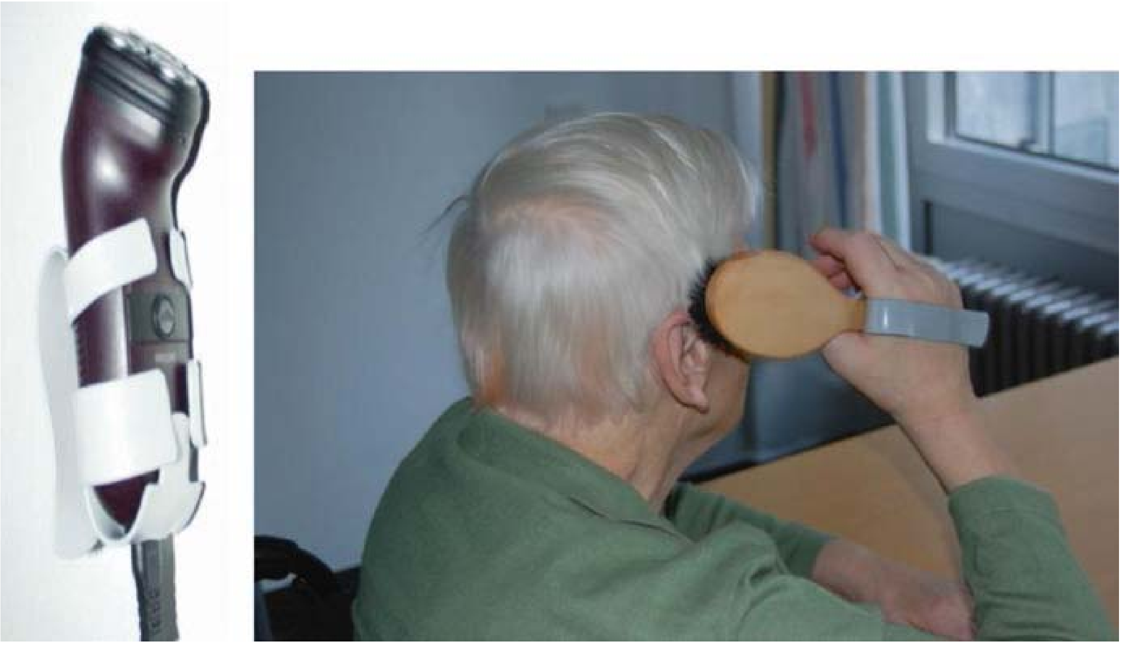

Fig. 22.5 Examples for adaptation of everyday items for enabling patients to perform activities of daily living such as grooming or self-care

living, adapted tools are provided. This includes, but is not restricted to, clamping holders for razors, hairbrush, toothbrush, silverware, etc. (Fig. 22.5).

In patients who do not achieve complete autonomy, the counselling of patients and family members, for example, regarding aids and appliances or the modification of the home environment forms is an important part of rehabilitation. An early involvement of family members and a thorough familiarisation with the operation of assistive devices ensure the optimal support after in-patient rehabilitation. The entire selection of medical aids and appliances is strongly depending on a variety of factors such as the patient's domestic and professional situation, the marital status, age and also pre-existing comorbidities.

The fast growing number of smart homes with remote or internet-based control of light and heating control, door opener or other electronic devices helps patients to achieve some part of autonomy without the need for additional expensive installations. Also the traditional voice control of mobile phones allows patients a self-initiated communication with relatively inexpensive equipment. It can be expected that following the idea of universal design, more devices may be operated by persons with tetraplegia in the future.

22.6 Restorative Therapeutic Strategies

A recent review on the effectiveness of restorative therapies came to the conclusion that training including exercise therapy and (functional) electrical stimulation of the upper limb following cervical SCI leads to improvements in muscle strength, upper-limb function and activity of daily living resulting in a better quality of life [33]. Some studies in the literature indicate that early initiation of SCI-specific rehabilitation is extremely important. A delay in starting these interventions may negatively influence ultimate functional capability [22, 43]. On the other hand, this does not mean that training initiated in the chronic stage does not result in improvements of muscle strength, of upper extremity function and consequently of activities of daily living or quality of life, but the effects are most probably smaller. Therapeutic exercises may have different aims in patients with tetraplegia, among them training of muscular strength and endurance, relaxation of muscles with increased muscle tone, reduction of upper-limb edema, maintenance of joint mobility and flexibility by moving limbs in their entire range of movement and improvement of coordination and fine motor skills by task-specific, goal-oriented, high-intensity training regimes.

22.6.1 Strength Training

One important prerequisite for functional restoration is to exercise weak muscles in order to strengthen them and provide the basis for their appropriate integration into relevant movements. This is mainly done with active-assisted and active-resistive exercises:

- *Active assisted* – Patients who are not able to fully perform a desired movement are supported by therapists during different phases of the movement execution as well as over the whole range of motion. The therapists normally work on an assist-as-needed basis meaning that the therapist provides only the minimal amount of support to successfully complete the task. The intention is to challenge the patient, but not to cause frustration. An important issue is to guide the movements of a patient on a physiological trajectory, so that trick movements and herewith training of already stronger muscles are avoided. In active-assisted strength training, often gravity-eliminating systems providing a sling-based weight support of the forearm (e.g. Swedish Help Arm produced by different manufacturers) are used. With the help of this device, patients can put their focus on the quality and repetition of the different movements necessary in daily life without excessive muscular fatigue.
- *Active resistive* – If a patient is able to complete the desired movements over the whole range of motion, an adapted amount of resistance to the movement is given by a therapist either for more effective strength training or for guidance of movements. Resistance-based training can be done unilaterally as well as bilaterally.

Electrical stimulation may also effectively contribute to upper-limb muscle and in particular wrist extensor strength [12, 13, 24, 41]. However, electrical stimulation should be integrated into a comprehensive occupational therapy regime to transfer the increased muscular strength into functional improvements like self-feeding abilities [24].

22.6.2 Use of Motor Learning Regimes Including Rehabilitation Robotics

The fundamental concept of restoration of motor functions is based on the assumption that practice of task-specific movements induces plastic changes in the altered CNS representing the structural correlate of motor learning. Moreover, the frequency and duration of practice correlates with the level of improvement of motor performance. Thus, repetition represents the key factor for successful motor learning. Although this may be the most effective way to improve short-term performance during the training session, it is not sufficient for retaining motor skills over time. A set of factors – called principles of motor learning (Table 22.2) – have been identified that contribute to the long-term retention of a newly acquired skill [27].

Among the principles of motor learning are the degree of active participation and motivation of the patient, an appropriate intrinsic and extrinsic feedback, the

Table 22.2 List of "principles of motor learning"

Principle of motor learning	Explanation
Task specificity	To improve a specific skill, the respective movement task or closely related needs to be practised
Active participation	Active participation of the patient forms the basis for initiation of neuronal plastic changes. Motivation and eagerness strongly influence the therapy outcome
Repetition	For transfer short-term adaptations in motor control into sustained movement patterns, the movement task has to be repeated often. It must be emphasised that the task has to be repeated often and not the movement
Adaptation of the complexity ("shaping")	The difficulty of a movement task has to be chosen according to the functional status of the patient. A too simple movement task is boring and thus does not challenge the patient; a too complex, not executable task is overloading the patient and is therefore frustrating
Feedback	Inherent as well as augmented feedback of the motor performance forms an essential component of a therapy for normalisation of pathological movement patterns
Variability "contextual interference"	Whereas repetition of the same movement task leads to an increased performance of the trained movement, the introduction of variability enhances the learning process and retention. Diversification increases the active participation of a patient
Distributed practice	In general, shorter, distributed sessions with intermittent pause periods seem to be more effective than longer block sessions ("massed practice")
Generalisation	Improved motor skills in an artificial environment, e.g. treadmill or locomotion robot, do not necessarily lead to enhanced skills in a natural environment. Dedicated therapeutic interventions are needed to transfer training skills to daily life activities

Fig. 22.6 Devices for a shaped manipulation training: large and light-weighted objects (*left*) are used in the beginning of rehabilitation, which in case of neurological improvements are exchanged by smaller (*right*) and also heavier objects

adaptation of the complexity of the movement task and the contextual interference, in which variability and diversification of the movement tasks are explicit components of the training.

In a task-specific grasping training, difficulty of the therapy is adjusted to the skills of the patients. Normally therapy starts with light and large objects, which can be manipulated more easily and provide the patient a positive feedback thereby leading to a higher motivation. To shape the therapy to the skills of the patient, increasingly heavier and smaller objects are used over the course of rehabilitation (Fig. 22.6). In the end, the difficulty level can be increased by providing additional resistance with objects applied with Velcro.

22.6.2.1 Robotic and Electrical Stimulation-Based Training Approaches

Robotic systems may serve as useful adjuncts in restorative therapies based on the principles of motor learning. They contain active or passive elements that support the weak movements of the users and therefore lead to a higher number of task repetitions. All of the robotic devices contain sensors for real-time measurement of joint angles and allow for their feedback to the user. The measured kinematic parameters can be used to control a variety of virtual motor tasks on a computer screen. The big advantage of this virtual training setting is the possibility for adaptation of the difficulty level to the residual motor functions of a user. By this, users not able to perform a real task can be enabled to perform a virtual task, which is highly motivating for a patient to actively participate in the training.

Robotic training devices are an emerging technology and have not yet been widely used in the clinical rehabilitation setting. Therefore, there is no sufficient evidence for their superiority to traditional therapy regimes. In contrast, most of the reviews on the clinical use of robotic devices come to the conclusion that robotic therapies are not superior to treatment as usual, if both are applied with the same intensity [42].

However, the term “robotic” is not precisely defined, so that the results of studies cannot be easily compared with each other. All of the devices called “robotic” have in common is that they provide some sort of feedback to the user about her or his current kinematics of joints or upper extremity segments.

But some of the devices are only based on passive, mainly spring-based actuators meaning only capable of providing a predefined amount of weight support independent from the position of the upper extremity. In order to call an assistive device “robotic”, it needs to integrate electric or pneumatic drives to actively support the movements of a user. Even then there are two different approaches to support patients’ movements, which are (1) an end-effector-based approach, in which the hand is moved mostly in a horizontal plane by a driven “knob”, or (2) an exoskeleton-based approach, in which the kinematics of each joint is supported independently. In end-effector-based devices, there is no need for alignment of technical to anatomical joints, which facilitates a fast and easy setup. However, a dedicated movement can only be trained by supervision of a therapist, who provides the patient with the correct instructions avoiding compensational movements. Upper extremity exoskeletons provide the possibility for dedicated support of each upper extremity joint in particular the shoulder, but their correct placement is challenging and time-consuming (Fig. 22.7).

In the therapy of stroke, a recent randomised controlled trial provides evidence that robotic therapy with an actively driven complete upper extremity exoskeleton results in a slightly better outcome compared to traditional therapy of the same intensity [23].

Although safety and feasibility studies of some active robotic devices exist [5, 55, 58], efficacy trials involving a substantial number of study participants with SCI are missing. Only very limited evidence from randomised controlled trials is available indicating that the use of a feedback-based weight support system (Armeo Spring, Hocoma, Volketswil, Switzerland) does not lead to a superior outcome compared to a conventional occupational training of the same intensity [59].

Another possibility to facilitate motor learning is the use of non-invasive functional electrical stimulation. Electrical stimulation activates innervated muscles by short-current impulses, which are mostly applied by self-adhesive electrodes placed on the skin (for more details, see Chap. 24). The stimulation intensity and activation

Fig. 22.7 The seven degrees of freedom upper extremity rehabilitation exoskeleton Armeo Power (with permission from Hocoma, Volketswil, Switzerland)

patterns of electrodes on the arm and hand can be adjusted in a way that a grasping and reaching function can be restored. Electrical stimulation thereby supports a task-specific training and generates a rich afferent feedback to the CNS, which may contribute in particular in the early phase of rehabilitation to a better neurological and functional recovery. There is some evidence from two studies that a combination of electrical stimulation with conventional occupational therapy alone is more effective in improving grasp force, upper extremity function and activities of daily living than conventional therapy alone [20, 25, 45, 46]. Most importantly these gains were maintained at 6 months follow-up [20]. Controversially, other studies showed no extra benefit, and it seems that electrical stimulation does not enhance fine motor control abilities [16, 25, 46]. In general, more well-designed, randomised controlled studies are needed with higher sample sizes to see if the results can be generalised to other patient populations and rehabilitation settings.

22.6.3 Restoration of Sensory Functions

An SCI is not only associated with a loss of motor but also of sensory function. The loss of sensory function includes the inability to feel touch, temperature, pain or joint and limb position. The loss of proprioception represents a severe confounding factor for restorative therapies in particular during the first phase of rehabilitation. Even if patients have preserved motor functions allowing them to grasp and manipulate objects, but have no sensation of their grasping force, they have to compensate the loss of hand sensitivity with visual control. Another important issue is that patients need to take care about their trunk posture, because only a stable sitting position allows for the effective use of the residual motor functions of the arms in everyday life.

In a situation where no touch sensation or proprioception is preserved, it is very hard to train sensation. However, if a certain degree of sensation is preserved, different stimuli are used to specifically activate different type of exteroceptors. For this purpose, different materials or materials of different temperatures are used to brush over the patient's skin with different levels of pressure. The patient is instructed to close the eyes and to concentrate on the sensation caused by the material while giving feedback about the location of the touch on the body. This exercise requires a high level of concentration from the patient and is thus restricted to a period of time of a maximum of 10–15 min. Assessment such as the light touch or two-point discrimination tests can be applied during the therapy to check for changes in sensory perception.

Somatosensory electrical stimulation of the median nerve with intensity set below motor threshold may be beneficial in improving sensory function when applied as an adjunct to massed practice of task-oriented skills training programmes [2]. Also, the rubber hand illusion therapy used in hand prosthetic users to treat neuropathic pain seems to improve the sensory perception, although the available evidence is based on a small number of subjects with cervical SCI [30].

