1999, Partridge et al. 2000, Rodgers et al. 2003) to significant positive effects (Blennerhassett and Dite 2004, Foley et al. 2003, Kwakkel et al. 1999, 2004). There are many reasons for these discrepancies, including lack of detail of the protocols used in therapy (what the patient actually did, how much, and for how long), differences in outcome measures, insufficient contrast between experimental and control groups, and methodological quality. However, merely increasing the time spent in a therapy session is unlikely to result in improved outcomes—what the patient is actually doing in the session must itself be effective if increasing the time spent is to improve the outcome.

Stroke and coronary artery disease share common risk factors and pathophysiological processes. However, there is a distinct difference in the physical rehabilitation provided and in the environment in which it is performed. Cardiac surgery patients are likely to be rehabilitated in facilities where exercise equipment, including treadmills, exercise bicycles, and heart rate monitors, is in full view. Their purpose is unlikely to be misunderstood—the patients know they will have to work hard to recover strength, endurance, and fitness. Emphasis in stroke rehabilitation is commonly placed primarily on the neurological impairments, with little attention to cardiovascular adaptation to physical inactivity, whereas cardiac rehabilitation has consisted for many years of retraining the cardiorespiratory system through carefully monitored and progressed aerobic exercise. It is becoming clear that functional recovery after stroke with return to independence cannot be explained solely by the state of the neuromuscular system. Adaptation to physical inactivity threatens the individual's ability to meet the elevated energy demands of gait and activities of daily living.

## Task-Oriented Training to Increase Skill and Motor Control

The physiological factors that affect muscle force generation are *structural* (cross-sectional area (i.e., size) of muscle, density of fibers, and efficiency of mechanical leverage across joints) and *functional* (number, type, and frequency of motor units recruited during a contraction, initial muscle length, and efficiency of cooperation between muscles in a synergy). The goal of physical therapy in neurological rehabilitation is the optimization of functional motor performance. After stroke, the major impairments limiting motor performance are muscle weakness or paralysis, adaptive changes to soft tissues, lack of endurance, and physical fitness.

It is common for patients to experience varying degrees of muscle weakness and the resultant immobility is likely to lead to further and more general adaptive decreases in strength. In addition, elderly individuals may have had muscle weakness due to declining physical activity pre-stroke. Weakness secondary to movement limitations imposed by the brain lesion may actually be more debilitating for the individual than the direct effects of brain injury, but these secondary changes may be preventable or reversible. A study by Hachisuka and colleagues (1997) reported that muscle weakness and atrophy due to disuse are essentially preventable by exercise that activates high threshold motor units such as sit-to-stand, stair walking, and eccentric knee extension training.

In able-bodied individuals, strength training has been shown to stimulate neuromuscular changes. Specifically, it leads to increases in muscle excitation, motor unit activation, recruitment of the motoneuron pool, inhibition of antagonist muscles, and improved synchronization of motor unit firing patterns. Strength training also stimulates metabolic, mechanical, and structural muscle fiber changes that lead to an increase in strength and muscle size as well as endurance. Exercises have the potential to alter passive viscoelastic properties of muscle and tendon. There may also be some advantageous effect of increase in muscle size after stroke (Häkkinen et al. 1998), since muscle atrophy can become a factor in disuse weakness. Even in very elderly individuals, an increase in muscle mass may have functional and metabolic benefits (Harridge et al. 1999).

It follows that strength training is necessary after stroke to increase the force-generating capacity and efficiency of weak muscles to improve functional motor performance. In general two types of exercise are included, weightbearing (closed kinetic chain) and nonweightbearing (open chain) exercises (**Fig. 5.12**). Functional weightbearing exercises to improve strength and control of the lower limb involve moving the body

