4

Observation and Analysis of Movement

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OUTLINE

All voluntary movement including walking, sit to stand (STS), reach and grasp, rolling and the underlying postural control that accompanies these actions involves the complex integration of cognitive, neuronal and biomechanical factors. Movement analysis is the systematic study of the movement produced during human action using skilled observational assessment, augmented by instruments that measure key aspects of performance.

This chapter will describe the analysis of movement of particular functions and illustrate deviations that are observed with specific neurological conditions.

WALKING

Walking refers to a means of locomotion involving the use of two legs where at least one foot is always in contact with the ground, and each leg alternately provides support and propulsion (Whittle et al 2012a). Successful walking satisfies three essential requirements (Patla 1991, 1997) (Table 4.1). Walking is an inherently unstable activity that demands a high degree of neural control (Patla 1991, Winter et al 1991). Whilst acting within the biomechanical constraints afforded by the human body, the central nervous system is required to generate a locomotor pattern, modulate propulsive forces, overcome the effects of gravity and integrate visual, proprioceptive and vestibular afferent information in a matter of milliseconds, on an ongoing basis, usually whilst the individual is involved in doing something else (Leonard 1998). Despite its complexity, it is possible to understand the essential components of walking and to apply this understanding to clinical

TABLE 4.1 The Essential Components of Walking (Patla 1991, 1997)

Component	Explanation
Propulsion	The generation, maintenance and termination of a basic locomotor cycle using patterned activation and coordination of the legs and trunk to propel the body in the intended direction
Postural control	Maintenance of dynamic stability of the moving body through the appropriate postural orientation of body segments relative to each other and environmental conditions, to overcome gravity and to respond to expected and unexpected perturbations
Adaptation	Modulation of the locomotor pattern to achieve goals in real-world environments, e.g., through changing speed and direction to meet the demands of variable terrain or to avoid obstacles; the focus on adaptability underscores the importance of understanding human walking as a skilled behaviour rather than as simply the generation of basic locomotor patterns

practice. This section offers an overview of the key constituents of walking, with a clinical focus on the impact of Parkinson's on walking.

The Gait Cycle

An analysis of walking involves the observation and measurement of relevant components of the gait cycle (Fig. 4.1). One complete gait cycle occurs from the point when one foot makes contact with the ground to the next occasion when the same foot touches the ground again. Simple gait analysis involves the observation of a person walking continuously over a period during which multiple gait cycles are observed.

The gait cycle is divided into stance phase when one foot is in contact with the ground (~60% of the cycle), swing phase when the foot is not in contact with the ground (~20% of the cycle) and two short periods during each full cycle when both feet are in contact with the ground (double support).

In stance phase, the lower limb extensors and biomechanical alignments bear the weight and prevent the limb from collapsing. During this phase and through double support, the trunk not only crosses the midline but also the body mass is propelled forwards over the lead leg beyond anterior stability limits. Postural adjustments are required as the body moves over the small and changing base of support, and the subsequent forwards step in front of the centre of mass (CoM) prevents falling forwards (Winter et al 1990).

In swing phase, the de-weighted trailing leg moves forwards and the foot swings through, clear of the ground. At the same time, the limb trajectory is prepared to enable accurate and safe foot placement at initial contact. Gaze control is critical for tasks that require accurate foot placement, as well as for activities that include turning (Earhart 2013). Up to 50% of everyday tasks are composed of turning steps (Glaister et al 2007).

The terms used for assessment purposes to describe the phases of the gait cycle and foot placements are shown in Fig. 4.1 and are defined in Table 4.2.

Walking Kinematics and Muscle Activity

Kinematic analysis measures average joint movement profiles (e.g., using video cameras) independent from forces acting internally and externally on the body. These studies suggest that most people use similar movement strategies to accomplish the task of walking. Knowledge of average joint angles at given stages of the gait cycle provides useful information for observational assessment. During walking, movement occurs in the sagittal, transverse and frontal planes, but the largest angular changes occur in the sagittal plane (Whittle et al 2012a). Fig. 4.2A shows the successive positions of the right leg at 40-ms intervals measured over one complete gait cycle, and Fig. 4.2B shows the corresponding sagittal plane angles at the hip, knee and ankle.

