Neurorehabilitation of the Upper Limb Across the Lifespan
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Managing Hypertonicity for Optimal Function

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1 Seeing the Bigger Picture: Using Clients’ Experiences to Shape Clinical Practice

Chapter objectives

• Discuss the impact of brain, injury on the lives of individuals and their families, highlighting the changes that clients experience over time and the subsequent need for long-term services and supports, particularly during times of transition between services.

• Outline requirements for effective collaboration with clients and caregivers, including principles and practices the clinician can adopt to ensure client-centred service provision that promotes clients’ and caregivers’ long-term quality of life.

Abbreviations

ABI  Acquired brain injury
CP   Cerebral palsy
TBI  Traumatic brain injury

1.1 Appreciating the client’s experiences

To ensure that neurorehabilitation, or any other aspect of service provision, is effectively targeted and contributes to positive outcomes for clients in their life contexts, the clinician must step back and appreciate the wider picture of what occurs in the lives of individuals and their families after brain injury. Health professionals may, at times, feel that they have limited control over the organisational context and practical constraints (e.g. funding mechanisms, staffing levels, resource availability) within which they are working. Indeed, service evaluation, long-term research and government lobbying is often required to drive positive change in service provision models, availability and quality. Nonetheless, the individual clinician usually has some control over how he or she practices – what is emphasised and prioritised in encounters with the client and family, which clinical skills are developed and refined, who the client will be referred to after this clinical service has ended, and the communication that will occur with the client and family, as well as with subsequent service providers.

Therapy services are typically categorised according to the amount of time post-injury, the service purpose (acute care, rehabilitation, long-term community-based services, residential care) or a specific client age range (children and youth, adults, older people). Therefore, each clinician will be involved for only part of the client’s story. Smoothing the pathway from one phase of service provision to the next requires a broader appreciation of the client’s rehabilitation journey outside the clinician’s own immediate service context.

To gain this broader perspective, the clinician can consider what has been learned from research into the experiences of clients and caregivers post-injury and their perceived long-term service needs. Although a variety of different factors come into play when working with clients with different diagnoses, research into chronic disability due to brain injury suggests some common themes across stroke, traumatic brain injury (TBI) and cerebral palsy (CP). Awareness of these ‘big picture’ themes can help clinicians develop practice habits and skills that support the client’s quality of life and promote positive long-term outcomes. Research findings suggest that the following themes are important in guiding service provision.

1.2 Providing or assisting access to long-term services

1.2.1 What are the needs?

It is clear that quality acute care supports better outcomes for people with acquired brain injury (ABI). This is illustrated by the variation among stroke outcomes in different European countries depending on the resources devoted to the acute phase of treatment [1]. It has further been suggested that, in addition to advances in brain stimulation techniques and pharmacological interventions, early provision of intense interdisciplinary neurorehabilitation contributes...
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substantially to better stroke outcomes [2]. In relation to children with CP, substantial progress has been made over the past two decades in developing coordinated interdisciplinary rehabilitation services [3] and research into related interventions has focused on provision of services early in life and throughout childhood [4].

Despite a concentration of resources within the acute and early rehabilitation phases of intervention, a growing body of research across different diagnostic groups indicates that people with brain injury continue to have therapy needs on a long-term basis, often for the duration of their lifetimes [5]. In a study of 60 people with TBI who were interviewed one year after their injuries, 38% identified significant restrictions to their lifestyle and work capacity and 15% were unable to care for themselves [6]. In a UK study of 1251 people ranging from one to five years post-stroke, approximately half of the participants reported a reduction in work activities and two thirds participated in fewer leisure pursuits than before their strokes [7]. In a comparison of the quality of life between people with recent (1–5 years) and extended (more than 5 years) brain injuries, the extended group reported more difficulties with instrumental activities of daily living, such as household tasks and community activities, indicating the need for continuous community living skills training [8].

As people with CP live longer, there are indications that atypical tone increases with age and secondary conditions, such as contractures and degenerative arthritis, are having lifetime effects [9]. In a review of long-term outcomes for adults with CP, Kembhavi et al. [4] identified that ambulation skills commonly deteriorated in adulthood and that joint deformities occurred regardless of mobility status or severity of the condition. Co-morbid diagnoses, such as stroke, multiple sclerosis and Parkinson disease, are not uncommon in adults with CP [9]. The recognition of these long-term issues within this client group has led to increased research into the impact of pain and fatigue on their participation in daily life activities [4].

In addition to these ongoing physical and rehabilitation needs, it is clear that emotional and psychosocial issues continue to be evident over time across all diagnostic groups. In a large UK study, one third of participants who had had a stroke between one and five years previously reported emotional problems [7]. Similarly, in a sample of French participants, two thirds of whom were more than one year post-stroke, depression was more common than in matched controls, and levels of both depression and difficulties in social interaction increased over time post-stroke [10]. Comparable difficulties were found in a study of people with TBI [11]. For people with stroke, emotional and social issues were more marked for those who had hemiplegia or were unemployed [10]. As such needs have become more recognised, it has become evident that promoting quality of life among people with ABI requires ongoing support of emotional and social role functioning, daily life activities and participation in enjoyable activities [12]. A similar breadth of needs can be identified for people with CP. Studies suggest that adults with CP commonly live isolated lives [13] and that those aged over 40 have been assessed to be lonelier than other adults [14]. Mental health issues, such as depression, are not uncommon in this population [9]. At a consultative clinic for adults with CP in New South Wales, Australia, while the main areas of need are neurological and musculoskeletal, depression and anxiety are also being identified [3].

Collectively, this research suggests that the service needs of people with brain injury change and increase over time and that services need to be responsive to these changes [5,15]. It is further suggested that the degree to which these service and support needs are met will significantly impact clients’ long term quality of life, psychological adjustment and participation in meaningful life roles [16–18]. The importance of ongoing service provision for adults with TBI is highlighted by the finding from one study that, for some people, the hope of continuous improvement over time played a critical role in developing a “new self” [6] (p.414). For example, one participant commented that “I’ll keep improving, with hard work of course, for the next … 10 years, or 20 years, no matter what …” (p.413).

1.2.2 Are the needs being met?

Despite increasing acknowledgement of long-term service needs, current service availability and access is falling short of the expectations of clients and families. Half of the participants in a UK study of people post-stroke reported unmet needs in relation to clinical services and information provision [7], while an Australian survey of carers of adults with TBI found that only 33% reported access to therapy services following hospital discharge [5]. In another study focusing on the transition of people with ABI from hospital to home, the services that were provided (even during inpatient rehabilitation) were considered insufficient in terms of timing, intensity and duration [15]. Adults with chronic lifelong disabilities have reported
difficulty accessing services in the adult health system equivalent to those available when they were children [19]; similarly, young people with CP experience a marked reduction in rehabilitation services once they finish school [3]. People living in rural areas and those with non-compensable injuries also face restrictions to service access in some countries [15].