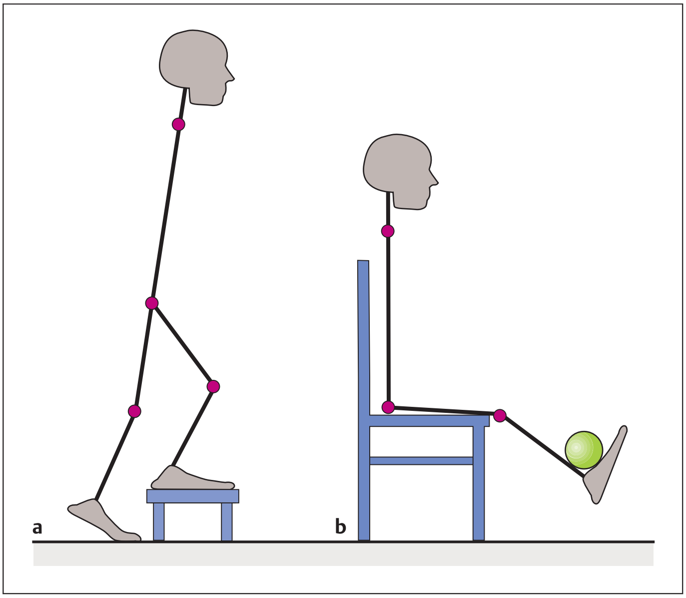

**Fig. 5.12 a, b**
**a** Hip, knee, and ankle muscles contract concentrically and eccentrically in kinetic chain body weight-resisted exercises such as step-ups.
**b** A single-joint, free weight-resisted exercise for quadriceps femoris.

mass over the feet as base of support, with body weight (and added weight where necessary) providing resistance. Open chain exercise includes single-joint exercises with resistance applied in various ways including free weights and dynamometry. There is increasing evidence that strengthening exercise increases strength and physical activity (Ada et al. 2006b).

The relationship between strength and functional performance is complex. The amount of strength required depends on a person's physical size, and on the task to be performed (e.g., walking on a flat surface compared with stair walking). That is, strength is relative. Sufficient muscle strength alone is not sufficient for skilled functional performance—it is factors such as timing of muscle forces and coordination of body segments that underlie motor control of a limb and enable effective and efficient movement. Biomechanical study of the coordination of the lower limbs provides insights into what needs to be regained after stroke.

## The Lower Limbs in Support, Propulsion, and Balance

The principal functions of the lower limbs in activities performed with feet in contact with the ground are to support the body mass, balance it over the base of support, and propel it in the desired direction (Forssberg 1982).

*Support* of the large upper body requires the generation of sufficient lower limb extensor activity to maintain segmental alignment in the presence of gravitational and other forces working to collapse the limb. Many mono- and biarticular muscles that span hip, knee, and ankle joints contribute to support by working cooperatively across the three joints. This cooperation is illustrated by the "support moment of force," an algebraic summation of the moments of force acting over the three joints (Winter 1987), demonstrated in studies of walking and of sit-to-stand (Shepherd and Gentile 1994). Any reduction of force at one joint can be made up for by increased moments of force at the other two joints.

*Balance* of the body mass relative to the base of support enables us to perform everyday actions under a variety of different conditions. The mechanical problem of remaining balanced in the presence of the destabilizing forces that occur as we move around is a particular challenge to the central nervous system. Both anticipatory and ongoing postural adjustments ensure the body is aligned and balanced over the base of support, stabilizing parts of the body while others move (Ghez 1991). Even the simple action of raising the arm in standing requires initial and ongoing muscle activations. Muscle activation patterns and joint rotations that balance us as we move about are flexible and vary specifically according to task and context (Belen'kiĭ et al. 1967, Eng et al. 1992).

In weightbearing actions (e.g., walking, stair walking, standing up and sitting down, reaching for an object in standing, squatting), ground reaction forces occur at the support surface in response to body movement. *Propulsion* of the body mass requires the generation and timing of muscle forces to accelerate the body in the desired direction.

The basic pattern of intersegmental coordination in many actions significant to daily life consists of flexion and extension at hips, knees, and ankles over the feet (**Fig. 5.13**). The body mass is raised and lowered over the supporting feet, the three joints acting as a single functional unit. Foot, shank, and thigh make up a segmental linkage, movement at one joint necessarily producing movement of the other two joints.

The motor control system appears to use simplifying strategies to control the segmental linkage, with cooperation between muscle forces produced over the three joints varying according to the task and the conditions under which it is performed. Regaining skill in motor performance therefore requires not only the ability to generate muscle forces but also to time the forces produced by a large number of muscles. Control of complex intersegmental relationships is required to bring about an effective movement. Studies of human movement in neuroscience and biomechanics have led to the development of specifically targeted task-oriented exercises designed to increase muscle strength, preserve soft tissue flexibility, and train functional motor control.