Fig. 4.3 shows notable short bursts of contraction of the ankle plantar flexors at push-off, hip extensor concentric contraction at heel strike and the hip flexor contraction at preswing (Whittle et al 2012a). In addition to active motor control, evidence also exists to suggest that propulsion is effectively catalysed by a release of stored energy from the combination of contractile and noncontractile structures, coupled with contractions within the triceps surae at push-off, to sharply plantarflex the ankle and almost 'catapult' the shank forward (Ishikawa et al 2005, Lichtwark & Wilson 2006). Within the complex foot and ankle structure, there is potential for the triceps surae to contract isometrically from preswing to toe off to control the release of stored energy in structures such as the Achilles tendon and plantar fascia (Lichtwark & Wilson 2006). Indeed plantar fascia tautness

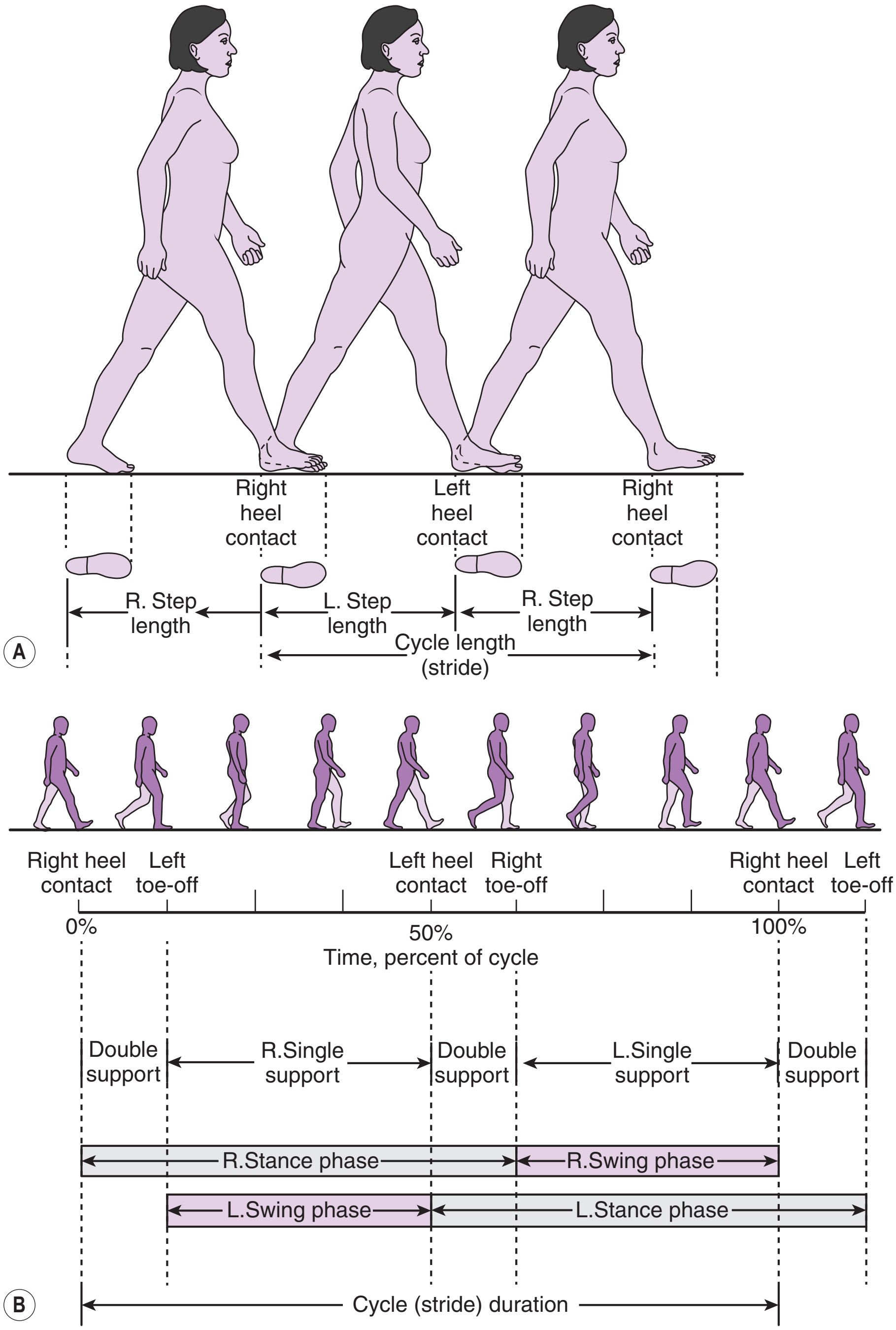

FIG. 4.1 Dimensions of the walking cycle. (A) Spatial dimensions of the gait cycle. (B) Time dimensions of the gait cycle. (From Inman, V.T., Ralston, H.J., Todd, F., 1981. Human Walking. Baltimore, Williams & Wilkins, p. 26, with permission.)