While limited resources are likely to be partly to blame for unmet service needs, some studies indicate that the attitudes of service providers were unhelpful and they reduced access to further services. In a Swedish study, people with TBI and their relatives reported feeling avoided and misjudged by health service personnel [20]. They relayed their experiences of professionals evading their questions about further service provision and making decisions about their care without consulting them or allowing their families to have meaningful input. Dennis [21] provides a vivid account of similar experiences after her mother had a stroke and service providers decided that rehabilitation was not warranted due to the severity of the stroke's effects. Dennis perceived that once this decision is made by health professionals, care and therapy ceases, causing further negative impact on the quality of life of people with more severe disabilities. Adults with CP have also reported that, while their experience of dealing with health professionals was generally positive, barriers to accessing health care included lack of interest and time provided to them by some health professionals [13] and a lack of specialist knowledge and professional training [4,22].

It may be difficult for individual clinicians to effect significant organisation- or health care system-wide changes to service access. However, the research outcomes described here can be used constructively to develop one’s own practice style and principles, focusing in particular on developing a client-centred approach to service provision and a personal attitude of compassion.

### 1.3 Initiating and supporting transitions from one service to the next

#### 1.3.1 How is transition experienced?

The process of transitioning from one service context or stage to another is another theme identified as important by clients and caregivers. Research into the transition from hospital to home or from inpatient to outpatient rehabilitation services suggests that this process often does not occur smoothly. For example, in an Australian study, a quarter of carers of people with TBI reported that they received inadequate information about services available after discharge. Few carers were accessing formal financial, travel or accommodation supports and only one third of clients were reportedly accessing ongoing therapy [5]. In a further study of individuals returning home after an ABI, participants reported that organising post-discharge services was a difficult process, mired in bureaucracy and inflexible or complex eligibility criteria [15]. In the latter study, case management services were not in place before or immediately after discharge, and clients experienced delays in commencing community-based services after returning home. As a result of this lack of coordination and planning, levels of caregiver satisfaction tend to drop substantially between inpatient and outpatient services [5,23]. It has been suggested that reduced satisfaction at this point in time might also be due to a slowing of the spontaneous recovery experienced by the person with brain injury [5]. However, the anxiety that this phase creates is only likely to be exacerbated by a simultaneous reduction in services that could play

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**Messages for the Clinician**

- Assume that clients are likely to have ongoing service needs at various points in their lifetime and that even after neurological rehabilitation is complete, consideration should be given to issues of quality of life.
- Collaborate with clients and their caregivers about future service needs and assist them to source possible services options and form links with these services.
- Monitor the long-term needs of clients and provide targeted rehabilitation when possible to address defined needs.
- Initiate working closely with other professionals (such as social workers and psychologists) to ensure that social and emotional needs are addressed at all ages and life stages.
- Ensure that, during rehabilitation and beyond, therapy promotes participation in daily life activities and valued life roles to assist adaptation to changes in ability over time.
- Seek out specialist training to develop relevant skills for ongoing management of chronic rehabilitation needs.
a role in assisting clients to come to terms with their current status and future potential.

For young people with CP transitioning into adulthood, lack of allied health services and orthopaedic care are identified as challenges [19]. A review of transition services in Victoria, Australia, found that families were often inadequately prepared for the transition to adult health services. Variation occurred in terms of the age at which transition was first raised and the information provided about new services. Young people and their families reported feeling apprehensive about moving from the safe, nurturing environment of paediatric services with which they had had a long-term relationship, to adult services which were perceived to be less friendly and helpful. There was little lead up to the transition, few formal processes in place and no consistent staff member to manage and coordinate the move. Families reported feeling lost in this new system and, in addition, sometimes encountered long waiting lists for services and a shortage of health professionals with relevant expertise [22].

1.3.2 What is required to smooth the way?
Recommendations from research and service evaluation across different diagnostic groups carry similar themes. Caregivers of people with TBI reported that the anxiety they felt on discharge from hospital could have been relieved through the provision of improved transition planning and monitoring of post-discharge service access [5]. Similarly, people with ABI and their caregivers felt that case management needs to be instigated well before discharge to organise formal support services [15]. The process of transition of young people with CP from paediatric to adult services can be facilitated by an identified coordinator leading the development of specific processes, such as a documented transition plan that indicates the target age for transfer, the skills that may be required by the young person and family to effectively engage with adult services, and an agreed programme to target these skills [22]. Clear information about what to expect from the new service is recommended across all client groups [5,24].

Addressing the client’s and caregivers’ emotional support needs is another area of focus for transition. Close collaboration with clients with an acquired injury and their families is encouraged to uphold inclusiveness and dignity, and to promote a sense of control over the situation rather than exacerbating anxiety and despair at this time of change [15,21]. For young people with CP, it has been advised that greater emphasis be placed on understanding and addressing the client’s and family’s emotional needs as they leave paediatric services and enter the adult sector [22]. A Canadian transition programme aims to acknowledge the difficulties parents face as their child with a disability enters adulthood and advocates a shared management approach to transition, using skill building programmes to gradually shift responsibility from the parent to the child/adult [24].

The relationship and interaction between services at transition points is a further consideration, with research indicating that planned dialogue and collaboration between services is critical for a positive client experience [3,15,19]. A review of the transition experience of young people with CP in Australia recommended that the paediatric service initiate contact with the adult service to assist in establishing an early relationship with a key coordinating person. It was further advised that the adult service make contact with the client prior to the first appointment, if necessary arranging a one-to-one meeting with the designated coordinator to provide information and allay anxieties prior to meeting the new interdisciplinary health service team. To support ongoing quality of service provision after transition, it was proposed that a professional development programme be developed that included formal and regular knowledge-sharing opportunities between previous and current service providers [22]. These specific recommendations for the process of interaction and mutual support between the pre- and post-transition services are equally relevant to hospital and community organisations servicing adults with acquired injuries.

1.4 Listening carefully and providing relevant information
Client and caregiver needs for clear information from professionals at all stages of service delivery is a recurring theme across a range of studies [5,15,22]. A US-based study found that outcomes for people with TBI and their carers were adversely affected by a lack of education throughout their healthcare experience [25]. Lack of information across the continuum of care has been identified as a prime reason for dissatisfaction with services [5]. A critical appraisal of the literature investigating the information needs of carers of relatives with an ABI described several requirements. In addition to general information about the injury, carers reported the need for health professionals to answer questions honestly while retaining hope for improvement [26]. Health professionals in a Canadian study defended the provision of vague information on the basis that
People with more severe disabilities may have greater difficulty conveying their narratives and may tend to rely on caregivers to fulfill this role. Given their evident importance in the recovery process, actively listening to clients’ stories deserves considerable attention from clinicians.