22.7 Therapeutic Challenges

In general, the rehabilitation of persons with SCI is sometimes very challenging, independent of the severity of the impairments, and therapeutic possibilities may be limited resulting in a poor outcome. Over the last two decades, there is a shift in the SCI population, at least in industrial countries [44], from young, traumatic towards older, non-traumatic patients having more comorbidities. This leads to the consequence that therapeutic aims need to be carefully aligned to the status and the constraints of each individual. It may happen that older patients with pre-injury diseases such as arthritis or diabetes may not achieve the theoretically possible rehabilitation goals. Older patients often have attention and concentration deficits that restrict the adherence to therapies and instructions of therapists. Additionally, older people tend to have more reservations against electronic aids or technical equipment in general, which result in longer training times and higher level of frustration in both patients and therapists.

Another confounding factor of successful functional upper extremity rehabilitation is severe spasticity. Spasticity and the associated increased muscular tone may lead to non-physiological joint positions, which may as a consequence prevent a tenodesis grip, may lead to nociceptive pain or may not allow for a stable sitting position. Severe spasticity interfers with training efforts and results in a lower degree of independence. Besides spasmolytic medication, passive stretching might have a positive influence on spasticity. On the other hand, light to moderate spasticity prevents muscular atrophy. Sometimes spastic movement patterns can be voluntarily triggered by the patient who may use them effectively for activities of daily living. Therefore, a careful evaluation of the patient's status needs to be performed to initiate the appropriate therapies.

An imbalance between innervated agonistic and denervated antagonistic muscles such as hypertonus in the biceps muscle and a flaccid triceps muscle might lead to a contracture of the elbow joint in flexion position [4, 8]. This does not only restrict the use of the hand and limit independence but additionally represents a challenge for proper (self-)care and personal hygiene. Appropriate positioning of the upper limb and the shoulder together with passive movements and muscle stretching may prevent the development of contractures or at least may preserve an acceptable status [26].

A common and widespread problem in patients with tetraplegia is shoulder pain. The weaker the shoulder muscles, the higher the risk for developing a (sub)luxation and the associated pain in the exclusively muscular-stabilised shoulder joint. It is important to consequently educate the patient, the caregivers and the whole rehabilitation team to avoid mechanical overload or muscular stress to the shoulder which might result in restrictions in activities of daily living [7, 36]. Besides an adequate positioning, stabilising tapes on the shoulder, massage or electrical stimulation might reduce the nociceptive pain.

One of the most challenging secondary complications with a high negative impact on quality of life is the presence of neuropathic pain, which in severe cases render any rehabilitative therapeutic effort impossible. Effective therapies for the treatment of severe neuropathic pain are still missing (see also Chapter 12).

On an individual basis, it is sometimes challenging to decide when to decrease the intensity of restorative therapies and to shift to compensatory training or substitution of lost functions by technical aids. This particularly applies to the development of the tenodesis grip. During splinting it is very important to control for recovery of hand and finger muscles to shift back to a restorative therapy approach by training of the intrinsic hand muscles. While to a certain extent standard therapeutic procedures are existing for patients with complete cervical SCI, no definitive rules are present for the treatment of incomplete patients or patients with a substantial zone of partial preservation below the level of lesion.

Additional to all physical factors restricting the rehabilitative efforts, there is the human factor that a newly spinal cord injured person needs to psychologically adapt to the new situation. It is often challenging to motivate especially older patients to become an active part in therapies in the very early period after SCI. On the other hand, the first 3 months after SCI are the most effective period for neurological recovery and restoration. Therefore, goal-oriented therapies need to start early, in particular in the light of the fact that the time for in-patient rehabilitation has significantly decreased over the last two decades.

22.8 Assessments in Daily Routine and Their Clinical Consequences

Regular assessments are not only needed for objective evaluation of the individuals' neurological and functional recovery over the course of rehabilitation but also to obtain information of the patients' skills, needs and priorities. A comprehensive assessment helps to obtain the individual needs of a patient and to match rehabilitative and therapeutic possibilities. Assessments are important to define an initial treatment regime and to provide an optimised therapy in particular regarding restorative or compensatory approaches. The analysis of outcome measures on a subgroup level of individuals with comparable initial neurological statuses allows healthcare professionals to quantitatively describe, predict and evaluate the neurological recovery in order to provide benchmarks for individuals with SCI. Assessments are also important to communicate the status and progress of a patient to the multidisciplinary team members.

As a summary, assessments support clinicians in their daily routine by providing:

1. Prognostic information by means of an early assessment after injury
2. Allow for individually tailored rehabilitation plans (i.e. compensatory versus restorative approaches, adaptive equipment need)
3. Short-term therapy planning (force training versus coordination, etc.)
4. The ability to evaluate the success of rehabilitation interventions

As mentioned before, the International Classification of Disability and Functioning (ICF) provides a coherent view of different perspectives of disability regarding “body functions and structures”, “activities”, “participation” and “environmental factors”. There is consensus that for a comprehensive description of an individual’s condition, assessments related to all these domains are necessary. However, in contrast to assessment schemes applied in research studies, routine examinations in the clinical environment need to comply with different demands: They should be focused on the most essential information relevant for clinical decision-making and should be able to be conducted in a short amount of time. During the initial in-patient phase, the therapeutic focus is on “body function and structures” and “activity” and so are the assessments.

For selection of the appropriate therapies, it is highly important to know if an improvement in activities results from neurological recovery or if it is based on better compensatory skills. Therefore, the distinction between clinical impairment and function measures needs to be made. Impairment scales focusing on body function and structures measure specific motor aspects that may limit but are not related to task accomplishment (spasticity, strength, isolated joint motion), whereas functional scales measure the task success on an activity level (key turning, jar opening, i.e. functional gains). However, functional gains can occur even in the absence of motor recovery, i.e. lost motor patterns have not returned. Most evaluations at the activity level neither specify how the task is accomplished nor which compensatory movements were used in place of motor patterns observed in non-disabled individuals. Difficulties arise in interpretation of such functional tests to indicate recovery because scores on these tests may improve either when the intervention results in improvements in motor patterns or in increasing compensations and the distinction between them is not made. An example of a relatively new scale that attempts to incorporate both measures of task success as well as movement quality during task accomplishment is the Wolf motor function test [2, 56] that is more often used for the documentation of stroke survivors than in individuals with SCI. More tests of this type that provide an appreciation of movement quality are needed in rehabilitation to better distinguish between motor recovery and compensation at the activity level.

22.8.1 Clinically Relevant Upper Extremity Assessments in SCI

In the next subchapters, an overview of the assessments most relevant for the documentation in the clinical environment is presented. The following compilation (Table 22.3) does not claim to be exhaustive but rather represents an attempt to list the common examinations typically used in in-patient rehabilitation.

22.8.1.1 Assessments on Body Function and Structures

For clinical decision-making, a thorough knowledge of the individual musculoskeletal and neurological status is mandatory at every stage of rehabilitation. The

Table 22.3 Overview of assessments relevant in the clinical environment and associated ICF categories

Body function and structure	Activity	Participation
GRASSP		Canadian Occupational Performance Measure (COPM)
Reflex status	Capabilities of upper extremity (CUE)	
Two-point discrimination test	Grasp and release test (GRT)	
Range of motion (ROM, neutral-0-method)	Nine-hole peg test	
Manual muscle test	Van Lieshout test short form (VLT-SF)	
Hand force measurement	Spinal Cord Independence Measure (SCIM) III	
	Occupational therapy assessment	

examinations should provide information about touch perception, strength, reflexes and passive and active joint range of motion.

In particular in the initial phase of rehabilitation for proper prognosis of the degree of recovery and for deciding on the appropriate therapeutic focus (restoration vs. compensation), a thorough knowledge about the degree of denervation is absolutely necessary. While neurophysiological assessments such as needle EMG or nerve conduction velocity measurements provide objective quantitative information, they are time-consuming, rely on expensive equipment not available in all institutions and are hard to integrate into clinical routine examinations mainly performed by therapists. To still be able to gain some insights into the degree of denervation, a testing of the reflex status of the upper extremities is recommended. There are mainly three reflexes, namely, the biceps, supinator and triceps reflex associated with the spinal segments C5 to C7. If reflexes are absent or impaired after the spinal shock phase, there is a high likelihood of denervation of motor neurons at the respective spinal level.

Additionally to the International Standards for the Neurological Classification of Spinal Cord Injury (ISNCSCI) with its dermatome-based examination of light touch and pinprick sensation, the two-point discrimination test is recommended for classification of impairments of touch sensation in patients with partly preserved sensory function. It determines the minimal distance at which a patient can discriminate between being touched with one or two points. The patient's vision is blocked during the examination and the skin area of interest is being pinned. If the patient is able to discriminate between two points with a distance of <6 mm, then the two-point discrimination is considered to be normal, 6–10 mm is rated as fair and a distance between 10 and 15 mm is considered to be poor. Although being a rather gross classification, the two-point discrimination test might be used to access the effects of therapeutic interventions focusing on facilitation of recovery of sensory function.

Testing of the active and passive range of motion of the finger, hand, elbow and shoulder joints represents an essential examination for assessing weakness of muscles, the degree of muscular tone and the integrity of joint structures such as capsules or tendons. A regular ROM assessment helps to identify the risk of developing joint stiffness and to early initiate stretching procedures. It is normally performed together with a manual muscle test for assessment of the strength of upper extremity muscles. The manual muscle exam should not only include the ISNCSCI key muscles, which were selected on the basis of their innervation from only two spinal segments, but also muscles that are more relevant for performing everyday activities.

An instrumented measurement of the overall hand grasp force forms an important component of strength assessments, because of its relevance for performing everyday activities. The test can be performed by dynamometers keeping in mind that devices designed for assessment of forces in the able-bodied population might not be sensitive enough to measure the low forces of patients with tetraplegia. Care must be taken to properly position the dynamometer in the hand to achieve a high reliability and reproducibility of the assessment.

An assessment that covers aspects of body function and structures together with activity is the Graded Redefined Assessment of Strength, Sensibility and Prehension (GRASSP) [19]. The GRASSP was specifically developed as an impairment measure for the upper limbs in tetraplegia and consists of three subcategories: strength, sensation and prehension. It results in five numerical scores that provide a comprehensive profile of upper-limb function. Administration time is estimated between 45 and 90 min. Strength is assessed by a manual muscle test which extends the five ISNCSCI key muscles test by another five muscles important for hand function. Semmes-Weinstein monofilaments are used for testing three palmar and three dorsal key sensory points. Prehension is divided into ability (cylindrical, lateral key and tip-to-tip pinch grasp) and six performance tasks (pour water from a bottle, open jars, pick up and turn a key, transfer pegs, pick up four coins and place in a slot and screw four nuts onto bolts). A full GRASSP was found to demonstrate excellent reliability and construct and concurrent validity for individuals with tetraplegia. It is to be expected that the GRASSP will evolve to a standard assessment of upper extremity function in subjects with tetraplegia due to SCI during all stages of clinical rehabilitation and also in research studies.

22.8.1.2 Assessments on Activity

There is a general consensus that generic hand function tests are too limited for individuals with tetraplegia and therefore are not appropriate [38]. Accordingly, several SCI-specific assessments for the upper extremities have been developed:

The Capabilities of Upper Extremity (CUE) has two variants, a questionnaire (CUE-Q) and a performance test (CUE-T). CUE-Q is a measure of functional limitation in tetraplegia, which can be administered by clinicians in interview format. It takes about 30 min to complete. CUE-T is an objective standardised assessment of upper-limb capabilities specifically developed for persons with tetraplegia [35]. The

16 unilateral and 2 bilateral items were derived from CUE-Q. It takes approximately 45–60 min to conduct this reliable and valid test.

The Grasp and Release Test (GRT) was specifically developed to assess hand opening and closing to be used as a functional test with neuroprostheses. GRT assesses the ability to pick up, move and release six different objects using a palmar or lateral grasp. It takes approximately 20 min to conduct. Two studies reveal that GRT has excellent reliability and adequate to excellent validity [40, 57].

The nine-hole peg test was developed to quantify fine hand motor skills [37]. It consists of a square board with nine holes in it, which are spaced 3.2 cm (1.25 in) apart. The nine wooden pegs should be .64 cm (.25 in) in diameter and 3.2 cm (1.25 in) long. The task is to pick up the pegs one at a time, using one hand only and put them into the holes in any order until the holes are all filled. The time is stopped in seconds for putting the picks from the container to the board and removal of them one at a time and putting them back to the container. An alternative scoring is the recording of the number of pegs placed in 50 or 100 s. The test only takes 10 min to conduct and is easy to perform. Normative data from able-bodied persons are available, and it has evolved as one of the standard tests for assessment of stroke survivors. However, its validity has not yet been shown in the SCI population.

The Van Lieshout test (VLT) was originally developed to assess basic functional modalities of the arm and hand in individuals with cervical SCI. The short form (VLT-SF) assesses in ten items the positioning and stabilising of the arm, hand opening and closing using the tenodesis effect, grasping and releasing of objects and manipulation of objects using thumb and fingers. Administration time is between 25 and 35 min.

The Spinal Cord Independence Measure version III (SCIM III) measures the ability of patients with SCI to perform everyday tasks according to their value for the patient on a comprehensive rating scale from 0 to 100. SCIM III covers 19 tasks grouped into four subscales: self-care (scored 0–20), respiration and sphincter management (0–40), mobility in room and toilet (0–10) and mobility indoors and outdoors (0–30). The SCIM has the advantage that it can be performed by either face-to-face interview or by phone. The SCIM does not need extra equipment and can be performed relatively quickly in 10–20 min. It is particularly useful as an adjunct measure to ISNCSCI in order to identify the rehabilitation potential of patients.