TABLE 4.2 Key Phases of the Gait Cycle and Related Terminology[a]

Stance Phase	
Initial contact	The point in the gait cycle when the lead foot makes contact with the ground; this marks the beginning of stance phase
Loading response	The initial double support stance period which occurs from initial contact through to the first 10% of the gait cycle (this subsection is also known as 'weight acceptance')
Mid-stance	The first half of single support; when the trailing limb leaves the floor until body weight is aligned over the forefoot of the supporting lead limb
Terminal stance	About 40% of the stance phase when the lead limb is in single support
Preswing (push-off)	The last 10% of stance, in double support, from the time of initial contact of the opposite limb to toe-off of the observed limb
Swing Phase	
Initial swing	The first third of the swing phase, defined as toe-off to the point when the swing limb is opposite the stance limb
Mid-swing	Middle phase of the swing phase, from the time the swing foot is opposite the stance limb to when the tibia is vertical
Terminal swing	The final third of the swing phase, the point when the tibia is vertical to initial contact
Other Commonly Used Terms	
Double support	The period when both feet are in contact with the floor. This short phase occurs at the beginning of stance phase and again at the end of stance phase (when observing one limb). It is a critical point for transferring weight from one limb to the other. The two episodes of double support in one complete gait cycle respectively represent ~10% of the full cycle
Single support	The period when only one foot is in contact with the ground (equal to the swing phase of the other leg)
Terminal contact	The point in the gait cycle when the foot leaves the ground (the end of stance phase or the beginning of swing phase)
Toe-off	When terminal contact is made with the toe as the foot leaves the ground at the end of stance phase
Foot flat	The point in time in stance phase when the foot is in plantar grade
Heel-off (heel rise)	The point in time in stance phase when the heel leaves the ground
Heel strike	In typical gait 'heel strike' may be used instead of 'initial contact'; in pathological gait heel strike is often absent and therefore initial contact is a more accurate term, but absence of heel strike should be noted
Push-off	The period in late stance where an ankle plantar flexor moment and power generated by the plantar flexors help to advance the limb into swing phase
Step length	The distance between the first contact point of one foot and the first contact point of the next foot
Stride length	The distance between successive points of contact of one foot and the next point of contact with the same foot
Stride width	Measured from the midpoint of each heel; this is the side-to-side distance between the two feet
Cadence	The number of steps taken in a given time (steps/min)
Velocity	The distance covered in a given time (m/s)
Lead leg	The leg that is in front, e.g., the leg that goes first in walking over obstacles
Trail leg	The leg that follows, e.g., the leg that goes last over obstacles

[a]For further details refer to Whittle et al (2012a).