Weightbearing actions can be trained and practiced concurrently within a few days after stroke. As a general rule the action to be learned should be practiced in its entirety, since one component of the action depends on preceding components. The required neuromotor and biomechanical mechanisms involved in any action can only be organized during performance of that action. Motor training (including strength training) research has shown that exercise effects tend to be specific to task and context (Morrissey et al. 1995, Rutherford 1988) with the greatest changes occurring in the training exercise itself (**Fig. 5.14**). However, there

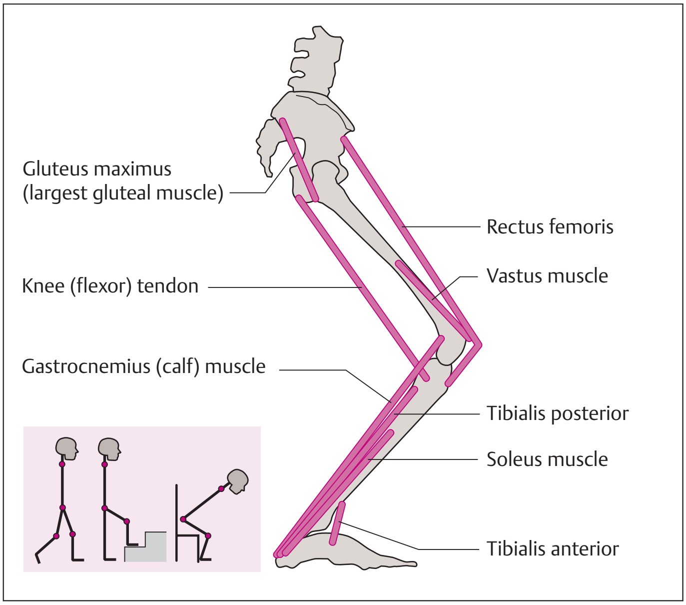

**Fig. 5.13** Diagram showing lower limb segments and eight major muscles involved in concentric and eccentric flexion and extension of the lower limbs over a fixed foot. G max, gluteus maximus; gastroc, gastrocnemius; hamstr, hamstrings; rect fem, rectus femoris; tib ant, tibialis anterior; tib post, tibilias posterior. *(Reprinted from Journal of Biomechanics, AD Kuo and FE Zajac, 1993, with permission from Elsevier Science.)*

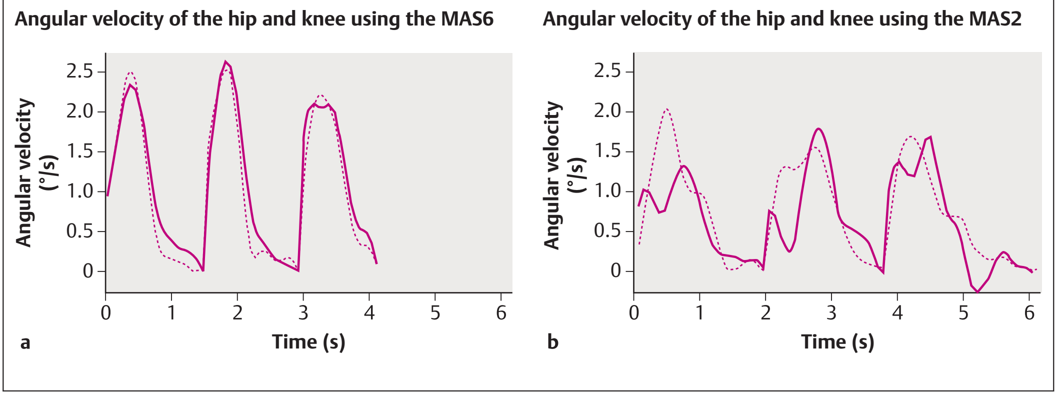

**Fig. 5.14 a, b** Improvement in kinematic characteristics and coordination following task training of standing up quantified by linear analysis.
**a** Hip (solid line) and knee (dashed line) joint velocities are almost perfectly coupled at MAS6, whereas **b** there was significant independent activity at MAS2. *(Reprinted from Human Movement Science, L Ada, NJ O'Dwyer, PD Neilsen, 1993, with permission from Elsevier Science.)*

is also evidence that transfer of the training effect can occur between actions that share similar biomechanical characteristics (Gottlieb et al. 1988). Exercises such as step-ups, heels raise and lower, standing up and sitting down, and modified squats strengthen weak muscles concentrically and eccentrically using body weight resistance and can improve segmental limb control. They take advantage of the specificity principle in that they provide similar functional stresses to the actions being trained. Muscles are therefore exercised in an action pattern that shares some of the dynamic characteristics of many weightbearing actions that are a major focus of the patient's rehabilitation. These exercises train the ability of extensor muscles to switch from shortening to lengthening contractions in muscles spanning several joints (e.g., biceps femoris, gastrocnemius). In addition, they require contraction of other muscles that also play a part in controlling the limb.