22.8.1.3 Assessments on Participation

The Canadian Occupational Performance Measure (COPM) is an important assessment allowing a user-centred definition of therapy goals and priorities [29]. The patient's current difficulties in the domains self-care, productivity and leisure activities are determined by in most parts standardised interviews. After the completion of the interview, the patient ranks the priority of each of the items and thereby defines the therapeutic goals for the near future. The COPM interview takes 10–15 min; however, patients often find it hard to focus in their answers and take the opportunity during the interview to tell everything they are unhappy with. It is therefore the duty of the interviewer to guide a patient through the assessment. If regularly performed the COPM forms an effective tool to define and adapt rehabilitation goals and to enhance the communication between patients and therapists.

The Occupational Therapy Assessment is intended for assessment of the consequences of the neurological impairment on participation and activities of adults [31]. It is based on a four-grade rating scale of different items in eight domains: assistive devices, self-care, autonomy, sensorimotor functions, neurological-cognitive functions, psychosocial interaction and participation in work and leisure activities. It has been validated only in German but is intended to be translated also into English. The assessment takes between 30 and 45 min and can also be performed via phone.

22.8.1.4 Assessments on Assistive Technology

In a client-centred rehabilitation approach, it is often important to obtain information on the user satisfaction with assistive technology. There are some standardised assessments existing to obtain information from end users of assistive devices in a systematic fashion. Among them is the Quebec User Evaluation of Satisfaction with assistive Technology (version 2.0) (QUEST 2.0), consisting of an eight-item device domain and a four-item service domain to measure user satisfaction with a broad range of assistive technology devices [9]. QUEST 2.0 shows excellent validity and takes about 10–15 min to administer either interview based or self-reported.

The Assistive Technology Device Predisposition Assessment (ATD PA) assesses the consumer's subjective satisfaction with current achievements in a variety of functional areas. The consumer characterises aspects of her or his functioning, temperament, lifestyle and views of a particular assistive device [49]. ATD PA has 63 items in two domains. The interview takes about 30 min and excellent reliability and validity has been reported.

Conclusions

The individual human being with high SCI is and will be the focus of all therapeutic efforts aiming at maximisation of her or his autonomy and independence. Over the last decade, a shift towards older patients with more comorbidities and complications occurred, leading to a more time-consuming, complicated and less compliant rehabilitation process. On the other hand, the percentage of patients with incomplete lesions increased over the last 20 years with the need for highly individualised therapy regimes. The shortening of the initial rehabilitation period makes it hard to decide when to move from restorative therapy approaches to compensatory or substitutive therapies.

The diversity of neurological and musculoskeletal conditions of individuals with SCI together with large differences in patients' priorities results in highly personalised treatment regimes. Due to this non-standardised rehabilitation approach, scientific evidence is low for the efficacy of occupational therapies. There is obviously the need for large-scale studies to show the superiority of one therapeutic procedure over the others; however, it will be hardly impossible to implement adequately powered randomised controlled trials (RCTs) to identify the best therapeutic approach and to set up rules for standard rehab procedures.

The available evidence for certain therapeutic procedures such as stretching or splinting is mainly based on a small number of study participants. There is the general risk that the heterogeneity of the study population masks therapeutic effects in subgroups, and one should be very careful not to disqualify therapies from being effective just on the basis of the results of RCTs.

A review of the available literature suggests that training of the upper limb following SCI, including exercise therapy and functional electrical stimulation, leads to improvements in muscle strength, upper-limb function and activities of daily living and finally in quality of life. Further research is needed on the use of new technology, such as cortical neuromodulation therapies (repetitive transcranial stimulation or transcranial direct current stimulation) and robotic devices, in improving upper-limb function (see also Chapter 24). Novel methods such as nerve transfers [50] might open up new possibilities for the restoration of upper-limb function. The outcomes of all these novel interventions need to be studied by carefully designed studies with high trial power and external validity.

Another issue hindering the comparison of study results is the variety of outcome measures used in different trials. Comparison of results across studies would be improved by standardisation of outcome measures. There are initiatives to develop international standards and data sets for upper extremity function in persons with cervical SCI [3]. However, in the framework of studies, these might not be comprehensive enough. The SCIM is often recommended to assess activities of daily living in patients with SCI the relatively new GRASSP might evolve in the future to a standard arm and hand function test; however, it will be hard to implement this assessment in clinical routine due to the time demands. Nevertheless, the routine use of standardised objective tests would allow future meta-analyses of the effectiveness of exercise interventions on upper-limb function from a number of smaller studies.

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Neurorehabilitation: Strategies of Lower Extremities Restoration

23

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Abstract

Treatment of acute spinal cord injury (SCI) comprises two major therapeutic concepts, which aim for either restoration or compensation. Both strategies aim to reach the highest level of quality of life, mainly reflected by independence and participation in social activities. Restoration in this context means to recover sensorimotor function, which has been impaired or abolished by an incomplete spinal cord or cauda equine lesion. Therefore, only in patients with spared sensorimotor axon pathways restorative strategies can be successfully employed. In contrast, compensation means to replace irreversibly lost function through an alternative strategy, e.g., wheelchair mobility will substitute for the mobility achieved through walking. A number of excellent textbooks describe compensatory strategies in SCI rehabilitation in detail. This chapter will focus on therapies to promote recovery of walking function.

In order to choose appropriate rehabilitative treatment strategies, a precise definition of realistic goals to be achieved in each patient is of utmost importance. Respective goals can only be determined once neurological dysfunction and functional deficits are properly assessed. Therefore, effective goal setting approaches and internationally accepted neurological and functional assessment schemes will be described. Accordingly, task specific therapies (e.g., body weight supported treadmill training), supporting therapies (conventional physical therapy targeting muscle strength, balance and trunk stability, functional electrical stimulation) and orthotic devices including wearable exoskeletons will be described.

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23.1 Planning and Goal Setting

The rehabilitation process of spinal cord injury (SCI) patients includes multiple phases and a variety of interventions with the aim to maximize independence and to participate in the social environment. This can be accomplished by means of compensation or restoration. Compensation in this context means that the rehabilitative therapy aims to change movement strategies, which will allow to substitute for the function that has been lost after SCI. For example, wheelchair mobility is the main compensatory strategy to replace lost walking ability in motor complete SCI. In contrast, restorative strategies in the rehabilitative context train incomplete SCI patients to regain lost motor function. As an example, locomotor training – from body-weight-supported treadmill training to unsupported overground walking – can be employed to restore locomotor function after sensorimotor incomplete SCI.

Due to the increasing number of incomplete SCI patients – mainly ASIA Impairment Scale (AIS)-C/AIS-D – a shift in the therapeutic focus has become apparent [1]. Compensatory therapies become more frequently supplemented by approaches to restore lost or improve impaired motor functions. In this chapter we focus on the recovery of standing and walking function. Irrespective of restorative or compensatory rehabilitative strategies, appropriate patient goals should be defined based on the International Classification of Functioning, Disability and Health (ICF). Accordingly, short- and medium-term goals correspond to the level of activity and function, whereas long-term goals reflect the patient's life goals and participation [2]. Short- and medium-term goals can change daily, weekly, or monthly and should be achievable within the time frame of the rehabilitation process. Respective goals should be oriented toward the long-term objectives and at the same time need to be adapted to the current situation during the rehabilitation process. The goals, especially those concerning participation, should be decided by the patient and not by the treatment team. Here, the fact of defining goals does not mean that they must always or can always be achieved. It is more a case of formulating long-term prospects that will probably have to be revised or modified during the treatment.

Clinical Case *A female patient with incomplete paraparesis (T8; AIS-C) wants to return back into her apartment, which can only be reached via a few stairs. As a consequence, the restorative concept aims to train getting up from the wheelchair and climbing stairs independently, thus defining short- and medium-term goals. In case climbing stairs through a restorative strategy cannot be achieved, assistive devices for stair climbing will be considered, and relatives will be trained to support the patient in this task.*

At the beginning of the inpatient rehabilitation treatment, the multidisciplinary professional team should meet to define the current status of the patient and to establish short- and medium-term goals considering the patient's perspective. To standardize this process, a goal setting scheme should include the neurological, musculoskeletal, nutritional and functional status of the patient (Tables 23.1 and 23.2). For each of these items, the goals and the appropriate rehabilitative approach

Table 23.1 Goal setting: according to the current neurological status, a realistic goal and the appropriate therapeutic intervention can be chosen (goal setting scheme – Heidelberg University Hospital).

Current status	Goal	Therapeutic intervention
☐ Sensory complete ☐ Sensory incomplete ☐ Motor complete ☐ Motor incomplete	☐ Compensation ☐ Sensorimotor restoration	☐ Wheelchair skills ☐ Wheelchair sports ☐ Body-weight-supported treadmill (with/without exoskeleton), overground walking ☐ Functional training upper extremities ☐ Turning, sitting, transfer ☐ Activities of daily living ☐ Functional electrical stimulation ☐ Muscle strengthening – not task specific ☐ Testing/prescription assistive devices ☐ Instruction/training of caregivers ☐ Other PT measures (bench, mat training)

PT physiotherapeutical

Table 23.2 Goal setting: according to the neurological complications, a realistic goal and the appropriate therapeutic intervention can be chosen (goal setting scheme – Heidelberg University Hospital)

Current Status	Goal	Therapeutic intervention
☐ Spasticity, myoclonus ☐ (neuropathic) pain ☐ Autonomic dysreflexia (AD) ☐ Others (sweating)	☐ Reduction of spasticity ☐ Reduction of pain ☐ Reduction of autonomic dysreflexia (AD)	☐ Identification of spasticity, pain, AD trigger ☐ FES, treadmill, tilt table ☐ Other PT interventions (proper positioning, Kinesio tape, lymphatic drainage, massage, TENS) ☐ Antispastic medication ☐ Analgesic medication

PT physiotherapeutical, *FES* functional electrical stimulation, *TENS* transcutaneous electrical stimulation

will be checked. Patient status, goals, and approaches will be reviewed weekly and adjusted if necessary. The focus on restorative versus compensatory strategies is based on the SCI severity and the level of neurological injury according to the International Standards for Neurological Classification of SCI (ISNCSCI). In addition, the patient's age and relevant comorbidities including disease prognosis (e.g., spinal cord compression due to metastatic cancer) will affect the goal setting process [3]. Among other things, increasing age is associated with a lower level of functional outcome despite comparable changes in the neurological status between different age groups [4].

Therapies for individuals with motor complete SCI (AIS-A/AIS-B) mainly focus on compensatory interventions. Restorative strategies have been shown to elicit neurological improvement such as improved electromyographic (EMG) activity in paretic muscles. However, it is not possible to achieve clinically meaningful functional improvement in severely affected SCI patients with such interventions [5]. In motor incomplete SCI patients (AIS-C/AIS-D), we aim for restoration, unless an unfavorable underlying disease prognosis, serious concomitant disease condition(s), or advanced age contradicts. Since the outcome cannot be exactly foreseen in incomplete SCI patients due to a considerable variability in respect to functional and neurological recovery, it is advised to add compensatory rehab strategies to the overall program. Since the length of stay in SCI centers has been dramatically cut down over the years, there is no room for starting compensatory approaches once restorative treatments have failed. The prime goal should always be to discharge an independent patient – be it through restoration of walking and standing or through independent wheelchair mobility. Vice versa, if a rather complete SCI individual gains sensorimotor function over time, restorative concepts will be added to the compensation-centered rehab approach. Of course, therapists should be aware of the fact that patients with prime focus on compensatory elements sometimes do not understand and support such a concept. They expect that functions can be restored irrespective of injury severity, especially when they extrapolate from more incomplete SCI patients, who are challenged with body-weight-supported treadmill training instead of training of wheelchair skills. Such conflicts require careful information of the patient's conditions and explanations, why rehab goals are important in order to obtain independence in everyday life. Nevertheless, despite appropriate goal setting, one of the main difficulties of reintegration reported by patients with SCI during the first year following discharge from hospital relate to mobility aspects such as transfer problems [6].

Overall, patient education in respect to the nature of the disease, shared decision-making related to treatment goals, and adaptation of the rehab strategy based on the extent of neurological recovery represent key aspects for a successful rehabilitation process [7, 8].

23.2 Assessments

A goal-oriented rehabilitation treatment plan requires to obtain objective information about the current patient status. This involves evaluating the physical and functional status as well as recording aspects, which may affect the rehabilitation process, e.g., presence and severity of pain, preexisting medical and functional conditions, and current medication. Respective assessments will facilitate the initial goal setting process and over time serve as a basis to adjust therapeutic goals and related interventions accordingly.

The relevant assessments can be divided into (1) testing of the function and structure of the body (e.g., examination of sensory and motor function, manual muscle testing, testing the range of motion, and movement control examinations) and (2) functional outcome measures (e.g., Walking Index for Spinal Cord Injury, Timed Up and Go, etc.).

23.2.1 Neurological Function

The ISNCSCI is developed and published by the American Spinal Injury Association (ASIA), currently on its sixth edition. It is the worldwide accepted tool to determine motor and sensory impairments in SCI individuals in standardized fashion. The examination contains sensory and motor components to determine the neurological level and to classify the severity of the injury according to the AIS. The neurological level of injury (NLI) refers to the most caudal segments with intact sensory and motor function. The severity of the injury is graded in five steps ranging from A (complete SCI) to E (normal sensory and motor function) [9–11]:

A	Complete. No sensory or motor function is preserved in the sacral segments S4–S5
B	Sensory incomplete. Sensory but not motor function is preserved below the neurological level and includes the sacral segments S4–S5, and no motor function is preserved more than three levels below the motor level on either side of the body
C	Motor incomplete. Motor function is preserved below the neurological level, and more than half of key muscle functions below the single neurological level of injury have a muscle grade less than 3
D	Motor incomplete. Motor function is preserved below the neurological level, and at least half of key muscle functions below the NLI have a muscle grade of 3 or more
E	Normal. If sensation and motor function as tested with the ISNCSCI are graded as normal in all segments

The sensory examination requires the testing of a key point in each of the 28 dermatomes (from C2–S4–5) bilaterally for light touch and pinprick. All sensations are scored with three points: 0 = sensation is absent; 1 = sensation is impaired or partial appreciation, including hyperesthesia; and 2 = sensation is normal. Besides deep anal pressure is examined and should be graded as being present or absent.