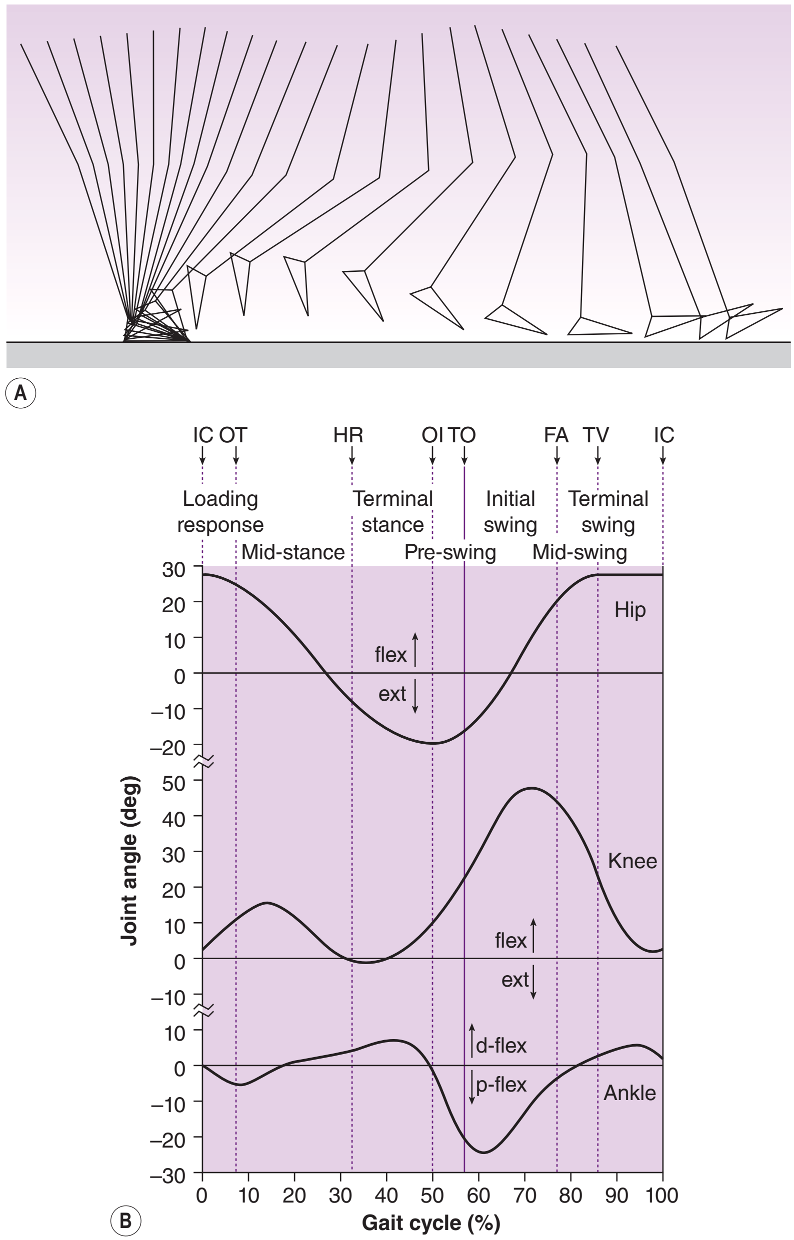

FIG. 4.2 (A) Position of the right leg in the sagittal plane at 40-ms intervals during a single gait cycle. (B) Sagittal plane joint angles (degrees) during a single gait cycle of right hip (flexion positive), knee (flexion positive), and ankle (dorsiflexion positive). IC, initial contact; OT, opposite toe off; HR, heel rise; OI, opposite initial contact; TO, toe off; FA, feet adjacent; TV, tibia vertical. Flex, flexion; ext, extension; d-flex, dorsiflexion; p-flex, plantarflexion. (From Figs. 2.4 and 2.5, p. 35 Levine, D., Richards, J., Whittle, M.W. (eds). Whittle's gait analysis: an introduction, 5th ed. Churchill Livingstone, Elsevier, Edinburgh, with permission.)

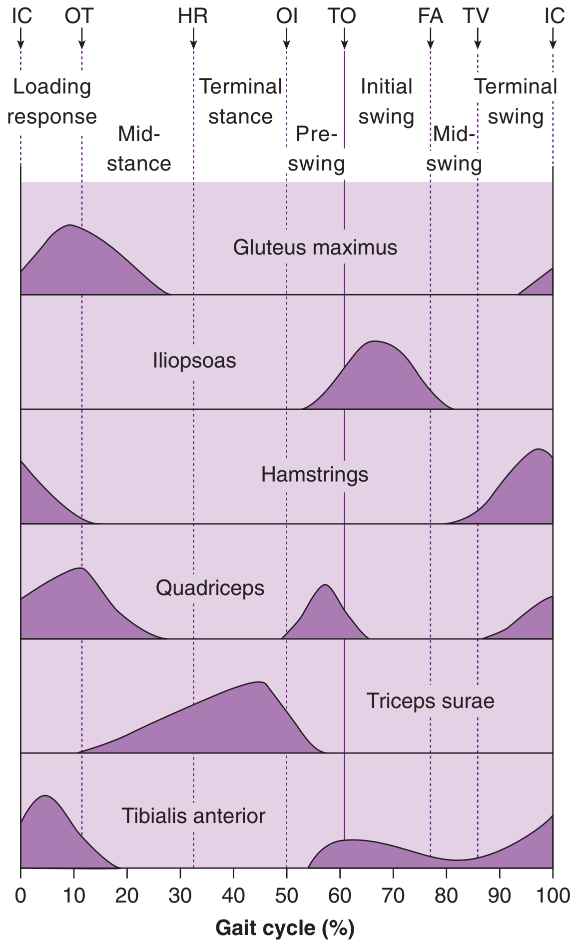

FIG. 4.3 Typical activity of major muscle groups during the gait cycle. IC, initial contact; OT, opposite toe off; HR, heel rise; OI, opposite initial contact; TO, toe off; FA, feet adjacent; TV, tibia vertical. (From Fig 2.10, Typical activity of major muscle groups during the gait cycle, p. 39, Levine, D., Richards, J., Whittle, M.W. (eds). Whittle's gait analysis: an introduction, 5th ed. Churchill Livingstone, Elsevier, Edinburgh, with permission.)