**Messages for the Clinician**

- Provide honest, easy to interpret information, in both verbal and written formats at all stages of the health care continuum. If outcomes are uncertain, convey this by providing broader information on the range of likely outcomes. Ensure that this information is provided in a sensitive way and offer ongoing support and the opportunity for clarification.
- Make an effort to actively listen to clients’ narratives of their experience. When relevant, listen to caregivers’ translations of these experiences.
- Fully acknowledge clients’ and caregivers’ concerns and take them seriously. If it is unclear why they may be experiencing certain difficulties or symptoms, assume the role of collaborator and assist them to investigate the stated concerns.

### 1.5 Collaborating on achievable goals

Goal setting has long been considered a routine part of the neurorehabilitation process, involving the therapist and client formulating a statement about the desired outcome of intervention [28]. In settings with a team of service providers, such as stroke units, interdisciplinary goal setting is seen as important [2]. Clients with brain injury and their caregivers have reported that the process of setting goals increases their interest in rehabilitation and influences their perceptions of intervention success [15].

However, identifying goals is not always straightforward. In a study examining the transition from hospital to community rehabilitation services for people with ABI, many participants reported general goals such as “getting my life back to the way it used to be” (p.826) and appeared to be unaware of the more specific rehabilitation goals that they were working towards. These participants were confused about the process of goal setting, with many stating that their therapists had set the goals and that they believed this to be the therapist’s role [15].

The experience of clients and families having difficulty specifying goals is not a new one to most
clinicians, given that clients are often unsure what to expect of intervention and therefore what aims may be realistic. In addition, clients with acquired injuries may continue to be wedded to the idea of ‘how things used to be’ for some time after their injuries. A study of people who were more than five years post-injury found that their quality of life had improved over time and that they were better adjusted to their new lives than were more recently injured people [8]. It is possible that, at this later stage, clients may find it easier to contemplate more specific, realistic goals. In any case, it is likely that the clinician will need to provide information about the possible outcomes of intervention and the limits on what might be achieved to assist clients to set well-targeted goals at any stage of the rehabilitation process.

Messages for the Clinician

- Collaborate with clients to formulate and document specific, achievable goals in language that is understandable to both client and caregivers.
- Assess the client before setting goals and use assessment information to inform realistic goal setting. Explain to the client and caregivers what might be possible given the current situation and client abilities, which outcomes are probable and which outcomes are unlikely (see Chapter 4).
- Refer back to the documented goals frequently throughout the intervention process. Review goal achievement after each stage of intervention and either set new goals or adjust current goals to target a more realistic outcome.

1.6 Actively supporting and involving caregivers

A growing body of research is being directed towards the caregivers of people with brain injuries [5,29–31]. This has occurred in recognition of the critical role played by caregivers in the client's recovery and long-term outcomes. Research suggests that people with acquired brain injuries consider their informal networks to be their most valued source of support and that this support is typically concentrated with one or two important people in their lives [15]. The health, stress and level of burden on primary carers are directly associated with the recovery of adults with TBI [32]. This is not surprising given that the person’s social and community integration or re-integration is often dependent on caregiver support [2]. This support is also influential for adults with CP. For example, although general exercise has been shown to improve functional status, frequency of exercise participation was found to be dependent on caregivers’ attitudes [33].

Carers also report a range of unmet needs that result in feelings of isolation and of being misunderstood [5,30]. In addition to difficulties accessing ongoing services, the need for support during the transition between services, and wanting to receive clear information (discussed in Sections 1.2, 1.3 and 1.4), caregivers report a lack of adequate training from health professionals. For example, a third of carers of people with TBI reported that they had not received relevant training from hospital staff before taking on their caring responsibilities [5]. A lack of social supports for carers over time has also been found to have significant consequences; carers without social support whose relatives lived with cognitive deficits and lack of insight reported experiencing increasing stress as time progressed post injury. However, these factors did not cause stress among carers who had social supports in place [29].

Caring for caregivers would therefore seem to be a worthwhile focus for health professionals in order to

Messages for the Clinician

- Pay attention to caregivers. Notice their apparent levels of stress and anxiety. Ask them about how they are managing and the types of formal and informal supports they have in place for themselves. Where possible, provide information about support services they can access.
- Regularly take time to explain what you are doing with the client and why. Seek the caregiver’s feedback. Routinely invite them to ask questions. Teach them techniques they can use in the client’s daily lives. Allow them to practise these techniques in front of you and, if required, provide encouragement, extra support and information to promote mastery.
- Promote a culture of teamwork between the health professionals in your service and the clients and caregivers who access it. Initiate regular evaluation of service outcomes that includes seeking caregiver perceptions regarding satisfaction with the service. Let caregivers know how you have used this information to adapt service provision.
promote positive long-term outcomes for their clients. The most direct solution to unmet caregiver needs is for services to provide or assist caregivers to source ongoing emotional, psychological and financial support [5]. However, even if organisational resources make it difficult to provide this type of assistance, there are simpler steps that individual clinicians can take to reduce carer burden. Satisfaction of carers with service provision has been found to depend partly on their knowledge of, and involvement in, the rehabilitation process [5]. In addition, research indicates that caregivers’ perceptions of support may be as beneficial to their wellbeing as the actual support provided [29]. This suggests that making efforts to fully involve caregivers in intervention, paying attention to their current and changing demands, and simply conveying a genuine caring attitude will go some way towards lightening the caregiver load.

1.7 This book: Promoting collaborative, client-centred intervention

So how does a book focused on the upper limb contribute to the wider experience of clients and caregivers after brain injury? It is hoped that the information provided in subsequent chapters will:

• Clarify causes of observed characteristics and movement patterns and their consequences for current and future function (Chapter 2), which will in turn assist the clinician to collaborate with the client on setting achievable goals (Chapter 4).

• Promote confidence in translating research into practice in a way that fully appreciates the realities of the client’s whole situation and day to day life (Chapters 3, 6–10).

• Build clinicians’ confidence regarding clinical reasoning and decision-making that considers the client’s context and the aspects of life that have meaning for him or her (Chapters 3, 4, 5 and 11).

• Provide a framework for client- and family-centred assessment, goal setting and intervention in an area of practice where clients and families often need support to become empowered members of the team (Chapter 3).

• Provide a common language among health professionals for understanding and communicating with each other and the client about upper limb function and how it might impact on the person’s wider experiences of life after brain injury.

Above all, it is our hope that clinicians will be inspired to join with clients and their family/caregivers in problem-solving the best way to optimise upper limb use and comfort in a way that positively contributes to their lives.

References

Chapter objectives
• Provide an overview of the neural and non-neural components of the motor system that contribute to upper limb movement.
• Describe the underlying causes of the upper motor neuron syndrome.
• Discuss the changes that occur in the upper limb due to the upper motor neuron syndrome.
• Consolidate learning about the influences of the upper motor neuron syndrome on the upper limb through clinical examples.