Within the motor examination, ten key muscles of the myotomes C5–T1 (*C5, elbow flexors*; *C6, wrist extensors*; *C7, elbow extensors*; *C8, finger flexors*; *T1, small finger abductors*) and L2–S1 (*L2, hip flexors*; *L3*, *knee extensors*; *L4*, *ankle dorsiflexors*; *L5*, *long toe extensors*; *S1*, *ankle plantar flexors*) are assessed on both sides with manual muscle testing. Furthermore, the voluntary anal contraction is assessed and scored as absent or present [9–11].

23.2.1.1 Manual Muscle Testing

Manual muscle testing (MMT) according to Janda is based on a subjective assessment, in spite of its well-defined scale of strength levels. Furthermore, the test only allows the state of the muscles at a specific instant to be evaluated and does not allow the assessment of muscle fatigue. Yet muscle testing according to Janda is a firmly established part of routine clinical practice and an important component of physical examinations. The approach identifies six fundamental stages (Table 23.3) [12]:

In the examination concerning the lower extremities, in addition to the key muscles of the myotomes L2–S1 of the ISNCSCI examination (as mentioned above), the hip extensors, the hip abductors and adductor, and the knee flexors should be examined.

23.2.1.2 Range of Motion

The range of motion (ROM) of individual joints and the spine has a considerable influence on the patient's function and the level of independence after SCI. For example, limited spine movement following extensive spinal fusion surgery can

Table 23.3 Manual muscle testing

Level of strength	Description
5	Corresponds to a muscle with normal strength, which is able to negotiate intensive resistance within the full range of movement. Important: this does not mean that the muscle is without pathological findings when performing all functions (e.g., fatigue)
4	The muscle tested can perform a movement to the full range and negotiate medium resistance (corresponds to approx. 75 % of normal muscle strength)
3	The muscle tested can perform a movement to the full range against gravity. Additional resistance cannot be negotiated (corresponds to approx. 50 % of normal muscle strength)
2	The muscle tested can perform a movement to the full range but only when gravity is eliminated since the tested extremity cannot hold its own weight (corresponds to approx. 25 % of normal muscle strength)
1	The muscle tested can be contracted, but the tested extremity cannot be moved (corresponds to approx. 10 % of normal muscle strength)
0	No signs of arbitrary muscle contraction

be a cause for patient's inability to carry out intermittent catheterization independently. The neutral zero method is used to describe the maximum possible passive and active range of motion of a joint in all possible planes of movement based on a standard initial position. First, the angle of maximum movement away from the body is given, then the 0-position (zero), and finally the angle of maximum movement toward the body. If motion is limited, the zero (0-position) will not appear in the middle but on the side upon which there is a deficit [13]. Taking the upper ankle joint as an example, unlimited range of motion would mean plantar flexion/dorsal extension: 50°/0/30°. In the case of *pes equinus*, the following result may be obtained, depending on the range of motion: 50/20°/0°. In this case, the neutral position cannot be achieved, and there remains a residual flexion of 30° between 20° and 50° plantar flexion. The lack of a neutral position in the upper ankle joint may prohibit a proper sitting position in the wheelchair causing secondary strain to the ischii. Worst case, sitting in the wheelchair may become impossible.

23.2.1.3 Spasticity Measure

The *Modified Ashworth Scale* is frequently used for grading spasticity in routine clinical practice. It can be easily performed and does not require any equipment. The velocity-dependent response of muscles to passive stretching is rated in a six-point nominal scale [14]: 0 = no increase in muscle tone; 1 = slight increase in muscle tone, manifested by a catch and release or by minimal resistance at the end of the range of motion when the affected part(s) is moved in flexion or extension; 1+ = slight increase in muscle tone, manifested by a catch, followed by minimal resistance throughout the remainder (less than half) of the ROM; 2 = more marked increase in muscle tone through most of the ROM, but affected part(s) easily moved; 3 = considerable increase in muscle tone, passive movement difficult; and 4 = affected part(s) rigid in flexion or extension.

Of note, the Ashworth Scale represents a subjective assessment and only checks single-joint resistance to passive ROM at a specific point in time. The interaction of muscle chains, the spasm frequency, or possible spasticity triggers are not examined. Even the impact of spasticity on function cannot be assessed.

The *Penn Spasm Frequency Scale* (*PSFS*) represents a patient-reported outcome measure. However, its reliability has yet to be confirmed. The patient completes a self-assessment questionnaire reporting spasm frequency (*0 = no spasms*, *1 = spasms induced only by stimulation*, *2 = infrequent spontaneous spasms occurring less than once per hour*, *3 = spontaneous spasms occurring more than once per hour*, *4 = spontaneous spasms occurring more than ten times per hour*) and intensity (*1 = mild*, *2 = moderate*, *3 = severe*) [15]. More details on spasticity measures can be found in chapter 13).

23.2.2 Functional Outcome Measures

23.2.2.1 Spinal Cord Independence Measure

The Spinal Cord Independence Measure, version III (SCIM III), specifically designed for individuals with SCI, is a comprehensive disability scale [16, 17]. The assessment reflects aspects of self-care management, medical conditions, and mobility. The tool is grouped into three areas of function and takes approx. 30 min to complete, ideally by observing the patient (Table 23.4). The test does not require any particular equipment and can be incorporated into clinical routine.

The first section involves the item of self-care – feeding, bathing, dressing, and grooming – with a total score of 20 points. The second section refers to activities of respiration, bladder sphincter management, and bowel sphincter management and collects a maximum of 40 points. The third section reflects all aspects of mobility with 40 points total to be achieved. Thus, a maximum of 100 points can be reached from all sub-items, whereas increasing number of points reflects improved independence [18].

23.2.2.2 Spinal Cord Injury Functional Ambulation Inventory (SCI-FAI)

The gait assessment is SCI specific and easy to assess and evaluates three components of walking: gait pattern (Table 23.5) with a maximum of 20 points, the use of assistive devices (e.g., cane, walker, orthosis) with a maximum of 14 points, and walking modalities such as speed, frequency, and distance with five possible points. Higher scores denote a higher level of walking ability, although the subscores should not be combined to make an overall score. The measurement is a combination of observation and the patient's self-report [18, 19].

23.2.2.3 Walking Index for Spinal Cord Injury

The Walking Index for Spinal Cord Injury (WISCI) is a functional scale for clinical use and for research to evaluate improvements in ambulation. In the second version (WISCI II) with two additional levels, the walking capability is rated from 0 to 20 based on the individual's dependence on assistive devices, braces,

Table 23.4 Main parts of SCIM III

Self-care
Feeding: cutting, opening containers, pouring, bringing food to mouth, holding cup with fluid (0–3 points)
Bathing: soaping, washing, drying body and head, manipulating water tap: upper body (0–3 points), lower body (0–3 points)
Dressing: clothes, shoes, permanent orthoses: dressing, wearing, undressing: upper body (0–4 points), lower body (0–4 points)
Grooming: washing hands and face, brushing teeth, combing hair, shaving, applying makeup (0–3 points)
Respiration and sphincter management
Sphincter management – bladder (0–15 points)
Sphincter management – bowel (0–10 points)
Use of toilet: perineal hygiene, adjustment of clothes before/after, use of napkins or diapers (0–5 points)
Respiration (0–10 points)
Mobility (*room and toilet*)/*mobility* (*indoors and outdoors*, *on even surface*)
Mobility in bed and action to prevent pressure sores (0–6 points)
Transfers: *bed to wheelchair*: locking wheelchair, lifting footrests, removing and adjusting arm rests, transferring, lifting feet (0–2 points)
Transfers: *wheelchair to toilet to tub*: if uses toilet wheelchair: transfers to and from; if uses regular wheelchair: locking wheelchair, lifting footrests, removing and adjusting armrests, transferring, lifting feet (0–2 points)
Mobility: indoors (0–8 points), moderate distances (10–100 m) (0–8 points), outdoors (more than 100 m) (0–8 points)
Stair management (0–3 points)
Transfers: *wheelchair to car*, approaching car, locking wheelchair, removing arm- and footrests, transferring to and from car, bringing wheelchair into and out of car (0–2 points)
Transfers: *ground* to *wheelchair* (0–1 points)

Adapted from Catz and Itzkovich [17]

and personal assistance. The examiner observes the patient, who walks 10 m, and rates the level, which is considered to be safe. Level 0 describes that the client is unable to stand and/or participate in assisted walking. At level 1 the patient ambulates in parallel bars, with braces and physical assistance of two persons, less than 10 m. At the highest level 20, the patient ambulates with no devices, no braces, and no physical assistance over a distance of at least 10 m [18, 20]. The use of the WISCI is limited in assessing individuals with only minor walking impairment due to a ceiling effect. Walking endurance is not reflected in this score [21].

23.2.2.4 6-Minute Walk Test

The 6-minute walk test (6 MWT) measures the distance a patient can walk on a flat surface as quickly as possible in 6 min. The patient may stop and rest (but not sit) during the test, and the use of auxiliary equipment is also permitted. Along with the ability to walk, endurance and cardiopulmonary capacity are also evaluated, among other things. The test was originally designed for patients with respiratory impairments. In

Table 23.5 Observational gait analysis part of the SCI-FAI

Parameter	Description
Weight shift	Weight shift to stance limb or weight shift absent or only onto assistive device
Step width	Swing foot clears stance foot on limb advancement or stance foot obstructs swing foot on limb advancement
	Final foot placement does not obstruct swing limb or final foot placement obstructs swing limb
Step rhythm (relative time needed to advance swing limb)	At heel strike of stance limb, the swing limb: begins to advance in <1 s or *r*equires 1–3 s to begin advancing *or* requires >3 s to begin advancing
Step height	Toe clears floor throughout swing phase or toe drags at initiation of swing phase only or toe drags throughout swing phase
Foot contact	Heel contacts floor before forefoot or forefoot or foot flat first contact with floor
Step length	Swing heel placed forward of stance toe or swing toe placed forward of stance toe or swing toe placed rearward of stance toe

Adopted from Field-Fote et al. [19]

the case of incomplete SCI patients, the 6 MWT is particularly suitable for individuals with minor impairments, in order to record further improvement [18, 22, 23].

23.2.2.5 Timed Up and Go

The Timed Up and Go (TUG) is a timed walking test, which was originally developed to assess the sense of balance in elderly individuals and the resulting danger of falling. The TUG records the time (in seconds) that the patient needs to rise from a chair, to walk three meters, to turn around when they get to the 3-m line, and to walk back and sit back down on the chair [24]. If it takes the patient more than 30 s to accomplish the task, they will normally require help for transfers and going up stairs, and they are not able to go outside alone. Use of auxiliary equipment is permitted. The test is easy to carry out and can be used to assess walking ability, even in SCI patients, although no standard value has been established for the SCI population at this time [18].

23.2.2.6 10-Meter Walk

For the 10-meter walk test (10 MWT), the patient must be able to walk at least 14 m as this is the total distance to be covered in this test. It measures the time in seconds that the patient needs to walk 10 m, from meter 2 to meter 12 (“flying start”). Assistive devices may be used [25]. However, the use of auxiliary devices is not taken into account when scoring, and no statement can be made about endurance due to the walking distance only being 10 m. The test can be used in a clinical context and to evaluate walking ability in individuals with SCI in clinical studies [18, 24].

23.2.2.7 Berg Balance Scale

Initially developed for elderly persons, the Berg Balance Scale (BBS) is now also used for stroke and SCI patients as well as those suffering from multiple sclerosis. It comprises a total of 14 items, which are each assessed on a 5-point scale. The overall number of points ranges from 0 points (severely impaired balance) to 56 points (excellent balance). The categories are as follows:

1. Sitting to standing
2. Standing unsupported
3. Sitting with back unsupported but feet supported on floor
4. Standing to sitting
5. Transfers from an armless chair to a chair with arms
6. Standing unsupported with eyes closed
7. Standing unsupported with feet together
8. Reaching forward with outstretched arms
9. Picking up an object from the floor
10. Turning to look behind over left and right shoulders
11. Turning 360°
12. Placing alternate feet on step or stool while standing unsupported
13. Standing unsupported one foot in front
14. Standing on one leg

The test can be used in all phases, but only for patients who possess a certain level of standing and walking ability [18, 26].

23.3 Therapeutic Strategies for Lower Extremity Rehabilitation

23.3.1 Compensation Toward Functional Independence

This chapter focuses on strategies to promote recovery of walking function. For compensatory strategies, it is referred to respective textbooks. The main goal of rehabilitation is to achieve the maximum level of independence, which can be achieved to a varying extent depending on the lesion severity, level of injury, and concomitant comorbidities. It is acknowledged that for individuals with severe/high-level SCI, compensatory strategies and assistive technology represent the only alternative to regain functional independence.

If it is not possible to restore the standing and walking function sufficiently for everyday life or if this is not yet foreseeable within the scope of the initial treatment, the rehabilitation team has to encourage the patient to work toward functional independence. Patients with severe motor impairments, who converted from walking at discharge to the wheelchair within 1 year after injury, experienced poor quality-of-life factors with high levels of depression and pain scores [27].

Individual rehabilitation plans have to be constantly adapted to the current level of therapy and supplemented by compensatory elements. It is essential to practice also wheelchair mobility, transfer skills, and activities of daily living and adapt the necessary devices. Just one example which is choosing the appropriate wheelchair is an individual decision and depends on a great many factors. Using a mechanical wheelchair requires sufficient functioning of the upper extremities, the trunk muscles, and corresponding cardiopulmonary capacity. If these conditions are not met, use of an electrical device/electrical wheelchair must be examined. Further criteria include, among other things, the sitting position, primary use (indoor, outdoor, for sport), and the patient's demands on the wheelchair. For detailed descriptions and instructions of compensatory strategies/skills, see, for example, Somers and Harvey [28, 29].