may in turn be finely controlled by metacarpal flexors (involving a 'windlass system') and peronei to convert the foot from a structure able to accommodate a changing underfoot support surface to one that assists with propulsion of the shank over the foot (Gu & Li 2012, Shah et al 2020). Whilst a typical walking pattern appears relatively stable in kinematic studies, the underlying muscle activity may vary between individuals and within one individual with respect to, for example, speed and fatigue (Whittle et al 2012a). Muscles contract and relax in carefully coordinated, repeatable, on-off bursts of patterned activation (Shiavi 1985), but a reasonable degree of flexibility exists to engage different muscles if necessary (Lacquaniti et al 2012). This means that there is considerable redundancy in the system that allows other muscles or muscle groups to take over the function of a muscle that is no longer working (Whittle et al 2012a). The following section summarises the key kinematic and typical muscle activity of walking in healthy adults. For more detailed information, see Levine et al (2012).

At *initial contact*, at the beginning of stance phase, the trunk is about half a stride length behind the leading leg and crosses the midline moving towards the leading leg as the foot on that side contacts the ground (Whittle et al 2012a). With reference to Whittle et al (2012a), the hip is flexed but is moving into extension through the concentric action of the hip extensors, gluteus maximus and the hamstrings. The knee moves through from close to full extension at initial contact to slight knee flexion during the loading response ('stance phase flexion'). Eccentric contraction of the quadriceps limits the speed and magnitude of the knee flexion. The ankle starts close to its neutral position (0°) and moves into plantarflexion through the eccentric action of tibialis anterior to bring the forefoot in contact with the ground.

At mid-stance, the hip continues to extend approaching 0° through gravity and inertia. Lateral pelvic horizontal movement (4–5 cm) towards the stance leg is controlled by contraction of the hip abductors, especially gluteus medius and tensor fascia lata. The knee reaches its peak of stance phase flexion and starts to extend through concentric action of the quadriceps. With the foot flat on the floor, the ankle moves from plantarflexion into dorsiflexion as the tibia moves forwards over the stationary foot through the isometric action of the plantar flexors (Whittle et al 2012a).

At terminal stance, the hip continues to extend, reaching maximum extension (10–20°) just as the opposite leg achieves initial contact. The abductors continue to work to stabilise the pelvis, but this activity is no longer maintained once the opposite foot makes initial contact. The knee begins to flex. Movement into plantarflexion occurs late in terminal stance. At preswing, hip flexion is initiated in preparation to swing the leg forwards, the knee moves rapidly into flexion in preparation for toe clearance with eccentric contraction of rectus femoris to prevent knee flexion occurring too fast. The ankle continues to move into plantarflexion through the concentric action of the plantar flexors. The toes extend at the metatarsophalangeal joints (Whittle et al 2012a).

Swing phase is precisely calibrated to produce an average toe clearance of ~1 cm (Murray 1967). According to

Whittle et al (2012a), rectus femoris, adductor longus, tension in the hip ligaments and gravity enable the hip to continue to flex as the foot leaves the ground. The knee continues to flex (effectively shortening the leg), reaching peak flexion just more than halfway through the initial swing; as the hip flexes, the lower leg is left behind because of inertia, resulting in knee flexion. The ankle reaches peak plantarflexion just after toe-off, tibialis anterior contracts during mid-swing to dorsiflex the foot during the rest of swing. The hamstrings contract at the end of swing phase, effectively applying a break to prevent knee hyperextension. This contraction continues into the start of the stance phase.

During walking, the upper body moves forwards, the shoulder girdle and pelvic girdle rotate in opposite directions, and the arms swing out of phase with the legs (left arm and shoulder forwards, right leg and pelvis forwards) in a coordinated manner. Further research is required to consider the role of the upper limb in the coordination of gait, given the understanding that alteration in arm movements during walking affect gait efficiency, coordination and dynamic postural control (Earhart 2013, Meyns et al 2013).

Walking Kinetics

Kinetics is the study of forces, moments, masses and accelerations using equipment such as force platforms (Whittle et al 2012b). During walking, the dominant forces acting at a joint do not necessarily reflect the movement of the joint as revealed by kinematic studies. In stance phase, the combined moments acting at the hip, knee and ankle are far less variable than their individual components and provide a net extensor moment that prevents the knee from collapsing under the weight of the body (Winter 1980). The forces used to generate this net extensor moment are variable from stride to stride and person to person (Whittle et al 2012a).