Abbreviations
ASP Arm Spasticity Patterns
BoNT-A Botulinum neurotoxin-A
CMC Carpometacarpal (joint)
CNS Central Nervous System
DIP Distal interphalangeal (joint)
EMG Electromyography, electromyographic
FCU Flexor Carpi Ulnaris
GMFCS Gross Motor Functional Classification System
GT Gschwind and Tonkin forearm classification
HGF House, Gwathmey and Fidler thumb classification
HIPM Hypertonicity Intervention Planning Model
IP Interphalangeal (joint)
MC Metacarpal (bone)
MCP Metacarpophalangeal (joint)
PPIP Proximal interphalangeal (joint)
UMN(s) Upper motor neuron(s)
UMNS Upper motor neuron syndrome
Z&Z Zancolli and Zancolli hand classification

2.1 Motor control and normal movement
Motor control involves the process of planning, initiating, organising and completing movements that are appropriate for each activity and task environment. The capacity to adapt movement to suit a variety of situations requires cooperation between different systems within the person, such as the sensory/perceptual, cognitive and neuromuscular systems. It also requires information processing across different levels of the central nervous system (CNS). For example, sometimes movement is fast, automatic and involuntary, involving only neuromuscular systems, such as when one withdraws the hand quickly after touching a hot surface. This automatic reflex movement involves neural connections between sensory input and motor output at a spinal cord level only (although the connections may involve interneurons and one or more spinal circuit segments). At other times, such as when learning a new skill, movement will be deliberate and more consciously controlled as cognitive/memory systems interact with sensory/perceptual and neuromuscular systems to make fine adjustments to motor output. This type of movement involves information processing across different systems, and between the cortical levels of the CNS involved in planning and programming movement, and the spinal levels involved in executing the movement [1,2,3].

For normal upper limb movement to occur, all components of the motor system (neural, muscular and skeletal) need to be intact and able to respond effectively to motor commands and activity requirements. The focus of this text is the upper limb and, in particular, promoting arm and hand function after brain injury. Therefore, this chapter provides a relatively brief overview of only those components of the motor system most involved in effecting the ‘mechanics’ of upper limb movement (such as the descending tracts, the spinal cord and its circuits, muscles and connective tissues). The ‘cognitive’ aspects of motor control (such as motor learning or movement initiation) are not detailed, nor are the...
many linkages between sensory/perceptual and motor systems, which are covered in other texts [4,5,6].

**2.1.1 Neural components of the motor system**

The neural components of the motor system include the spinal cord, brainstem, descending pathways, motor cortex (primary motor, premotor and supplementary) and the association cortex (prefrontal and posterior parietal). These components can be described as being organised into 'lower' and 'higher' levels in terms of their responsibilities for the different aspects of movement control (see Box 2.1). While 'lower' level components have more direct control over muscles, the 'higher' level components have responsibility for more abstract and complex aspects of movement control. However, despite each component having different responsibilities within the motor system, they interact and cooperate with one another to produce coordinated movement.

**Box 2.1 Hierarchy and Heterarchy**

The terms hierarchy and hierarchical have been attributed different meanings over time as theories of motor control have developed. Traditional reflex-hierarchical theories of motor control described three levels of CNS control: higher (association cortex), middle (motor cortex) and lower (spinal cord reflex) levels [7,8]. This was also described as ‘top down’ organisation since each higher level was viewed as controlling the level below it. Following brain injury, movement was thought to have regressed to the lower level of CNS control, where “removal of the influence of the higher centres” led to “reduction to a more automatic [reflex] condition” [8, pp. 6, 8]. In contrast, contemporary motor control theory proposes that each CNS level is able to influence the others (higher or lower), depending on the movement required to achieve a task. Thus, organisation may be either ‘top down’ or ‘bottom up’ and control is heterarchical, that is, ‘distributed’ among the different levels of the motor system according to functional needs [3].

The spinal cord and brainstem are involved in controlling movements through automatic, reflex activity. For example, the spinal cord controls the speed and force of muscle contraction through reflex action and, similarly, the brainstem is concerned with maintaining balance and posture. Local brain stem and spinal cord circuits contain the cell bodies of the lower motor neurons which send out their axons to control skeletal muscles in the head and body, respectively. Descending pathways form the third component of the motor system and are comprised of the axons of upper motor neurons (UMNs), that is, neurons whose cell bodies are located either in the cortex or the brainstem. The role of the UMN is to regulate the excitability of the lower motor neurons, either directly, or indirectly via interneurons. In contrast to the reflex activity of the ‘lower’ components of the motor system, the motor cortex and association cortex areas are involved in planning, initiating and coordinating skilled, voluntary movements.

While not structurally a part of the motor or association cortices, the basal ganglia and cerebellum are functionally connected with the motor system through their influence on the descending pathways. The basal ganglia are three interconnected groups of neurons (the caudate nucleus, putamen and globus pallidus) concerned with selecting and initiating voluntary movement, and with suppressing unwanted movement. The cerebellum is involved in detecting errors between planned and actual movements [9,10]. Table 2.1 lists the neural components of the motor system together with the motor disorders that are commonly attributed to each following brain injury.

**2.1.2 Non-neural components of the motor system**

The musculoskeletal system forms the non-neural component of the motor system and includes muscles, connective tissues, bones and joints. The functions and properties of muscle (including muscle tone) and connective tissues are described in this section.

**2.1.2.1 Skeletal muscle: excitability and contraction**

The main function of skeletal muscle is to provide movement, which is facilitated through its properties of excitability, contractility, elasticity and extensibility (see Box 2.2). Excitability and contractility (capacity for contraction) are described in this section. Skeletal muscles and connective tissues share the properties of elasticity and extensibility which are addressed in Section 2.1.2.3.

Skeletal muscles facilitate limb movement by adjusting their length and tension through the contraction of muscle fibres which are organised into motor units. Each motor unit consists of a single alpha motor neuron (with its cell body located in either the brainstem or ventral horn of the spinal cord), its axon (the long fibre of the
Table 2.1 Neural components of the motor system: responsibilities and disorders [9,10,11].