23.3.2 Restoration of Locomotor Function

The main goal in lower extremity functional restoration is recovery of – ideally unaided – walking function. Depending on the degree of spared functions, the therapy can also address the ability to get up and stand to facilitate movement transition, e.g., during transfer or to make use of remaining upper extremity function.

Walking is a complex process, which requires adequate voluntary motor function, sufficient coordination of leg movements, and – often neglected – appropriate sensory feedback, in particular proprioceptive feedback. These basic prerequisites allow to shift the body weight on one side during the standing phase, achieve an upright posture and stability of the trunk, maintain the balance, and adapt to the environment as needed. For successful restoration of walking function, sufficient joint mobility in the lower extremities represents an important prerequisite [30]. In the course of locomotor training, auxiliary equipment including support (compensation) through the intact upper extremities might be necessary. Therefore, this chapter will not only focus on the task-specific aspects of locomotor training but in addition discuss supporting elements, which are key for restoration of locomotor function such as trunk stability, endurance, and the implementation of supportive devices (e.g., orthoses).

23.3.3 Task-Specific Locomotor Training

In order to learn or relearn defined motor skills, the principles of motor learning have to be employed. These principles rely on practice (number of repetitions) and augmented feedback about performance. Moreover, training needs to be task specific – if you want to walk, you have to walk. An optimal rehab program aiming for recovery of walking function should not only rely on task-specific locomotor training. Supporting measures, e.g., trunk stability or muscle training (see below) have to be employed to improve the efficacy of task-specific training. Unfortunately, evidence in respect to the optimal timing/dose of task-specific training, the most efficient feedback approach or the ideal balance between task-specific and unspecific training is scarce.

The most important principles for locomotor training are increasing the ability of the lower extremities to take on weight and reducing the amount of weight taken on by the upper extremities, augmenting sensory input, and strengthening movement sequences as well as reducing compensatory strategies (e.g., assistive equipment, therapist support) [3, 31]. In the early phase after spinal cord injury, in particular in cases of more severe motor impairment, automated locomotor therapy represents an important therapy option. Despite severe sensorimotor deficits, task-specific training can be employed at a rather high repetition rate without exhausting the therapist too much [3, 32]. However, the limited variability and perturbation options due to the restrictive nature of robotic assistance represent the downside of such a therapy [31]. Until now none of the proposed task-specific locomotor training concepts have been clearly shown to be superior in patients with incomplete SCI [33]. The choice of the machines to assist training depends on the extent of sensorimotor deficits in the lower extremities and trunk as well as the cardiopulmonary capacity.

In patients with a high level of injury, severe sensorimotor deficits and orthostatic dysregulation are treated first on a tilt table, which allows stepping movements (see below). Once orthostatic dysregulation has ceased, body-weight-supported treadmill training with exoskeletal support will be tested. In case only minor leg assist is required, stepping movements can be induced without external support, and body weight can be taken over at least partially by the patient; treadmill training with body-weight support, however without exoskeletal support of the lower extremities, will continue. Subsequently treadmill training will be mixed with overground locomotor training and as soon as possible replaced by overground training activities (Fig. 23.1).

During supported treadmill training, requirements for overground mobility should already be addressed by the therapist. Ideally, at the end of each treadmill session, the progress in locomotor function should be practiced without assistive devices. Depending on the degree of neurological recovery, getting up from height-adjustable benches, weight shift while standing, taking one step forward and to the side, stepping on the spot, or overground walking can be exercised [34].

23.3.3.1 Locomotor Training Devices

Tilt Table with Stepping Device

The tilt table with stepping function (ERIGO®) is based on a traditional tilt table allowing stepping with a physiological load pattern in combination with an adjustable tilt and stepping frequency. The patient is secured through a harness with a chest and shoulder fixation (Fig. 23.2). Each thigh is fastened by a cuff and each foot is fixed on a footplate by two straps. The upper body part of the tilt table can be continuously tilted from the supine position up to an angle of 80°.

To realize a physiologically gait-related loading of the foot, a special spring damper was integrated in the footplate: Load is applied to the foot sole during the stance phase (hip and knee extension) due to clamping of a spring beneath the plate. In case of hip and knee flexion, the spring is released from the plate and load reduction is generated. The overall load on the foot increases with the degree of tilting since the patient’s body weight becomes more and more exposed to gravity pushing against the spring-damped footplate [35].

Stepping movement requires loading of the legs to induce a patterned leg muscle activation in healthy subjects and individuals with spinal cord injury. The

Fig. 23.1 Practice of walking function in an incomplete SCI patient. (**a**) Body-weight-supported treadmill training with exoskeletal support (Lokomat®). (**b**) Overground walking on parallel bars. (**c**) Overground walking on parallel bars with visual feedback (mirror). (**d**) Initiation of overground walking by getting up from the bench to stand. (**e**) Overground walking with a walker on a homogenous surface

appearance of a locomotor pattern depends on afferent input detected by "load receptors" in combination with hip joint position-related proprioceptive input [36, 37].

The efficacy of ERIGO® training has only been demonstrated in ameliorating orthostatic dysregulation [38]. Heart rate and blood pressure increased over time superior to effects seen with a tilt table without stepping function. It can be assumed that early training with the ERIGO® improves locomotor function. However, this has yet to be determined. Nevertheless the ERIGO® is employed to practice gait training in patients with poor sensorimotor function at a very early stage of rehabilitation. The concept behind this strategy is to deliver weight bearing to the legs as early as possible in order to avoid maladaptive changes on one hand and to prepare an optimal setting for subsequent more task-specific locomotor training [3].

Fig. 23.2 Tilt table with stepping function

Manually Assisted Body-Weight-Supported Treadmill Training

Treadmill training with body-weight support has become an important part of gait rehabilitation for patients suffering from incomplete SCI. In addition to an increase in walking speed and walking distance as well as a reduction in the need to use assistive devices, locomotor training has also been correlated with an increase in bone and muscle mass along with positive cardiovascular effects [5, 31, 39–43]. Comparing standard physical therapy alone with a combination of body-weight-supported treadmill training and standard physical therapy in patients with acute incomplete SCI indicated that patients receiving the combinatory treatment gained independence from assistive devices/walking aids more rapidly and achieved a higher walking speed than patients with standard physical therapy [44].

Treadmill training is ideally suited to implement the abovementioned principles of locomotor training. Body-weight support can be adjusted to the maximum weight transfer possible to both legs (it should still be possible to straighten knee and hip joints). As a consequence, the amount of weight taken by the upper extremities [3, 45–47] can be reduced. In addition, walking speed can be adjusted close to the average walking speed (0.75 – 1.25 m/s) [3, 40]. Treadmill training allows almost physiological joint movements of the hip, knee, and ankle joints, with particular emphasis on the hip joints [3, 40, 46] including an upright positioning of the trunk [3, 40]. Depending on injury severity, 1–2 therapists have to support coordinated leg movement during swing and stance. Therapy goals have to be reevaluated for each therapy session and respective variables of the walking device have to be adjusted

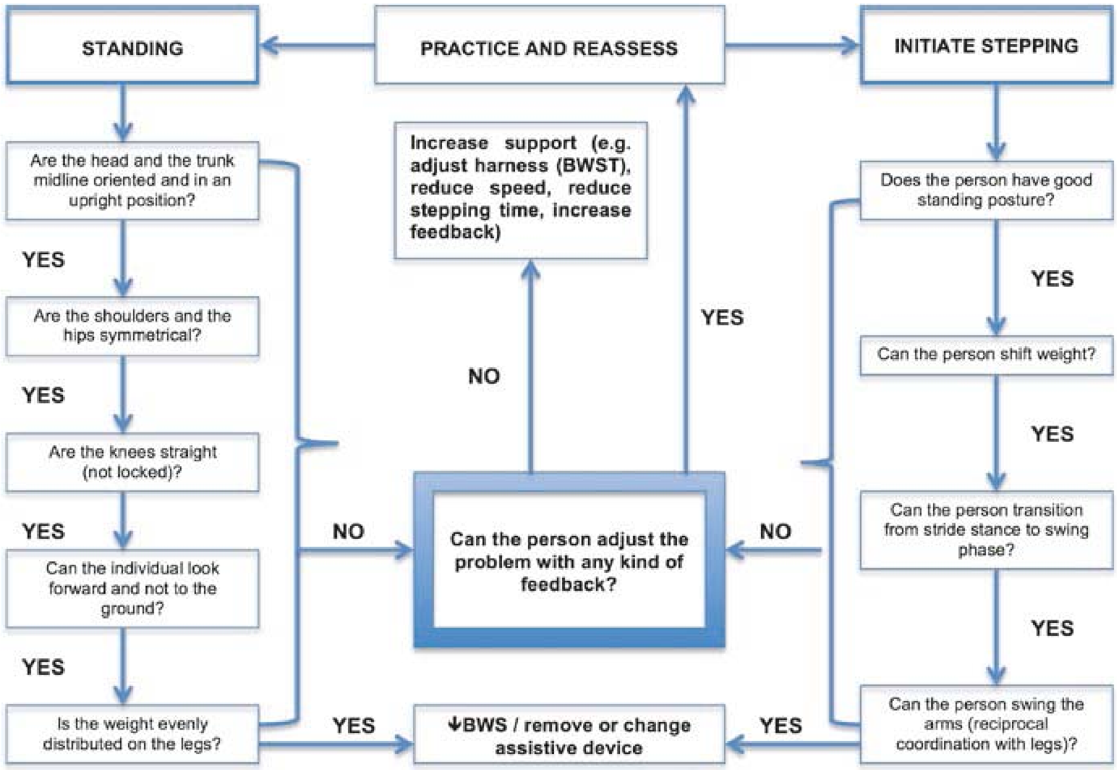

Fig. 23.3 Decision-making algorithm for standing and step initiation progression (Adapted with permission of the American Physical Therapy Association. ©2005 American Physical Therapy Association [48]). *BWST* body-weight-supported treadmill, *BWS* body-weight support

accordingly. Objectives can be to increase walking speed, to reduce body-weight support, to reduce the amount of manual support, or to prolong the training sessions (Fig. 23.3). In the case of reduced proprioception, external feedback via auditory feedback (e.g., therapist) or visual feedback (mirror, technical systems capable to detect gait kinematics) can help to restore a more physiological gait pattern. Instrumented kinematic real-time feedback therapy in individuals with incomplete SCI has been shown to normalize the gait [49].

Robotic-Assisted Body-Weight-Supported Treadmill Training

The main objectives to develop a robotic-assisted body-weight-supported treadmill were to reduce the workload of therapists to position the legs and stabilize the trunk while walking on the treadmill, to generate reproducible gait pattern and as a consequence to intensify gait training with a high number of repetitions. In electromechanical devices for automated-assistive walking training machines, end-effector devices can be distinguished from exoskeleton devices. The Lower Extremity Powered Exoskeleton (LOPES®) [50], the Active Leg Exoskeleton (ALEX®) [51], and the Lokomat® represent exoskeleton-based robotic-assisted body-weight-supported treadmills. Examples for end-effector-based devices are the G-EO-System, the LokoHelp, the Haptic Walker, and the Gait Trainer GT1 [52].

Exoskeleton Based Robotic-Assisted Body-Weight-Supported Treadmill Training

The Lokomat (Fig. 23.4) consists of a robotic gait orthosis, a weight support system, and a treadmill. The gait orthosis primarily consists of a hip and knee orthosis which can be readjusted and adapted to each individual patient. Active actuators are installed in the knee and hip joints for the swing phase. The ankle joint movement is supported by a passive foot lifter. In order to achieve a physiological gait, the powered orthosis is controlled by a computer. Here, the actuators for the hip and knee joint movement follow a physiological specification and provide a reproducible gait pattern. This was determined prior to the administration in patients by testing the Lokomat® on healthy subjects. The devices are equipped with a feedback system for self-control of therapy. Once the patient has been positioned in the Lokomat®, only one therapist is required to perform the therapy, to adjust the parameters (speed, weight support, hip and knee position), and – very important – to give instructions. To ensure the patient's safety, it is recommended that two therapists safely position the patient in the Lokomat® [3, 32, 53]. The Lokomat® has been shown to increase the gait velocity, endurance, and walking distance [54]. In respect to gait quality, the Lokomat® is comparable to manually assisted treadmill training [55–58]. However, the Lokomat® requires less therapists and produces a more reproducible gait pattern.