Propulsion of the body results in the generation of forces on the ground, called ground reaction forces (GRFs). GRFs reflect the horizontal and vertical acceleration and deceleration of the CoM during weight bearing (Winter 1987). In quiet standing (Fig. 4.4A), the GRF is equal and opposite to the weight of an individual and acts only in a vertical direction. However, during walking, there are both vertical and horizontal GRFs. In late stance (Fig. 4.4B), an unopposed horizontal force (F_x) propels the body forwards, whilst a vertical GRF, which is greater than the weight of the person, causes an acceleration of the body upwards (Whittle et al 2012b).

Spatiotemporal Characteristics

Walking speed is one of the most important variables for determining functional competence in the community, and it may be used to predict functional outcomes (Fritz & Lusardi 2009). For example, following stroke, gait speed is an important predictor of outcome and discharge destination, independent of age and functional status on admission (Rabadi & Blau 2005).

Normative spatiotemporal data synthesised from the recorded gait speed of more than 23,000 individuals over distances of 3–30 metres provide age and gender standards against which individuals can be compared (Bohannon & Williams Andrews 2011) (Table 4.3).

Clinical Focus: Walking for People With Parkinson's

Gait impairment is associated with increased activity limitations (Tan et al 2011) and may make a significant contribution to reduced quality of life among people living with Parkinson's (Soh et al 2011, Walton et al 2015). Gait impairment is a significant feature of Parkinson's, present in early stages of the disease (Rehman et al 2019, Zanardi et al 2021). Recent research involving 'machine learning' approaches has quantified gait characteristics to reveal strong associations between key parameters, such as self-selected walking speed, stride length, cadence, double support and swing time, and traditional disease severity scale measures such as the Hoehn and Yahr scale, the score of the Unified Parkinson's disease Rating Scale or disease duration. The use of wearable inertial sensors is proposed to provide an option for continuous monitoring to inform clinicians of disease progression (Balaji et al 2021, Rehman et al 2020). Inertial sensors as wearables may soon also contribute to the diagnosis of Parkinson's (di Biase et al 2020). People with Parkinson's adopt slower walking speeds, lower cadence, shorter strides and more mediolateral head and pelvis motion, which appears linked to a high risk of falling but could possibly be part of a compensatory strategy to prevent a fall (Creaby & Cole 2018). Freezing of gait (FOG) can affect all stages of Parkinson's and the incidence increases as Parkinson's progresses; up to 80% of people in the later stages of Parkinson's are reportedly affected (Tan et al 2011, Zhang et al 2021). FOG increases the likelihood of falling and nursing home placement (Kerr et al 2010). Table 4.4 presents the common problems associated with walking in Parkinson's and provides evidence-based explanations for these difficulties.

SIT TO STAND

STS is a transitional movement to the upright posture brought about by moving the CoM from a stable to a less stable position over extended lower limbs (Vander Linden et al 1994). As a crucial component of daily living, healthy adults undertake this complex skill on average 60 times a