Transfer from practice of one action to improvement in another with similar dynamics was illustrated in a study of individuals more than 1 year after stroke (Dean and Shepherd 1997), in which seated subjects reached forward quickly to grasp an object placed on a table at the limit of reachability. The results showed that repetitive practice of the reaching action not only improved the distance reached and the speed of reaching but also the performance of an action not practiced, sit-to-stand. Beyond-arm's-length reaching in sitting shares similar biomechanical characteristics with sit-to-stand. Both involve an initial major horizontal shift of body weight forward over the feet and the production of vertical ground reaction forces generated through the feet.

It is apparent from clinical observation that after stroke there can be difficulty switching between concentric and eccentric activity, especially when weightbearing. The force-producing capacity (tension regulation) of muscle differs according to whether the contraction is concentric or eccentric (Pinniger et al. 2000). Voluntary eccentric contractions produce greater force than concentric contractions yet involve lower rates of motor unit discharge (Tax et al. 1990). In able-bodied individuals, exercises involving concentric and eccentric contractions produce better gains in strength than exercises with concentric contractions alone. When the muscle is actively stretched in an eccentric contraction, tension in the series elasticity component increases and the stored elastic energy is used in the subsequent concentric contraction (Svantesson and Sunnerhagen 1997).

The effect of what is called the *stretch–shortening cycle* is seen when an eccentric contraction immediately precedes a concentric contraction, as in the brief flexion counter-movement seen in performance of the vertical jump. The concentric phase generates more force when it follows the flexion movement and the person jumps higher. A similar mechanism probably exists in walking (Komi 1986) and in standing up (Shepherd and Gentile 1994). The brief flexion at the knees in standing up, occurring at movement onset, provides a stretch to the knee extensor muscles, immediately prior to limb extension. In stroke patients, it is reported that a significantly larger concentric force occurred during limb loading in standing up after eccentric exercise on an isokinetic dynamometer (Engardt et al. 1995). From their research into changes in the mechanical properties of muscles in the affected limb after stroke, Svantesson and colleagues (2000) suggest that training activities in rehabilitation that emphasize eccentric–concentric exercise may result in more normal function and enhance recovery.

It follows that functional weightbearing exercises, practiced repetitively, can provide a focus for training control of the limb at the same time as providing an action-specific strength training stimulus. These exercises directly address the weakness and lack of motor control which are major neural impairments following stroke, compounded over time by the adaptive effects of disuse and immobility. Preparatory and ongoing balance adjustments are also made during practice of weightbearing exercises so the individual is also practicing the skill of balancing the body mass over the feet while moving.

If muscles are below a certain task-related functional threshold (Buchner et al. 1996), exercises oriented to a particular action component may need to be practiced. For example, contraction of plantar flexors at the end of stance phase of gait produces the power generation at push-off that is critical to the upcoming swing phase. Power generation affects walking speed and ensures energy exchange between segments (Olney et al. 1986). It is likely that these mechanisms can be optimized by exercises to strengthen the calf muscles at the joint angle at which the major burst is required, between about 10° dorsiflexion and 20° plantarflexion (Olney et al. 1988), e.g., by faster treadmill and level walking, and walking up a ramp.

In summary, training of an action such as walking or standing up involves practice of the action itself with task-oriented exercises that incorporate similar dynamic characteristics to the action. Research into movement dynamics indicates that the control system utilizes simplifying strategies as a means of controlling the many degrees of freedom inherent in the body's segmental linkage. This information enables us to plan a program of training incorporating exercises that increase muscle force generation and are likely to transfer into improved performance of several similar actions, as well as specific training of the action to be learned.

## Task-Oriented Training

### Functional Weightbearing Exercises

#### Step Up and Step Down

Hip, knee, and ankle extensor muscles are trained to work cooperatively, concentrically and eccentrically, to raise and lower the body mass. Forces are distributed evenly over the three joints when stepping up and down in a forward direction (**Fig. 5.15**), and are more concentrated at the knee in lateral step-ups (Agahari et al. 1996). Resistance is supplied by the body mass, and can be increased by raising step height. These exercises can also be practiced in a safety harness if necessary (**Fig. 5.16**).

#### Heels Lower and Raise On a Step

Ankle plantar flexors are critical muscles, providing power for propulsion in the stance phase of walking, and enabling walking up a slope (**Fig. 5.17**). They contribute to ankle stability and control forward postural sway. This exercise actively stretches the eccentrically contracting calf muscles when the heel is lowered and is important for preserving the calf muscle length critical for push-off in gait and to performance of many weightbearing actions.