<table>
<thead>
<tr>
<th>Component</th>
<th>Motor responsibilities</th>
<th>Motor disorders due to damage at component level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spinal cord</td>
<td>- Automatic spinal reflex circuits (sensory and motor)</td>
<td>- Lower motor neuron syndrome (paresis, paralysis, areflexia, muscle atrophy)</td>
</tr>
<tr>
<td></td>
<td>- Control of muscle length and tension</td>
<td></td>
</tr>
<tr>
<td>Brainstem</td>
<td>- Coordinates and adjusts motor control signals between the brain and spinal cord</td>
<td>- Abnormal extensor patterns (may include decerebrate rigidity)</td>
</tr>
<tr>
<td></td>
<td>- Regulates muscle tone and complex postural reflexes</td>
<td>- Reduced vestibular and postural control</td>
</tr>
<tr>
<td></td>
<td>- Motor innervation to face, head, neck (cranial motor nerves)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Origin (UMNs) of descending pathways (rubrospinal, vestibulospinal, reticulospinal)</td>
<td></td>
</tr>
<tr>
<td>Cerebellum</td>
<td>- Influences movement via the brainstem</td>
<td>- Movement changes on ipsilateral (same) side as the brain injury</td>
</tr>
<tr>
<td></td>
<td>- Motor planning and timing</td>
<td>- Intention tremor</td>
</tr>
<tr>
<td></td>
<td>- Motor learning and adaptation of movement</td>
<td>- Dysmetria (impaired coordination, accuracy, timing)</td>
</tr>
<tr>
<td></td>
<td>- Balance and postural adjustment</td>
<td>- Dyssynergia (decomposition of movement)</td>
</tr>
<tr>
<td></td>
<td>- Detection of errors between intended and actual movement</td>
<td>- Dysdiadochokinesia (impaired performance of smooth, rapidly alternating movement)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Ataxia (disorder of balance and posture)</td>
</tr>
<tr>
<td>Basal ganglia</td>
<td>- Processes signals between cortex and thalamus</td>
<td>- Hypokinesia (slowness or poverty of movement; including akinesia, difficulty initiating movement and bradykinesia, slowness in completing movement)</td>
</tr>
<tr>
<td></td>
<td>- Initiates and modulates movement</td>
<td>- Tonal impairments (dystonia, cogwheel rigidity, athetosis, chorea, hemiballismus)</td>
</tr>
<tr>
<td></td>
<td>- Regulates postural reflexes and automatic movements</td>
<td>- Resting, non-intentional tremor</td>
</tr>
<tr>
<td></td>
<td>- Inhibits unwanted movements</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Contributes fibres to the extrapyramidal (motor) system</td>
<td></td>
</tr>
<tr>
<td>Thalamus</td>
<td>- Relays motor and sensory information between basal ganglia, cerebellum and motor cortices</td>
<td>- Weakness, ataxia on contralateral (opposite) side to the brain injury</td>
</tr>
<tr>
<td>Primary motor cortex</td>
<td>- Control of individual or sequential movements that involve multiple muscle groups</td>
<td>- Contralateral paresis (muscle weakness) or plegia (paralysis)</td>
</tr>
<tr>
<td></td>
<td>- Regulates movement direction, degree, speed and force</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Origin of the majority of the corticospinal (pyramidal) fibres</td>
<td></td>
</tr>
<tr>
<td>Premotor cortex</td>
<td>- Preparation for movement</td>
<td>- Reduced movement planning</td>
</tr>
<tr>
<td></td>
<td>- Sensory aspects of motor actions</td>
<td>- Incorrect contextual organisation of movement</td>
</tr>
<tr>
<td></td>
<td>- Spatial guidance of reaching</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Interprets the inferred intention of a movement from its context</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Stores motor patterns</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Contributes fibres to the corticospinal tract</td>
<td></td>
</tr>
<tr>
<td>Supplementary cortex</td>
<td>- Complex movement sequences and bilateral movements</td>
<td>- Reduced spontaneous movement</td>
</tr>
<tr>
<td></td>
<td>- Mental rehearsal of skilled movements</td>
<td>- Hemi-neglect</td>
</tr>
<tr>
<td></td>
<td>- Anticipates movement forces</td>
<td>- Contralateral dyspraxia/apraxia (inability to perform previously learned movements)</td>
</tr>
<tr>
<td></td>
<td>- Contributes fibres to the corticospinal tract</td>
<td></td>
</tr>
<tr>
<td>Association cortex</td>
<td>(prefrontal, posterior parietal)</td>
<td>- Deficits of attention, recognition, spatial relationships and motor planning</td>
</tr>
<tr>
<td></td>
<td>- Cognitive aspects of complex motor behaviour (attending to, identifying, and planning motor responses)</td>
<td>- Reduced motivation for movement</td>
</tr>
<tr>
<td></td>
<td>- Transforms multi-sensory signals into motor commands</td>
<td>- Apraxia</td>
</tr>
<tr>
<td></td>
<td>- Learning</td>
<td>- Hemi-neglect</td>
</tr>
<tr>
<td></td>
<td>- Speech</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Contributes fibres to the corticospinal tract</td>
<td></td>
</tr>
</tbody>
</table>

(continued overleaf)
Table 2.1 (continued)

<table>
<thead>
<tr>
<th>Component</th>
<th>Motor responsibilities</th>
<th>Motor disorders due to damage at component level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary somatosensory cortex</td>
<td>• Processes presence, size and location of sensory stimuli from skin, muscle and joints</td>
<td>• Astereognosis (inability to identify an object by touch without looking at it)</td>
</tr>
<tr>
<td></td>
<td>• Closely linked to the primary motor cortex, contributes fibres to the corticospinal tract</td>
<td>• Loss of senses of vibration, proprioception and fine touch</td>
</tr>
<tr>
<td>Descending motor pathways</td>
<td>• Control discrete, skilled voluntary movements</td>
<td>• UMNS; produces contralateral motor symptoms (paralysis/paresis, hyperactive reflexes, loss of fine movement)</td>
</tr>
<tr>
<td></td>
<td>• Corticospinal (pyramidal) tract includes lateral and anterior pathways</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Brainstem (parapyramidal) tracts include the rubrospinal, tectospinal, reticulospinal and vestibulospinal pathways</td>
<td></td>
</tr>
</tbody>
</table>

Box 2.2 Skeletal Muscle Characteristics [12,13]

• **Excitability:** the ability to receive and respond to a stimulus from the nervous system.

• **Contractility:** the ability to shorten (contract) when stimulated by a motor neuron. There are several types of contraction:
  - **Isometric contraction:** (same distance, not moving), the muscle maintains an equal length when contracting against an immovable object, for example, pulling against an object that is too heavy to lift or gripping a tennis racquet. The amount of force depends on the length of the muscle.
  - **Isotonic contraction:** (same tension), the muscle length changes and movement of a body part occurs but the tension in the muscle remains constant, for example, bending the elbow from a straight position or lifting an object at a constant speed. There are two types of isotonic contraction: (a) *concentric*, where the muscle shortens and overcomes the resistance, and (b) *eccentric*, where the muscle contracts but instead of shortening, it lengthens because the resistance is greater than the tension produced in the muscle, for example, smoothly lowering a heavy object.
  - **Isokinetic contraction:** (*kinetic* means motion), similar to isotonic because the muscle changes length during the contraction, but isokinetic contractions produce movement of a constant speed, for example, breast stroke where the water provides a constant resistance to arm movements while swimming.

• **Elasticity:** the ability of a muscle to return to its normal length after a contraction or stretch (see Box 2.3). Elasticity should not be confused with extensibility; the difference between them is that elasticity refers to the inherent capacity of a tissue to resume its original length once a force is removed, whereas extensibility has no implication of reversibility.