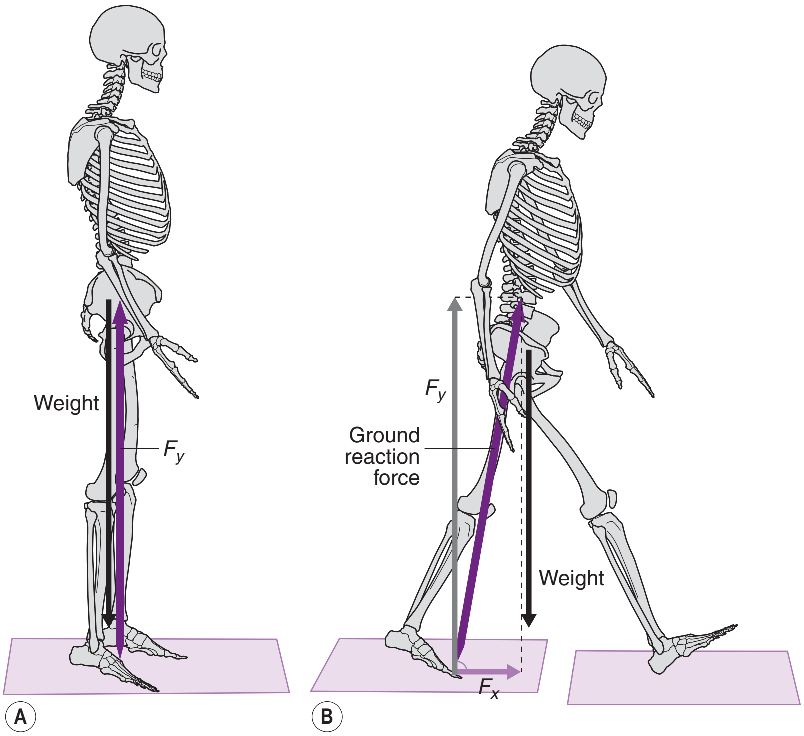

FIG. 4.4 (A) Standing still, the ground reaction force is equal and opposite to the weight of the person, acting in a vertical direction with no horizontal component. (B) Late stance phase: there is a horizontal force Fx which is unopposed and will cause acceleration or propulsion of the body forwards. The vertical force Fy is greater than the weight of the person causing an acceleration of the body forwards. (From Fig 1.19a and b, p. 22, Levine, D., Richards, J., Whittle, M.W. (eds). Whittle's gait analysis: an introduction, 5th ed. Churchill Livingstone, Elsevier, Edinburgh, with permission.)

day (Dall & Kerr 2010). Effective execution of STS is an important goal of neurological rehabilitation. Analyses of STS have focused on understanding the biomechanical, kinetic and kinematic components of this action as it is typically produced and when performed by people living with a range of health conditions. Insights from these studies offer an understanding of the invariant features of STS (the signature or fundamental pattern of the action that determines the order of events), as well as the critical movement parameters (the adjustable quantities of an action such as the timing, scale, force, direction, velocity and acceleration). Any or several of these components of STS may need to be targeted to successfully retrain individuals who have difficulty with this critical functional activity.

Typical Phases of Sit to Stand

Schenkman et al (1990) identified four distinct phases of STS which provide a useful guide for observational analysis in the clinic (Fig. 4.5). In healthy adults, the phases unfold in a smooth, continuous, curvilinear path which traces a forwards and upwards trajectory (Carr & Shepherd 2010). The key components of each phase are summarised in Table 4.5.

Using simultaneous force plate readings taken from the buttocks and feet, Hirschfeld et al (1999) identified anticipatory actions that occurred before observable STS movements, that is, before the first phase observed by Schenkman et al (1990). Based on these readings, Hirschfeld et al (1999) divided STS into two phases (Table 4.6). While Schenkman et al (1990) provided a clinically useful analysis of STS, Hirschfeld et al (1999) identified the importance of the preparatory forces required for STS, and the precise timing and coordination of muscle force needed to produce a smooth and mechanically efficient movement pattern. Both analyses have relevance for clinical practice. More detailed analyses of STS may be required for research purposes (e.g., see Etnyre & Thomas 2007).

TABLE 4.3 Normative Walking Speed (Results of a Meta-analysis)

Strata Gender (Age in Years)	Source Articles (n)	Subjects (n)	Gait Speed (cm/s)	Grand Mean (95% CI) range	Homogeneity Q (p)
Men (20–29)	10	155	135.8 (127.0–144.7)	121.7–147.4	3.255 (0.953)
Men (30–39)	5	83	143.3 (131.6–155.0)	132.0–153.8	1.169 (0.883)
Men (40–49)	4	96	143.4 (135.3–151.4)	127.0–147.0	2.609 (0.625)
Men (50–59)	6	436	143.3 (137.9–148.8)	112.2–149.1	4.721 (0.580)
Men (60–69)	12	941	133.9 (126.6–141.2)	103.3–159.0	15.217 (0.294)
Men (70–79)	18	3671	126.2 (121.0–132.2)	95.7–141.8	12.848 (0.914)
Men (80 to 99)	10	1091	96.8 (83.4 to 110.1)	60.8 to 122.1	4.159 (0.940)
Women (20–29)	11	180	134. 1 (123.9–144.3)	108.2–149.9	5.307 (0.870)
Women (30–39)	5	104	133.7 (119.3–148.2)	125.6–141.5	0.785 (0.940)
Women (40–49)	7	142	139.0 (133.9–141.1)	122.0–142.0	5.666 (0.579)
Women (50–59)	10	456	131.3 (122.2–140.5)	110.0–155.5	12.291 (0.266)
Women (60–69)	17	5013	124.1 (118.3–130.0)	97.0–145.0	11.515 (0.932)
Women (70–79)	29	8591	113.2 (107.2–119.2)	83.0–150.0	16.775 (0.998)
Women (80–99)	17	2152	94.3 (85.2–103.4)	55.7–117.0	11.428 (0.954)

CI, Confidence interval.
Modified with permission from Table 2 in Bohannon, R.W., Williams Andrews, A., 2011. Normal walking speed: a descriptive meta-analysis. Physiotherapy. 97, 182–189.