End-Effector Based Gait Training

This concept is based on two mechanically driven footplates, whose trajectories simulate stance and swing phases during gait training. As a consequence, the

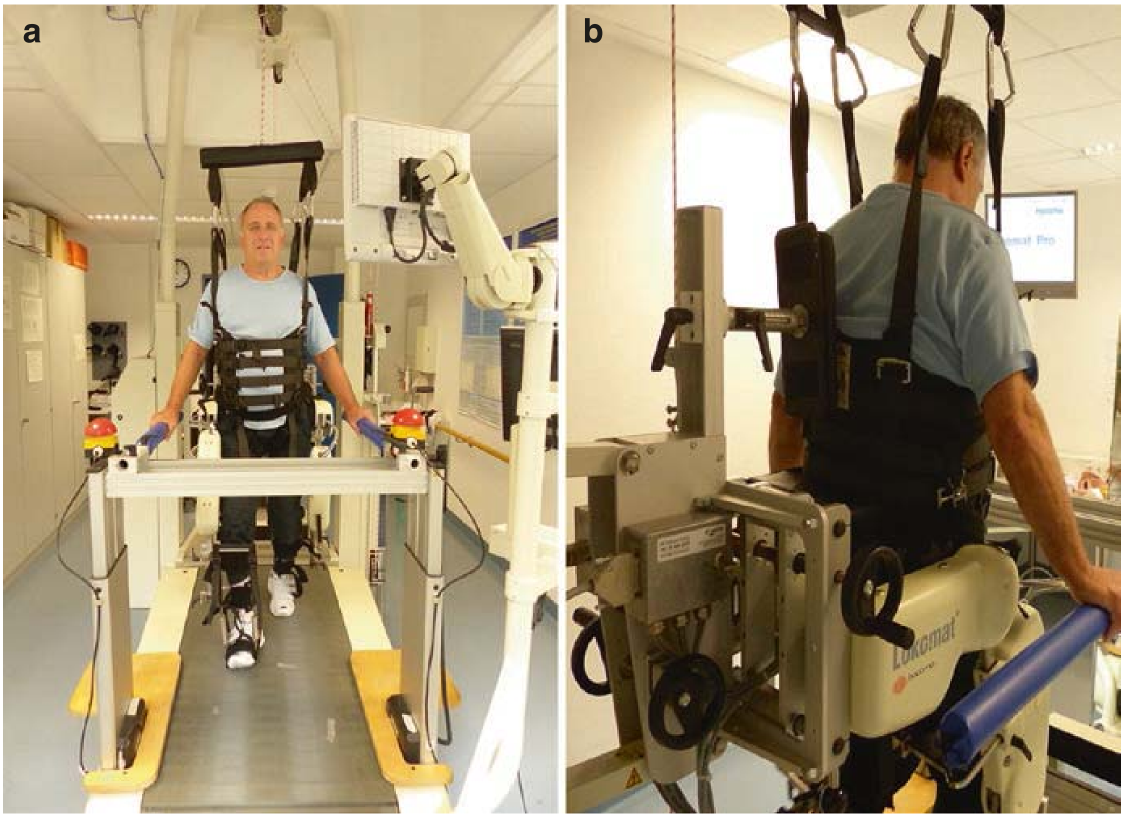

Fig. 23.4 (**a**, **b**) Robotic-assisted body-weight-supported treadmill training with the Lokomat®

machine moves the feet (end effector). The more proximal joints (knee, hip) follow this movement (e.g., G-EO-System, LokoHelp, Haptic Walker, Gait Trainer GT1 [52]). In a multicenter study with 155 acute non-ambulating stroke patients (DEGAS study), end-effector-based gait training in combination with physical therapy has been shown to be superior to physical therapy alone [59]. More advanced machines such as the "Haptic Walker" consist of programmable footplates to simulate a variety of overground walking conditions (stairs, other obstacles) and to introduce perturbation (sudden slipping) [60]. An evaluation of 18 studies (11 trials used an exoskeleton device, 7 trials used an end-effector device) on gait training in stroke patients showed a higher rate of independent walking after training with the end-effector device [52].

A direct comparison of the Lokomat® and the Gait Trainer GT1 in motor incomplete acute SCI patients (predominantly AIS-D) revealed similar improvements in all outcome categories (Lower Extremity Motor Score, Walking Index for Spinal Cord Injury II scale, 10-m walk test). In the reported study, both systems seem to be an adequate tool to improve walking functions in incomplete SCI patients [61]. However, in SCI patients with severe motor impairments in the lower extremities, proximal and distal joints need substantial support, which cannot be provided by end-effector devices. Here, only exoskeleton-based devices represent a feasible treatment option.

MoreGait

The abovementioned devices require trained therapists as well as sufficient space and infrastructure. Due to the high costs, only inpatient rehab facilities or large outpatient institutions can effectively run such a device. However, even in such institutions, unstable patients in the very early rehabilitation phase or patients with multiresistant germs frequently cannot be introduced into respective devices. Moreover, shortening of inpatient stays by health-care providers limits the use of these devices. To address these aspects, a specific locomotor training device – so-called Motorized orthosis for home rehabilitation of Gait (MoreGait) – was developed at Heidelberg University Hospital (Fig. 23.5). The MoreGait consists of a seat with inclined backrest for a semi-reclined position, two active powered

Fig. 23.5 MoreGait

exoskeletons (knee and ankle joints), and a footrest (“stimulative shoe”) to allow physiological stimuli to be applied to the foot. Thanks to the semi-reclined position, weight is not applied to the foot due to the patient’s body weight but via a mechano-stimulation unit. A movement comparable to walking can be carried out using the training device, whereby a physiological rolling movement of the foot is simulated. A feedback function is integrated in the device to allow control of the therapy and to supply the patient with feedback in respect to his/her training activity. A folding base allows the device to be transported. The therapeutic concept has been evaluated within the scope of a pilot study on chronic motor incomplete SCI participants in an outpatient setting. The results indicated that MoreGait therapy is effective in the home environment. After conclusion of an 8-week training period, a significant improvement was observed in walking velocity along with an increase in endurance [62, 63]. Initially developed for the use at home, the MoreGait device can due to its mobility easily be applied to patients colonized with multiresistant germs.

23.3.3.2 Locomotor Training Overground With/Without Body-Weight Support

Overground walking is the actual objective of the entire locomotor training process. Device-supported therapies only serve to prepare for this objective. Although device-supported therapies are task specific, they are different to overground walking in respect to gait characteristics and muscle activity. Treadmill training represents an effective restorative/rehabilitative treatment option in particular in acute phase following SCI and in cases with severe sensorimotor impairment. As pointed out exercises can be repeated at higher frequency and speed [64]. However, treadmill training cannot replace task-specific overground locomotor training, since it does not allow to manage unexpected obstacles or varying surface conditions [65].

As a first step toward overground locomotion, walking along parallel bars can be trained. In cases with higher sensorimotor deficits, in particular in the pelvic and hip regions, the patient can be instructed to take side steps while his/her hands reach for a parallel bar or an elevated bench for support.

Once the patient can walk overground for the same duration and level of intensity as on the treadmill, walking-related outcome assessments show that device-supported training is no longer advantageous to overground training [43, 66–68]. After each device-supported therapy session, the patient’s ability to stand and walk should be checked, and if applicable, overground gait training should be introduced/expanded. In case specific aspects of the gait pattern are not sufficient to allow overground walking, trunk control, involvement of arms, and joint positions should be separately addressed in subsequent – not necessarily task specific – sessions. Overall, device-based treadmill training should be employed as much as necessary and as little as possible, once overground training is feasible (Fig. 23.6).

Subsequent steps during overground training are to reduce assistive equipment (e.g. crutches, walkers, splints) and therapist support. In addition, walking over different terrain and a variety of distractions can be introduced. Five different categories for overground walking have been defined [69]: 1) walking balance (e.g. walking on different surfaces/in different directions), 2) skilled walking tasks

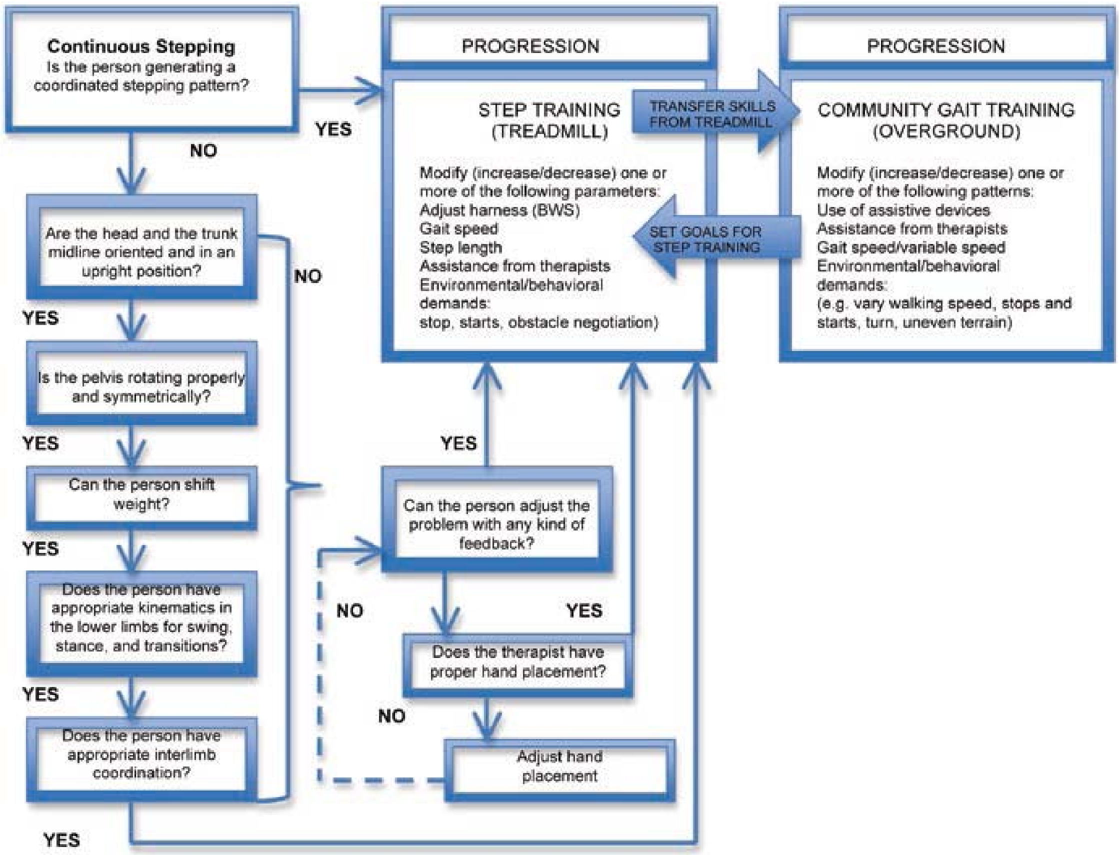

Fig. 23.6 Decision-making algorithm for continuous stepping progression (Adapted with permission of the American Physical Therapy Association. ©2005 American Physical Therapy Association [48]. *BWS* body-weight support)

(e.g. negotiating obstacles, stairs, crowded environments, doors), 3) walking with secondary task (e.g. walking and looking/talking/carrying an object), 4) endurance (e.g. walking over longer distances indoors/outdoors), and 5) speed (e.g. walking short distances at fast pace). Training should also involve walking backwards and practising falling and getting up again.

Overground training can be combined with body-weight support as in the LiteGait system (Mobility Research Inc., Tempe, USA). The mobile training device, which consists of a weight-bearing strap system attached to two overhead supports, can be used over a treadmill and overground. The advantages of this system are its flexibility and its moderate price. Its disadvantages are the number of therapists required to position the patient's legs and correct the trunk. Due to the weight of the device, it also has to be moved by more than one therapist. The wheels attached to the frame allow training only on even ground without obstacles [70].

The so-called Zero G system (Aretech, Ashburn, Virginia 20147, USA) provides also body-weight support while walking overground. The harness is attached to a ceiling track, which can be equipped with a static or a dynamic body-weight support system. The latter guarantees constant weight support and the possibility to change positions. Besides the harness no therapy device surrounds the patient. The therapist has almost unrestricted access to the patient and can provide assistance as needed.

Individuals can walk on different ground surfaces and challenged in varying body positions, e.g., sitting freely on uneven ground. Moreover, assistive devices such as crutches or a walker can be tested while patient is suspended/secured [70]. The fixed position of the ceiling tracks restricts the spatial flexibility of this device. Published clinical studies in SCI or stroke are still pending.

Overall, one should keep in mind that all of the abovementioned assistive devices cannot replace, only assist experienced and skilled therapists. None of them work like a washing machine, where you throw in dirty clothes and receive clean clothes after so many automated washing cycles.

23.3.4 Supporting Therapies

23.3.4.1 Electrical Stimulation

Functional electrical stimulation (FES) is a technique that uses electrical impulses to generate muscle contractions and body movements artificially in individuals with paralysis due to lesions of the central nervous system (upper motoneuron lesion). However, SCI can affect both upper and lower motoneurons. Therefore, electrical stimulation (ES) for each lesion type will be described separately. According to the official definition, we will refer to FES in the context of upper motoneuron lesion and ES in the context of lower motoneuron lesion.

Functional Electrical Stimulation in Upper Motoneuron Type Paresis

FES treatment in lower extremities aims to reduce muscle tone/spasticity [71–73], avoid muscle atrophy, promote muscle strengthening [74, 75], and increase muscle endurance [76, 77]. Moreover, FES-induced muscle contraction/movement in paretic muscles can augment voluntary movement through mechanisms such as embodiment. Furthermore FES can substitute lost central control of paralyzed muscles, e.g., FES-based neuroprosthesis for the correction of drop foot [78]. Positive side effects have been reported such as improvement of bone density [75], cardiovascular strengthening [77], and prevention of decubitus [79].

Paretic/plegic muscles can be activated via FES of corresponding motor nerves. The pulse width used is roughly in the range of 100–500 μs. Stimulation parameters such as frequency, electrode positions, and duration of treatment are selected individually related to the degree of spasticity and fatigue during treatment. Spasticity can be reduced by FES. So far, transcutaneous FES represents the only proven non-pharmacological option to treat spasticity in SCI.

In early FES treatment, spasticity increases during a phase of muscle strengthening. It persists during this training phase, but decreases once a steady force level is observed. This means that the muscle force has reached a plateau. Sometimes spasticity decreases immediately; in other cases, it takes months [71]. In few instances high-frequency FES treatment has to be terminated due to unwanted increase in muscle tone.

Lower stimulation frequencies of 2–6 Hz are adequate to make patients familiar with the stimulation procedure, because single muscle twitches are easily palpable and visible. This trains endurance and prepares the muscle carefully for strengthening with 16–20 Hz, sometimes up to 35 Hz. A further increase of frequency and intensity can provoke spasticity. Therefore, frequency and intensity need to be adapted carefully according to the training status of the muscles [73].