• **Extensibility:** the ability to be stretched or extended when a force is applied; influenced by the characteristics of both muscles and connective tissues (intramuscular, tendons, ligaments, joint capsules).

• **Excursion:** the movement of a muscle through its full length, that is, its full range of extensibility and contractility.

neuron that conducts nerve impulses and synapses with the muscle fibre at the neuromuscular junction), and the muscle fibres that it innervates. The muscle fibres within each motor unit are of the same metabolic type, and the number of fibres associated with each motor unit depends on where the muscle is located and the nature of its action. For example, in the hand where finer movements are required, a motor unit will be associated with fewer fibres (it is a small motor unit) and will generate less force, while in a large, more powerful muscle it may be associated with thousands of fibres (a large motor unit) and will generate greater force on contraction [8].

There are different ways of classifying motor units. A common approach is to classify them according to the speed of contraction (or twitch) and the fatigability
Table 2.2 Characteristics of motor units and muscle fibres [9,14–16].

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Motor unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type 1 Slow-contracting, slow-fatigable (S)</td>
</tr>
<tr>
<td>Muscle fibre, axon,</td>
<td>Large muscle fibres, fast conducting axons,</td>
</tr>
<tr>
<td>motor neuron</td>
<td>large motor neurons</td>
</tr>
<tr>
<td>Contraction speed</td>
<td>Slow</td>
</tr>
<tr>
<td>Fatigue resistance</td>
<td>High</td>
</tr>
<tr>
<td>Power or force</td>
<td>Low</td>
</tr>
<tr>
<td>Recruitment</td>
<td>First</td>
</tr>
<tr>
<td>Activity type</td>
<td>Sustained effort (standing, long-distance running)</td>
</tr>
<tr>
<td></td>
<td>Type 2A Fast-contracting, fatigue-resistant (FR)</td>
</tr>
<tr>
<td></td>
<td>Moderately fast</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Moderate-high</td>
</tr>
<tr>
<td></td>
<td>Second</td>
</tr>
<tr>
<td></td>
<td>Sustained effort, high power output</td>
</tr>
<tr>
<td></td>
<td>(middle-distance running, swimming)</td>
</tr>
<tr>
<td></td>
<td>Type 2B/2X Fast-contracting, fast-fatigable (FF)</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Last</td>
</tr>
<tr>
<td></td>
<td>Brief, intense effort</td>
</tr>
</tbody>
</table>

(or endurance) of their muscle fibres (Table 2.2). Classified in this way, there are three motor unit types: type 1 or slow-contracting, slow-fatigable (S), type 2A or fast-contracting, fatigue-resistant (FR), and type 2B/2X or fast-contracting, fast-fatigable (FF) [14,15,17].

The production of muscle force depends on a variety of neuromuscular factors (see Table 2.3), including the number and type of motor units recruited in a contraction and their firing rates. Muscle strength or force increases when the number and/or the firing rates of already-activated motor units increases. Changes in firing rates allow adjustment of force production, with different motor units having an optimal range of firing over which tension increases. An orderly recruitment pattern also occurs according to the amount of force required for task completion. Low force-producing motor units are recruited first (type 1), with higher force-producing motor units recruited as necessary (type 2A then type 2B/2X). Thus, the succession of recruitment of motor units provides a smooth increase in tension development [18,19]. In general, the muscles of the upper limbs contain more type 2B than other types of fibres, at least in their superficial areas, with an increase in type 1 fibres in their deeper areas. This means that the muscles are able to respond with fast contraction, which is then sustained by recruitment of less fatigable fibres [20].

Sarcomeres are the contractile part of muscle, found within the muscle fibres and grouped together into fascicles. Each sarcomere is made up of two types of overlapping muscle proteins or filaments: myosin (thick filaments) and actin (thin filaments). During contraction, the actin filaments slide toward one another past the myosin filaments, breaking and reforming cross-bridges in a process called cross-bridge attachment (see Figure 2.1). The amount of tension that can be generated by a muscle during contraction depends on the number of cross-bridges that form, or alternately, the amount of overlap between the actin and myosin filaments. The best position for the muscle to develop maximal contraction and force generation (that is, the optimal range of overlap for the filaments), is when the muscle is at its resting length. If the muscle is held in a shortened position, then the thin actin filaments are already close together, and are unable to overlap the thick myosin filaments any further because the overlapping zone is already as large as possible. If the muscle is held in a lengthened position the thick and thin filaments may be too far apart to and the zone of overlap will be small. In both these situations the potential of the muscle to contract and generate force is reduced. Skeletal muscle cells can contract until they shorten by about 30% [21].

Titin (or connectin) is another protein molecule found in the sarcomere. It is a long, coiled molecule that is wrapped around the myosin filaments and attached to the Z-line that forms the borders of each sarcomere. Titin behaves like a spring, returning the sarcomere to its original length following stretch [22,23]. It has been suggested that different muscle groups may contain different forms of titin which influence the tension and elastic limits within sarcomeres, meaning that some muscles may have more capacity for stretch or extensibility than others [24].
### Table 2.3 Neuromuscular factors influencing muscle force production [25–28].

<table>
<thead>
<tr>
<th>Factor</th>
<th>Influences on force production</th>
</tr>
</thead>
</table>
| **Motor unit**                | • Motor unit number, type and firing rate influence force production  
• Recruitment of more motor units results in more force  
• Type 1 recruitment (slow twitch muscle fibre with slower contraction speed) leads to lower force production  
• Type 2A recruitment (moderately fast muscle fibre with intermediate contraction speed) affords moderately high force production  
• Type 2B (fast twitch muscle fibre with moderate contraction speed) causes high force production  
• Increased firing rate (stimulation) supports increased force  |
| **Sarcomere (contractile factor)** | • The amount of myosin and actin overlap influences force production  
• Maximum contraction and force production occur at resting length  
• Least force production when there is little overlap between myosin and actin (lengthened muscle) or when there is too much overlap (shortened muscle)  |
| **Fascicle length**           | • The main element that determines muscle excursion (how much the muscle is able to change its length, from shorter to longer length)  
• Depends on the number of sarcomeres in series  
• Shorter muscle fascicles are more limited in the range through which they can develop force and power, the speed at which they can shorten, and the length at which they develop passive tension  |
| **Muscle belly length**        | • Reduced muscle belly length is suggestive of contracture (shortened fascicles and sarcomeres) and, therefore, reduced capacity for force production because fascicles are most likely also shorter  
• A lengthened muscle belly also has reduced capacity for force production because the sarcomeres within the fascicles are over-lengthened and unable to contract sufficiently  |
| **Anatomical cross-sectional area (ACSA)** | • Measured perpendicular to the longitudinal axis of the whole muscle at its widest point  
• The physiological cross-sectional area is a better measure of force production  |
| **Physiological cross-sectional area (PCSA)** | • Measured perpendicular to the muscle fibres, it is a ratio of muscle belly volume to fascicle length  
• Provides an estimate of the number of sarcomeres working in parallel  
• Greater PCSA results in greater force production  |
| **Muscle thickness**          | • Used as a measure of activity in the muscle since thickness changes when in either a relaxed or contracted state (becomes thicker when contracted and thinner when relaxed)  
• Increases with resistance training, therefore is also used as a measure of strength  
• Highly correlated with PCSA  |
| **Fascicle angle**            | • The angle at which fascicles attach to the tendon or aponeurosis (fascia that attaches muscle to the bone)  |
| **Pennate angle**             | • Oblique angle at which fascicles in a pennate muscle attach to the tendon or aponeurosis  
• Determines the load axis of the muscle (its line of action or pull)  
• Angle increases as the muscle contracts and shortens, and as muscle thickness increases  
• Pennate muscles allow higher force production (as there are more sarcomeres in parallel) but smaller ranges of motion  |
| **Tendon length and compliance** | • Influences the length and velocity of muscle fascicles and, therefore, force generation  |