TABLE 4.4 Commonly Observed Problems With Walking in Parkinson's

Commonly Observed Problems	Explanations From Gait Analyses
Shuffling steps	The foot continues to move forwards at the point of initial contact, causing shuffling, with little if any heel strike; scuffing of the foot mid-swing may also be observed and cadence is reduced (Baker et al 2012).
Bradykinesia	People with Parkinson's walk with reduced speed (bradykinesia), short stride length [hypokinesia: a scaling down of the size of the movement (Morris et al 2008)] and increased double support time (Švehlik et al 2009). Reduced gait speed may also work as a self-selected compensation in response to fear of falling (Creaby & Cole 2018, Maki 1997).
Freezing of gait (FOG): a sudden or gradual inability to take steps during walking and to initiate subsequent steps despite having the intention to walk (Morris et al 2008); FOG is experienced as a motor block where the feet feel as if they are stuck to the floor (Giladi et al 1992)	FOG may be observed at the initiation of gait, during straight line walking and turning, and may be triggered by environmental cues and spatial constraints such as thresholds and obstacles (Nieuwboer & Giladi 2013). People with FOG have difficulty maintaining a stable rhythm, controlling cadence, and regulating stride-to-stride variations (Hausdorff et al 2003). Although FOG is transient and observed as an episodic phenomenon, the underlying disruption is thought to be continuous (Hausdorff et al 2003, Weiss et al 2015). The exact mechanism underlying FOG is yet to be determined but may involve environmental, cognitive, emotional and motor factors (Nieuwboer & Giladi 2013).
Festination	Festination describes an involuntary progressive reduction in stride length, an increase in cadence during a walking task and a reduction in walking speed (m/s). Freezing may eventually occur (Iansek et al 2006, Morris et al 2008).

(*Continued*)

TABLE 4.4 Commonly Observed Problems With Walking in Parkinson's—Cont'd

Commonly Observed Problems	Explanations From Gait Analyses
Difficulty turning	People with Parkinson's turn slowly, take more steps, have poor foot clearance and may pause before executing a turn (Stack & Ashburn 2008). These alterations to normal movement patterns may preserve postural stability by reducing neuromuscular demands through the reduction of movement amplitude (centre of mass displacement and velocity) (Song et al 2012), but also increase the number of steps that must be controlled and coordinated (Stack & Ashburn 2008). Similar difficulty in motor sequencing, observed as a decoupling of the sequential components of linked tasks, are evident in sit-to-walking transfers (Buckley et al 2008). In people with early-stage/mild Parkinson's, difficulty executing turns may occur before other walking difficulties are evident and may be independent of disturbances that effect straight-line walking (Crenna et al 2007, Song et al 2012). Axial rigidity and impaired intersegmental coordination, where the head and trunk turn at the same time rather than the head turning first followed by the trunk, are indicative of task-specific movement impairment (Crenna et al 2007).
Reduced arm swing	Arm swing is generally reduced and asymmetrical in Parkinson's (Huang et al 2012). The most affected arm has less arm swing. Unlike people after stroke, the less affected arm does not seem to compensate by increasing the swing range (Meyns et al 2013).
Weakness	Muscle strength and power are reduced in people with Parkinson's (Allen et al 2009), resulting in reduced motor unit recruitment and muscle weakness (David et al 2012).

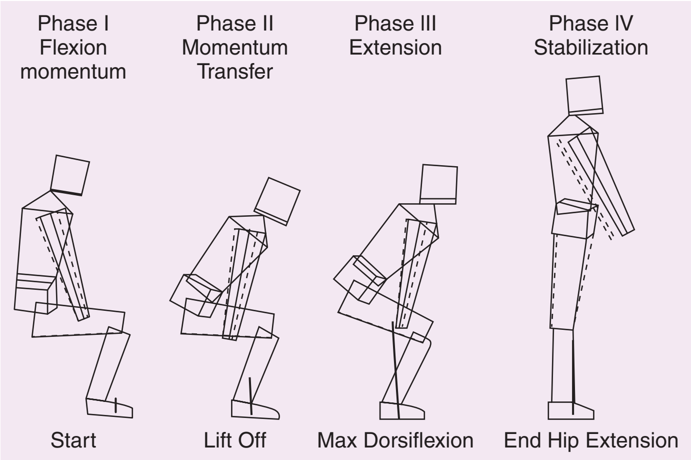

FIG. 4.5 Typical phases of sit to stand. (Reprinted from Schenkman, M. Interrelationship of neurological and mechanical factors in balance control. In: Duncan, P., ed. Balance: Proceedings of the American Physical Therapy Association Forum. Alexandria, VA: American Physical Therapy Association; 1989:29–41, with permission of the American Physical Therapy Association. © 1989 American Physical Therapy Association.)