Muscle strengthening starts at 10–16 Hz, generating force and movement. The patient may be able to use residual voluntary muscle control for active support. In many cases the frequencies are raised up to 100 Hz, which would lead to a more continuous contraction in healthy subjects. Using frequencies beyond 20–35 Hz is not recommended in SCI subjects for muscle strengthening, since paralyzed muscles have longer twitch contraction times [80].

After this initial phase, FES-supported ergometer training is an option to enable active cycling using residual capabilities. The FES cycle moves the legs passively for a few minutes, before motion-synchronized FES at predefined intensities helps the patient to support the cycling movement voluntarily. FES is applied preferably to the gluteus maximus, quadriceps, biceps femoris, semitendinosus, tibialis anterior, and triceps surae muscles. The training should be repeated at least three times per week for 30 min for at least 3 months to prevent muscle atrophy. At least 12 months of training are required to maintain bone density [75, 77].

Patients with residual voluntary function in their lower extremities can be supported during ambulation with implantable or surface electrode-based FES systems. Reviews report improvement of ambulation during the FES application [81] and sometimes even lasting aftereffects when the system is removed, e.g., Ness L300 (Bioness Inc.). See also chapter 24 for more details.

Electrical Stimulation in Lower Motoneuron Type Paresis

Muscles paralyzed from lower motoneuron damage – typically observed in cervical SCI, conus, or cauda equina injury – can be activated only directly through ES of the paretic muscle. The used pulse width is roughly between 5 and 500 ms.

Lower motoneuron injury leads to a rapidly progressing muscle atrophy. Such denervated muscles contract after electrical single pulses, which slows down muscle atrophy. Daily treatment should begin as soon as possible after injury and should consist of several thousand impulses per day [82]. The objective to prevent muscle atrophy via ES is to maintain rather healthy muscle tissue in case nerve regeneration with consecutive muscle reinnervation takes place [82]. Continuing ES over even longer periods of time can reduce the risk to develop pressure sores [82]. The pulse width has to be chosen as long as necessary to elicit muscle contraction. However, an increasing pulse width can cause electrolysis-induced skin lesion right below the electrodes. Muscle fibers can recover after daily and intensive application of electrical pulses. With increasing excitability over time, pulse width can be reduced. The decreased pulse width allows higher stimulation frequencies, which are in particular suited to prevent atrophy of denervated muscles.

23.3.4.2 Conventional Physical Therapy

Overall, the goal of a restorative rehabilitation approach is to reinstall previously established sensorimotor functions such as standing and walking. Before and during task-specific interventions such as body-weight-supported treadmill training, basic prerequisites have to be addressed. Firstly, the patient needs to be stable in terms of blood pressure, heart rate, and respiratory parameters. Secondly, individual muscles of the trunk and the lower extremities need to be strong enough to allow specific task-specific interventions. And finally, the overall balance needs to be reestablished for proper standing and walking function. Conventional physical therapy addresses specific components either individually or in combination. Unfortunately, the scientific literature provides very little evidence of most efficient physical therapy-based approaches.

Muscular Strengthening and Endurance

Arm and/or leg cycling helps to train muscular and cardiovascular endurance. Individuals with SCI can start during an early phase of their rehab regardless of whether they are bedridden or not. It is an appropriate method even if other activities, e.g., body-weight-supported treadmill training, are too exhausting. Moreover, arm and leg cycling can be practiced without therapist support. In preparation for bipedal locomotion, crawling and swimming improve endurance as well as the individual's inter-limb coordination skills. Rowing machines or cross-trainers can provide an aerobic benefit but, however, are challenging to use for SCI subjects. Respective patients need substantially spared motor function. In chronic SCI the recommended time to improve endurance is twice a week for at least 20 min each session [83].

A circuit training to strengthen an individual with incomplete SCI should involve weight machines at the beginning, because the guided movement is much easier to accomplish than working out with cable pulleys or free weights. Irrespective of the device used, every major muscle group should be addressed. It is recommended to increase strength by using 70-80 % of the individual maximal lift for 8–10 repetitions and 2–3 sets. For muscular endurance, moderate weight (60 % of the individual maximal lift) should be chosen for 15–20 repetitions and for 3 sets [84, 85].

The Major Muscle Groups and Their Appropriate Training Method (Table 23.6)

Trunk Stability and Balance

Strong shoulder and triceps muscles as well as sufficient upper body control/trunk stability in combination with walking aids such as crutches, canes, or walkers are important to compensate weaker lower extremities. Nevertheless, reasonably balanced loading of the feet has to occur, and overloading/overuse of the upper extremity should be avoided. If the patient has to carry more body weight with the arms

Table 23.6 Major muscle groups and exercise suggestions

Lower extremities Quadriceps, adductor, gluteus, hamstring, calve muscles	Leg press, squats, good mornings, calf/heel raises, lunges, crawl
Upper extremities Shoulder muscles, triceps and biceps muscles	Frontal/lateral pull down, (reverse) butterfly, rowing machine, biceps/triceps curl, push-ups, crawl
Trunk Back and abdominal muscles	Frontal/lateral pull down, reverse butterfly, rowing machine, crunches, swimmers, supermans, planks, push-ups, crawl

than with both feet or if it is too exhausting to keep the trunk in a straight position, body-weight-supported treadmill training should be preferred [3].

As pointed out crawling can help to practice inter-limb coordination in incomplete SCI individuals [86] asking for a reciprocal movement pattern (right hand and left knee, left hand and right knee). Forelimbs in animals and upper extremities in human subjects are linked to hind limbs/lower extremities through propriospinal neuronal pathways and have been shown to influence locomotor function both in quadrupeds as well as in bipeds [87, 88].

Balance training in SCI patients heavily depends on the neurological level of injury and the sensorimotor completeness. Therefore, the recommendations listed here describe basic concepts, which have to be adjusted for each patient. A good starting point to train balance is the sitting position ideally supported by both arms/hands and the feet on the ground. Assistance as needed to support the balance is provided. Incremental advances can be the removal of the arms for support, head turning, or catching objects while sitting. Introducing a knee-stand instead of the sitting position will get the more caudal sensorimotor system involved. Even more challenging for an SCI individual is the "one-knee-stand" due to a smaller supporting surface. More advanced exercises with a "Swiss ball" improve trunk balance and stability in incomplete SCI subjects.

The individual can be:

- Sitting on top of a "Swiss ball" with both feet on the ground
- Eyes open or closed
- Performing distal lateral flexion in the lower spine
- Planks or push-ups with both feet on the ball
- Both shoulders are on top of the "Swiss ball" with the hips straightened and both knees are in a 90° angle flexed/bent

Another way to work on the trunk balance, stability, and strength could be a Bodyblade®, different kind of swing sticks, or an adjustable crawler, which can be challenging and funny at the same time. Nearly every position gets tougher with a Bodyblade® or a swing stick – supine position, side plank, or a stand with feet shoulder wide apart. Using an adjustable crawler during therapy sessions is like a serious body workout and therefore should not be underestimated.

The following exercises can be realized by incomplete SCI individuals and some complete SCI individuals: Balance of the trunk can be trained by standing in a standing frame, which has adjustable degrees to tilt and turn (Fig. 23.7) or between parallel bars. The standing/balancing frame as displayed (Fig. 23.7) allows to shift weight from leg to leg and to train balance while being secured with a harness system.

The sequence of getting up can be facilitated in a stepwise fashion by raising the seat level, thus improving the patient's leverage reducing the effort and strength to perform the task. Alternatively, the harness of a body-weight-supported treadmill training can be employed to reduce the body weight and stabilize the trunk. For a comprehensive list of exercises, see www.physiotherapyexercises.com.

Fig. 23.7 Standing/balance trainer

23.3.4.3 Orthoses/Braces

A significant number of individuals with incomplete SCI, who recovered substantial sensorimotor function allowing them to walk, will need more energy performing the same movement. The walking distance might be decreased. Walking on uneven ground and overcoming obstacles become a much more challenging task due to impaired afferent input, strength, and coordination. In order to at least partially compensate for individual deficits, specific devices, namely, orthoses or braces, can be prescribed to SCI individuals. Moreover, orthotic treatment can help to prevent degenerative musculoskeletal changes due to muscular imbalance of nonphysiological joint load during gait.

Interdisciplinary Rehab Team

In accordance with the patient's expectations, skilled therapists and experienced rehab physicians define the required orthotic support using a variety of tests: strength, sensation, balance while standing, spasticity, stiffness, instability of joints, and range of motion at hips, knees, ankles, and trunk, as well as coordination. If a patient is able to take some steps, the clinicians will observe and evaluate spatial temporal gait parameters (velocity, cadence, step length, step time) and look for safety issues like toe clearance during swing phase and knee extension during stance phase. Orthotists should be involved in the rehab team to provide options for technical solutions to achieve the proposed rehabilitation goal. Orthotic prescriptions must be based on the abovementioned examinations, followed by the patient's biomechanical needs, and should be controlled frequently during the orthotic fitting and the therapeutical interventions. Because neurological improvement is likely to occur over time after an incomplete injury, the patient's needs may change over time, and the orthotic function needs to be adapted accordingly.

Orthotic devices are supposed to give better balance or stability, keep joints in a physiological alignment during stance phase, obtain clearance of the foot during swing phase, protect joints from nonphysiological kinematics and loads, and ensure stance stability and safety during standing and walking by compensating sensorimotor deficits. Nowadays, such devices are usually made of carbon fiber to reach high stability at low weight. They may be off-the-shelf prefabricated orthoses or custom-made by an orthotist.

Orthotic Devices

Foot Orthoses (FO)

The main function of foot orthoses is to gain an optimized pressure distribution and to correct for malalignments (Fig. 23.8). Dynamic foot deformities, e.g., as a consequence of paretic tibialis anterior peroneal muscles, need to be corrected as far as possible. This leads to a stable base of support and must be seen as a crucial component of any orthotic solution. The stabilization of the foot structures allows for stable lever arms and has therefore a direct impact on the proximal biomechanical chain. In addition, FOs may support skeletal foot structures and thus compensate for weak intrinsic foot muscles. Nonphysiological loads can be avoided.

Ankle Orthoses (AO)

AOs provide dynamic lightweight support with a cushioned ankle wrap for mild drop feet (upper or lower motoneurons lesion), which supports dorsiflexion either via a plastic inlay fitting between the tongue and laces of the shoe or barefoot by using a hindfoot bandage instead of the shoe, which will be connected to the ankle wrap, respectively (e.g., Foot-Up® or Neurodyn Spastic®, Sporlastic Orthopaedics). The latter supports the foot up, corrects slight supination, acts against a plantar flexion using crossover elastic restraints, stabilizes the ankle joint, and prevents sprains by nonelastic lateral restraints. It is indispensable to adapt associated footwear and/or foot orthosis during dynamic fitting to allow an efficient gait and to compensate for typically seen foot deformities due to muscular imbalance.

Fig. 23.8 Foot orthosis: back side finally modified, front side basically adapted

Ankle-Foot Orthoses (AFO)

AFOs do involve the ankle and the foot. Depending on their construction, they can compensate for a drop foot with or without an active effect to the proximal joints, i.e., the knee and hip. This can be achieved by a construction, which includes a long orthotic forefoot and a ventral support at the proximal shank. The combination of a long forefoot lever arm with the ventral support induces a knee-extending moment and may support weak knee extensors during stance. A crouching gait can be avoided. Musculoskeletal deformities such as flexion contractures of the hips or knees and deformities of the trunk, e.g., scoliosis or torsional deformities of the lower extremities, can contribute to impaired gait, which cannot be compensated by AFOs.

AFO variations:

- Posterior leaf spring (Heidelberger Winkel)
  - Lightweight support for people with mild-to-moderate drop feet. These orthoses lift the foot off the ground during swing phase. It is not recommended for severe ankle-foot deformities (i.e., *pes equinus*), structural in- or eversion, or severe spasticity.
- Lightweight (carbon fiber) dynamic AFO
  - Lightweight support for people with mild-to-moderate drop feet (Fig. 23.9). Dynamic AFOs provide increased stability during stance including a knee-extending moment and thus moderately affect proximal joints, in particular

Fig. 23.9 Dynamic lightweight AFO

the knee joint. Control and support of plantar- and dorsiflexion is provided by energy-storing and energy-returning carbon fiber. Due to a defined shape and construction, these kinds of premanufactured orthoses (e.g., ToeOFF®, Camp Scandinavia) should not be used in patients with severe spasticity combined with structural deformities or people weighing more than 120 kg.

- Carbon fiber orthosis with hinge joints or dorsal leaf spring (GRAFO)
  - Ground reaction force AFOs (GRAFOs) aim to support body weight during stance. These custom-made carbon fiber orthoses may include adjustable hinge joints at the ankle with adjustable dorsoplantar stops and a spring to support foot lift. Hinge joints allow to define the range of motion with respect to the physical abilities and biomechanical needs (Fig. 23.10). Furthermore, hinge joints might be replaced by a stable carbon fiber dorsal leaf spring (Fig. 23.11). Springs are able to compensate for poor foot control in stance from initial contact on and are able to support the patient during terminal stance by energy return for an adequate push-off.