---

*aSee Figure 2.1.*  
*Fascicles are groups of muscle fibres.*  
*Muscle belly is the length of the whole muscle (i.e. many fascicles).*
What Happens to the Upper Limb After Brain Injury?

2.1.2.2 Connective tissue: strength and flexibility

Ligaments, tendons, joint capsules, tendon sheaths, cartilage and other related structures are collectively described as connective or fascial tissues. The structural fibres of connective tissues (collagen, elastin and fibrin) are held together by chemical bonds and are surrounded by a filler gel that lubricates the fibres. Collagen is a fibrous protein that gives connective tissues their strength and flexibility. Connective tissues differ in terms of the type (more than 20 types of collagen have been identified), amount, density and alignment of their collagen fibres [29]. For example, the collagen fibres of dense connective tissues (bone, tendons and ligaments) are tightly packed and mostly aligned in one direction. In contrast, loose connective tissues (in muscle, joint capsules and fascia) have irregular or crisscrossed collagen fibre alignment and are more flexible [30,31].

Tendons attach muscle to bone and transmit mechanical forces through the muscle–tendon unit, allowing for joint movement [32]. They are integrated into the neuromuscular system through sensory receptors (Golgi tendon organs) that are embedded in the muscle–tendon junction, sending information about changes in muscle tension to the CNS [8,33]. Ligaments connect bones or cartilage to one another and, together with joint capsules, provide stability to joints [30,34].

Articular or hyaline cartilage is another form of connective tissue. It is flexible and functions to distribute loads within the joint and to minimise friction between articulating joint surfaces. Cartilage differs from other connective tissues in that it does
Box 2.3 Rheological Properties of Muscles and Connective Tissues [12,22,37,38,39]

- **Rheology**: the study of materials with both solid and fluid states and, in particular, how those materials flow or change due to their elastic, viscous or plastic characteristics. For example, the study of how blood flows through the heart and blood vessels, or how soft tissues respond to stretch.
- **Elasticity**: the property of a tissue to return to its original resting shape when a deforming force is removed. Elastic tissue behaves similarly to a rubber band or spring, being slack at rest with tension developing on stretch. Fast, high-force, short-duration stretch leads to greater elastic stiffness and tissue viscosity, reducing the capacity of the tissue to respond with flexibility.
- **Viscosity**: the property of internal resistance to deformation. Reduced tissue viscosity (for example, through ‘warm-up’ exercises, the application of an external heat pack or use of ultrasound) leads to reduced resistance to movement and increased flexibility, reducing potential for tissue injury. Slow, constant stretch reduces viscosity and promotes tissue flexibility.
- **Plasticity**: the property of a tissue to permanently deform after a load is applied that stretches it beyond its elastic limit. Plasticity implies minor tissue damage which reduces the ability of the muscle to return to its original length; therefore, to promote plasticity, low-force, long-duration, slow stretch should be provided at the pain threshold point for that person, that is, the threshold at which the person experiences pain due to stretch.
- **Viscoelasticity**: having both viscous and elastic characteristics in response to a load. Viscoelastic properties include stress relaxation (loss of tension when held at a fixed length for a period of time) and creep (slow increase in length over time in response to sustained tension).
- **Thixotropy**: the property exhibited by certain gels, of becoming more fluid when internally agitated (kinetic), and returning to a more viscous state after standing (static). In skeletal muscles this means that the resting tension and stiffness displayed by the fibres are largely determined by the immediately preceding movements and contractions (that is, passive stiffness and resting tension in muscles are history-dependent).

not contain blood vessels. This means that it grows more slowly and is also slower to repair itself if damaged [35].

Bone is a specialised connective tissue that contains tightly packed, parallel collagen fibres and inorganic minerals (mainly calcium phosphate) which provide rigidity. Bone has many blood vessels and is therefore able to repair itself relatively quickly. It is also highly adaptable to the mechanical demands that are placed on it. For example, changes in density are common in response to either disuse or increased use [34,36].

2.1.2.3 Muscle and connective tissue: elastic, plastic, viscous and viscoelastic properties

Soft tissues show different responses to various deforming forces, whether compressive, tensile (stretch) or shear (sliding). The different responses to such forces include elasticity, plasticity, viscosity and viscoelasticity (see Box 2.3) [12,30].

Muscles and tendons are both characterised by elasticity, although this is due to different mechanisms. The elastic property of tendons is mainly due to the ‘crimped’ (zigzag, or wavy) structure of their collagen fibrils, which straighten as tension is applied [22,32]. The elasticity of muscles is thought to be due to several possible mechanisms. These include (i) the small amount of the protein elastin in the intramuscular connective tissue that surrounds muscle fibres, (ii) weakly formed actin and myosin cross-bridges in the contractile sarcomere and (iii) the coiled protein, titin, also found in the sarcomere (see Section 2.1.2.1). Titin is described as the structure most likely to be responsible for muscle’s elastic response [22,23].

In addition to their elastic properties, connective tissues display viscoelasticity when their load (or stretch) is maintained. This is related to the combination of their elastic properties and their fluid or gel components (these components are viscous, having a glutinous consistency). When connective tissues are subjected to a slow stretch and are then held at their new length with the joint at a stable angle, resistance in the tissues gradually reduces to a steady level (this reduction is called stress relaxation), and less force is needed to hold the joint angle stable. If the tissues are subjected to a slow but constant force (torque) during stretch, the tissues will continue to elongate (this elongation is called creep) and the joint angle increases [12,22]. When resting muscle is subjected to small, low-load passive stretch it shows a very high resistance to that stretch, called short range stiffness.
The bonds between myosin and actin filaments are proposed to be responsible for this stiffness [37]. However, if the muscle is held in a constant, stable position, the resistance reduces and stress relaxation will occur as described above for connective tissues. If, after stretch and viscous deformation (creep), the muscle is shortened and returned to its original position at which the stretch was begun, resistance will be found to have returned as well. This return of resistance is called stress recovery [12,22].

2.1.2.4 Muscle tone
Muscle tone is described as the constant state of mild tension observed in muscles at rest. Clinically, normal muscle tone is identified as the slight resistance or stiffness that is felt in the muscles when the limb is moved passively at a slow, consistent rate of movement (between 2° and 12° per second) [40]. Normal muscle tone enables effective stabilisation of joints by balancing the tension in opposing muscle groups around a joint. Normal postural muscle tone assists in maintaining body posture with minimal energy costs [8,38].

Historically, normal resting muscle tone has been described as the result of a constant, small amount of muscle contraction (due to the stretch reflex). However, no electromyographic (EMG) activity is typically found in normal muscles at rest or during slow passive stretch (the muscles are EMG-silent). Normal muscle tone, therefore, appears to be due to the intrinsic, passive rheologic (resistive) properties of the soft tissues, as described in Section 2.1.2.3 and Box 2.3. That is, the resistance or stiffness felt when ranging a relaxed limb that is not affected by brain injury is due to characteristics such as the elasticity and viscoelasticity of the surrounding connective tissues and muscle fibres, and the actin and myosin cross-bridges formed in the resting muscle [40]. Simons and Mense [41] have therefore defined normal resting muscle tone as “elastic and/or viscoelastic stiffness in the absence of contractile activity (motor unit activity)” (p. 3).

2.2 Upper limb movement
The upper limb is involved in a variety of functions during daily activities. Depending on the context and the task, the arm and hand are involved in reach, grasp and manipulation, transporting, lifting, assisting in balance and, on occasion, providing support for the body [42]. Vision, postural stability (at the trunk and pelvis) and shoulder stability and movement (at the scapula and clavicle), are all important components that support placement of the arm and hand for reach and grasp [43]. The trajectory, speed and orientation of the arm and hand during movement are all influenced by the nature of the reaching task, the type, size and orientation of the object being grasped, the position of the person (for example, sitting or standing), and the context in which the task is occurring. Although effective upper limb movement requires many joints and muscles to work together, the CNS ‘simplifies’ control of such movement through the use of ‘synergies’, that is, by coupling or linking movement segments together so that less effort is expended on controlling each aspect of commonly used movements [44,45].

2.2.1 Reaching to grasp
Reaching to grasp is divided into three phases, namely, transport, grasp and manipulation [46]. The transportation phase involves positioning and moving the limb towards an object and is quicker than the grasping phase, when the final finger and thumb adjustments are made for picking up the object. Nevertheless, preparing for grasp begins at the start of the transport phase, with hand opening (or aperture) at its widest as the transport phase slows at the end of the reaching movement. As the hand nears the object to be grasped, stability is provided by wrist extension and the index finger initiates hand closing. During reaching, the thumb is positioned in a stable abducted and extended position, possibly allowing visual monitoring of the size of the grasp aperture. If sensation is impaired, the hand aperture is wider than usual and a more conservative grasp (for example, a whole-hand grasp rather than a finger-tip grasp) seems to be chosen [46,47].

Reach and grasp may be achieved using either one limb or both together. When undertaking a bimanual (two-handed) task, both limbs may be doing the same action (for example, holding the steering wheel when driving) or different actions (such as, when driving, using one hand to hold the steering wheel while the other manipulates the gear stick). Two-handed tasks are therefore associated with complex spatiotemporal coordination and organisation [42].

2.2.2 Grasp and manipulation
The next phase of reaching to grasp involves handling and controlling the grasped object. Coordinated grasp and manipulation (or prehension) require the shoulder, elbow, forearm, wrist, fingers and thumb to move into, and maintain, a variety of positions, depending on the task demands [46]. Thus, grasping requires a blend of mobility and stability across the forearm, wrist, and in the three structural arches of the hand [46] (Figure 2.2). The distal transverse arch is oblique, rigid at the index and middle finger
metacarpophalangeal (MCP) joints, and mobile at the thumb, ring and little finger MCP joints. The third metacarpal head (middle finger) is slightly higher on the dorsal surface of the hand than those of the second (index) and fourth (ring) fingers; the metacarpal head of the little finger drops away from that of the ring finger. In addition, the metacarpals become slightly shorter from the index finger towards the little finger, creating an oblique angle from the radial to the ulnar border of the hand. Positioning that does not maintain the distal transverse arch impairs cupping of the palm for grasp and also the ability of the thumb to oppose the fingers (see Figures 7.2, 7.9 and 7.14).

The longitudinal arch of the hand is mobile and follows the long lines of the metacarpal and phalangeal bones. It allows flexion of the MCP, proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints. The thumb, ring and little finger

Table 2.4 Common hand grasps [49–52].

<table>
<thead>
<tr>
<th>Grasp</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical</td>
<td>Whole palmar surface grasps around a cylindrical object, with the thumb flexed and opposed on the opposite side of the object from the fingers (holding a jar or drink bottle)</td>
</tr>
<tr>
<td>Hook</td>
<td>Fingers extended at MCP joints, flexed at IP(^1) joints. The only functional grasp that doesn’t involve the thumb (lifting a suitcase)</td>
</tr>
<tr>
<td>Lateral</td>
<td>Thumb pad is pressed against the lateral side of the flexed index finger, near the distal IP joint (holding a playing card or a key)</td>
</tr>
<tr>
<td>Locking</td>
<td>Ulnar side of the hand, particularly the little and ring fingers, provide stability for the object being grasped (holding a knife and fork when eating)</td>
</tr>
<tr>
<td>Oppositional</td>
<td>Pads of the index finger and thumb are used to grasp, with finger MCP and PIP joint flexion, thumb joints and finger DIP joint flexed (holding a coin)</td>
</tr>
<tr>
<td>Palmar</td>
<td>Fingers hold an object into the palm, all joints flexed, thumb assists (similar to spherical power grasp)</td>
</tr>
<tr>
<td>Pinch</td>
<td>Flexion at all index finger joints, thumb MCP joint extension with IP joint flexion so that the tips of the pads are opposing one another (removing a piece of fluff from clothing)</td>
</tr>
<tr>
<td>Power</td>
<td>Fully flexed fingers with thumb flexed and opposed over fingers. Force is applied through fingers into the palm (holding a hammer or a bat)</td>
</tr>
<tr>
<td>Raking</td>
<td>Fingers ‘rake’ the object into the palm and hold it there without thumb involvement (a baby picking up a rattle or sultanas)</td>
</tr>
<tr>
<td>Spherical</td>
<td>Finger and thumb tips are opposed to hold a small round object, or a larger round object is held against the palm (holding a strawberry or an apple)</td>
</tr>
<tr>
<td>Supporting</td>
<td>Finger MCP flexion and IP joint extension, with either extension of all thumb joints or thumb IP flexed over the object to stabilise it (carrying a plate)</td>
</tr>
</tbody>
</table>

\(^{1}\)Interphalangeal