Knee-Ankle-Foot Orthoses (KAFO)

KAFOs are prescribed for patients with knee instability and/or insufficient knee extension due to paretic knee extensor muscles. In contrast to AFOs, the knee joint is included in the construction (Fig. 23.12). Pure knee instabilities in the coronal plane might be supported by free hinge joints – a good motor function (muscle strength 4) is required. The orthotic knee joint should be aligned with respect to the anatomical joint axis of rotation. A more posterior alignment leads to an increased

Fig. 23.10 GRAFO with adjustable hinge joint

Fig. 23.11 GRAFO with a carbon fiber dorsal leaf spring

Fig. 23.12 KAFO with swing phase lock joint (Fillauer LLC, Netherlands)

stability and supports knee extension slightly – with respect to the functional benefit an incongruent positioning is accepted in patients with insufficient knee extensors (muscle strength 3–4). Patients with more severe paresis of knee extensors (muscle strength ≤ 3) should be fitted with a manually locked knee joint. The lock compensates for the muscular weakness and keeps the knee joint in an extended position during stance. As a consequence the knee joint is also locked during stance and swing. The ipsilateral limb will be circumducted or the contralateral limb will be vaulted to achieve toe clearance during swing. It is obvious that this walking pattern will be rather inefficient and energy consuming. Modern components and orthotic knee joints Swing Phase Lock (Fillauer LLC, Netherlands, Fig. 23.12), E-Mag (Otto Bock, Germany), and Neurotronic (Fior & Gentz, Germany) have addressed this issue. The knee joint can be locked to provide stable stance. During swing it is unlocked to avoid the inefficient gait pattern. Depending on the model, the function is controlled mechanically or by a µ-processor unit. Both mechanical or electronic joint components in KAFOs require a specific gait training to take advantage of the full potential of these types of orthoses.

Neuroprostheses for Lower Extremities

Functional electrical stimulation (FES) integrated into an orthotic device (MyGait, OttoBock; Ness L300, Bioness Inc.) allows to stimulate paretic muscles to provide muscle contraction at the appropriate time point within a more complex movement cycle like walking. For example, the paretic tibialis anterior muscle (drop foot) will be activated externally by FES to provide an active dorsiflexion during swing. The combination of a sensor-based recognition of stance and swing in combination with FES allows for the coordinated toe lifting. A battery-powered signal generator stimulates the nerve transcutaneously via surface electrodes, corresponding muscles are activated, and a contraction occurs. Unpleasant sensations resulting from the transcutaneous stimulation represent a major limitation. Stimulating parameters can be adjusted to reduce such sensations. In contrast to conventional orthotic devices, the range of motion of the ankle joint is not affected by this neuroprosthesis. The patient is still able to perform active plantar flexion for a physiological push-off.

Nighttime Splinting

Nighttime splinting allows adequate positioning of major joints in lower and upper extremities in SCI patients. Respective measures can help to avoid contractures and structural deformities due to paretic muscles and spasticity. An example is a dynamic redression orthosis. Dynamic redression should be realized by low-load prolonged stretch. Dynamic spring control hinge joints help for a well-controlled force [89, 90]. Loss of sensation has to be considered to avoid skin lesions by the orthosis (Fig. 23.13).

Even with the administration of orthotic devices, balance and other “pre-gait” activities need to be performed before the actual gait training with/or without body-weight support can be initiated.

Fig. 23.13 Nighttime splint with dynamic spring-controlled hinge joints (Caroline, Germany)

23.3.4.4 Wearable Exoskeletons

Relatively new approaches to perform standing activities or reach-assisted walking in patients with motor complete spinal cord injuries are wearable exoskeletons. The devices include a frame and motor-driven gait orthosis to compensate any weakness of an individual's lower extremities and limited control of the joints. Different systems (e.g., Ekso GT, Ekso Bionics; ReWalk, Argo Medical Technologies; Indego, Parker Hannifin Corp) are available at the moment, and each system has pros and cons. All devices provide a reciprocal gait pattern. Some of them are able to trigger a step by shifting their weight to one side or notice a slight tilt of the individual's chest. The devices require the use of a walker or forearm crutches to maintain balance for standing and ambulation. The ultimate goals of these rather expensive devices is to allow activities in the standing position, to walk overground, to overcome obstacles (stairs, uneven terrain) and to improve the quality of life of SCI patients. However, at the moment respective devices are still being investigated and not yet established in the clinical or home routine. Appropriate trunk stability including sufficient upper extremity function to use crutches or a walker are required [91, 92].

23.3.5 Prevention/Management of Secondary Damage

Restorative rehabilitation therapies after SCI aim to retrain sensorimotor functions such as standing and walking as described in this chapter. Not all patients, which are introduced into a restorative rehabilitation program, will in the end regain sufficient independent walking function. This might be due to several factors such as too severe sensorimotor impairments, lack of fitness, comorbidities, disabling spasticity/pain and/or joint problems (contractures) [93]. Potential long-term complications related to impaired walking function such as joint deformities need to be considered and weighed against quality-of-life aspects [41].

Subsequent injuries after SCI constitute a significant problem. In a study, which included 1328 patients (AIS-A–D) at least 1 year after traumatic spinal cord injury, 19 % reported at least one injury within the last year, which required medical treatment. Patients with the ability to walk showed a high rate of injuries, not all of them related to falls [94]. Among 119 patients suffering from chronic incomplete SCI with a walking ability of at least 10 m, 75 % reported at least 1 fall irrespective of an accompanying injury within the last year. Most falls happened at home and in the majority of cases, patients only suffered slight injuries (bruises, scrapes, etc.). Of note, 18 % of the subjects reporting a fall suffered a bone fracture. Moreover, 45 % of the subjects who had fallen reported a reduced ability to get out into the community [95]. Dizziness, concomitant diseases (e.g., arthritis) and fear of falling increase the number of falls. In contrast, using a walker and regular exercises can reduce the number of falls [96]. In another study out of 515 ambulating subjects with chronic SCI 20 % reported at least one injury caused by a fall in the last year. Poor balance, the use of one crutch and the misuse of pain medication were associated with an increased rate of injury. If mobility was achieved equally through walking and wheelchair use the fall incidence was increased. In contrast, both predominant wheelchair users and predominant walkers showed a lower incidence of fall related injuries [97].

For these reasons, fall prevention should be given major consideration in therapy planning. Balance plays an important role since it represents the key to walk safely. In addition, it constitutes a predictor for walking quantity [4]. Therefore, therapy should include targeted balance training, as described above. Other approaches include targeted muscle training with strengthening of weaker muscle groups, practicing unfamiliar situations, regular evaluation of walking ability including checking the remaining deficits, and reevaluation for assistive devices. Only in exceptional cases unilateral walking support should be prescribed, e.g., if there are load limitations for one arm. If the risk/rate of falling is high and the walking velocity is rather low, patients should be advised to use a wheelchair as their prime mode of mobility. This does not exclude further gait training. However, training integrates the retained functions into activities related to transfers, changing positions in bed or relief from the wheelchair. Therapy must include fall training if walking is intended to be continued.

Clinical Case *A 75-year-old patient with traumatic SCI (NLI Th 12, AIS-D, 8 weeks post-injury) covers a distance of 10 m with a walker requiring some assistance. The patient can urinate voluntarily, but suffers from a concomitant stress incontinence. She is not able to walk to the toilet in time on her own once she experiences the urge to urinate. After reassessing the therapy goals, wheelchair and transfer skill training – in particular transfer from the wheelchair to the toilet and undressing/dressing while standing – at the expense of locomotor training were intensified to allow for a higher level of independence.*

Another limiting factor to be considered is the presence of pain. The spine and all joints can be affected by pain. In the lower extremities, body-weight-related overloading due to insufficient muscular support is the main cause – in addition to preexisting joint damage. While an orthotic solution is possible for the knee and ankle joints, this proves difficult for the hip joint and the trunk. Assistive devices can be helpful to compensate for paretic limbs, thus maintaining walking function. In most instances, this approach will challenge the musculoskeletal integrity of the upper extremities, in particular the shoulder girdle. In 14 ambulating individuals with incomplete SCI the strain on their shoulder joints during walking with crutches or a walker was examined. The strain on the shoulder joints was extremely high in both instances – use of crutches or walker – with a greater strain being observed using crutches. Surprisingly, the load peaks were even higher than the forces needed to propel a wheelchair [98]. A survey in 783 people with incomplete SCI highlights the relevance of this aspect. 66 % of the interviewed SCI individuals use at least one assistive device (walker, crutches, canes, braces, support person) [99]. Interestingly, individuals using the wheelchair more infrequently reported more pain and fatigue in comparison to frequent wheelchair users or walkers. These findings support the notion that incomplete SCI patients can only maintain walking function at the expense of increased effort and energy consumption in order to compensate for sensorimotor deficits [93, 99]. In terms of therapeutic consequences, the following aspects should be considered: if pain occurs or increases, the cause needs to be identified and adequately addressed (use/modification of orthotic devices/braces, walking with body-weight support, training individual components responsible for pain). The use of pain medication is an option, if the treatment is transient. Otherwise it needs to be weighed against the risk to mask functional weaknesses, which can promote longer lasting musculoskeletal problems. As pointed out before, balance will be affected by pain medication and can thus increase the risk of falls [97].

In this context, orthoses/braces, in particular correcting orthoses, should also be carefully monitored. Respective devices can causes or propagate pain [99]. Furthermore, in particular in areas with severe sensory deficits, pronounced muscular atrophy or existing contractures the risk of pressure ulcers has to be weighed against the benefit of orthoses/braces.

It should be emphasized that gait training during the acute phase bears the risk to raise false expectations that cannot be achieved in the end. Therefore, regular reevaluation of the therapeutic goals and consecutive readjustments are mandatory, which have to be discussed with the patient to properly plan the therapeutic interventions to obtain skills required for everyday life (e.g., wheelchair mobility). After all, the end justified the means. If sufficient mobility can be achieved through wheelchair use, but not through walking, an important goal determining quality of life has been achieved [93, 100].

23.4 Adjunct Therapies for the Modulation of Neuronal Activity

Most of the neurorehabilitative therapies for restoration of the ambulatory function are based on the neuroplasticity of the CNS. Neuroplastic changes meaning adaptation of neural networks to an injury of the spinal fiber tracts may occur at different levels of the CNS, starting with the peripheral, musculoskeletal system, continuing at the level of the motor and interneurons of the spinal cord and ending at supraspinal levels such as the brainstem and the cortex [101]. Although it is not clear, to which degree the reorganization of neuronal structures and changes in the synaptic transmission at different levels contribute to the improvement of function, there is growing evidence that stimulation methods modifying the activity of neural networks at spinal and cortical level may enhance the outcomes of task-oriented therapies [102–104]. Noninvasive techniques offer the possibility to be used early in the rehabilitation of individuals with incomplete SCI due to the ease of application and the relatively low price of the technical equipment and can therefore effectively be integrated as adjunct therapies into activity-based training regimes. The basic principle of activity-modulating therapies is depending on the selection of the stimulation parameters: On the one hand, an inhibitory effect may reduce spastic activity and thereby allowing a better use of residual voluntary motor functions. On the other hand, the general activity level of neuronal networks might be increased providing the ground for a faster and more effective learning and a higher persistence of motor functions.

The most widely used and best investigated noninvasive activity-modulating therapies are noninvasive brain stimulation techniques, namely, transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS), and, on the spinal level, transcutaneous spinal cord stimulation (tSCS) activating dorsal, afferent spinal roots of lumbar segments.

TMS is a noninvasive, easy-to-apply method that utilizes a wired coil to produce a powerful and rapidly changing magnetic field, which passes the bony structures of the skull and produces small electrical currents in the region of the brain just under the coil via electromagnetic induction. These currents in turn elicit action potentials in neurons of the targeted area. TMS with single impulses and the associated measurement of motor evoked potentials in limb muscles have become a widely used neurophysiological tool both in clinics as well as in research [105]. When using TMS of the motor cortex in a repetitive manner (rTMS), a frequency-dependent effect occurs: while low-frequency (1 Hz) rTMS inhibits cortical excitability, high-frequency (5–20 Hz, in theta-bust stimulation up to 50 Hz) rTMS produces an increase in cortical excitability, which can facilitate motor sequence learning. Although the number of studies is low, a recent study was able to show the superiority of a combination of a gait rehabilitation program and 15 sessions of a 20Hz-rTMS over the primary leg motor area versus a sham rTMS. A significant improvement was observed after the last rTMS session in the active group for Lower Extremity Motor Score (LEMS), walking speed, and spasticity. Improvement in walking speed was maintained during a 2 week follow-up period. Sham stimulation did not induce any improvement in LEMS, gait assessment, and spasticity after the last session and neither during follow-up. More research is necessary to optimize rTMS parameters and to adapt the therapy to the individual impairment caused by the SCI [106, 107].

Although the use of direct currents for therapeutic purposes dates back the nineteenth century, tDCS has been systematically investigated in early 2000 [108]. It offers the possibility to change cortical excitability in a polarity-specific manner (anodal versus cathodal) and this can be achieved by the application of electrodes with different polarity to different locations on the surface of the skull to excite the underlying neural tissue. tDCS effects are most likely induced by membrane polarization, altering the firing rates of neurons. Anodal tDCS induces depolarization, while cathodal tDCS induces hyperpolarization, so that anodal stimulation produces excitation and cathodal stimulation produces inhibition. tDCS can be easily integrated into neurorehabilitation because of the cheap equipment, ease of application and high acceptance of the non-perceptable currents by patients. The few results of the use of tDCS for enhancement of a locomotor therapy are controversial, underlying the need for better definition of effective training parameters and adequately powered randomized studies to prove the therapeutic superiority [109, 110].

Another exciting method currently under investigation is the use of transcutaneous spinal cord stimulation. In contrast to the preceding methods, which target brain structures, tSCS is aiming at modulating the state of the lumbosacral spinal circuitry either for reduction of spasticity [111] or for supporting the effects of locomotor training approaches [112]. The basic principle of SCS is that lumbar posterior roots can be activated by transabdominal electrical currents so that a frequency-dependent modulatory effect occurs. While stimulation frequencies of 30 Hz led to an augmentation of voluntary residual muscle activities in individuals, higher frequencies of 50 Hz showed a reduction of reflex activity and muscle tone. Both effects contributed to a better ambulatory function in individuals with chronic incomplete SCI. Like in rTMS and tDCS clinical studies involving a larger number of end users need to be conducted to clearly show the efficacy and general usefulness of this method.

Although there are many open questions about neural activity-modulating therapies regarding the selection of safe and most efficient parameters, combinatorial therapeutic approaches will most likely boost the success of neurorehabilitation and lead in the end to a increased quality of life in persons living with the consequences of SCI.

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