#### Squatting

Semi-squatting (**Fig. 5.18**) is practiced by reaching down to pick up (or touch) a target object. The depth of squat can be modified, with the target object placed on a stool or on the floor.

**Fig. 5.15 a–c**
**a** Step-up exercises forward,
**b** laterally and
**c** forward step-downs, to train hip and knee extensors and ankle plantar flexors to work together, both concentrically and eccentrically, to raise and lower the body mass against body weight resistance. These exercises also train ankle dorsiflexors and place an active stretch on the soleus muscle.

**Fig. 5.16** Step-ups can be practiced in a harness. This provides confidence while strengthening the lower limb extensor muscles concentrically and eccentrically. The patient has her paretic foot on the step. She raises and lowers her body weight to place her nonparetic foot on to the step. This is less challenging than repetitive raising and lowering as demonstrated in **Fig 5.15 b**.

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**Fig. 5.17 a–c** Heels raised to plantigrade and lowered to strengthen and actively stretch the plantar flexors. This exercise trains the calf muscles specifically at the length required for push-off at the end of stance. The patient holds on to a stable object as he practices.
**a** When he attempts to raise his heels to plantigrade, his paretic knee flexes. It is difficult for him to control the paretic knee in extension when the two-joint gastrocnemius contracts.
**b** He has got the idea of controlling the muscles that cross the ankle and knee.
**c** This woman can control her quadriceps to keep her knee extended while soleus and gastrocnemius contract to plantarflex the ankle. Now she increases repetitions and speed to improve control and endurance.

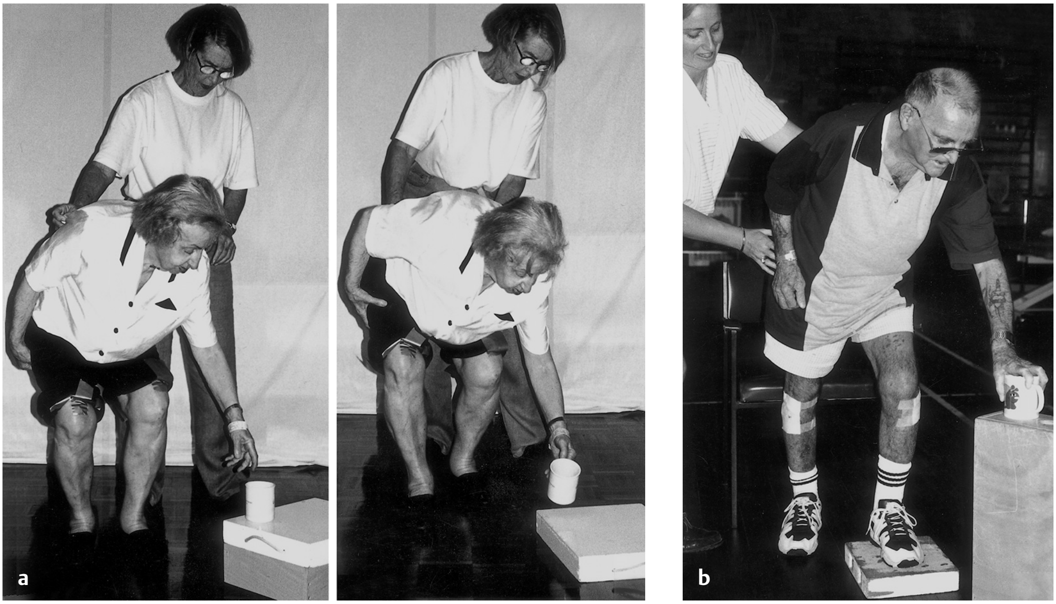

**Fig. 5.18 a, b** Squatting exercise: adapting the task by modifying the environment to enable an individual to train.
**a** Practice with the object on a box develops confidence to reach even lower.
**b** This man practices loading his paretic limb in a more difficult position for balance. His right leg is also weak so he practices to both sides.

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### Repetitive Sit-to-Stand (Fig. 5.19)

Major force generation comes from quadriceps muscles with assistance of other lower limb extensors. If muscles are weak, seat height is increased so less muscle force is required. As muscles become stronger, seat height is lowered and a prescribed number of repetitions are increased to improve endurance. The paretic limb is forced to bear weight by placing the paretic foot behind the nonparetic foot before movement starts. The action is performed at close to normal speed, that is, not too slowly.

The above exercises are practiced repetitively, with maximum repetitions (up to 10 with no breaks) in sets of three, with a short break between sets. A counter is a useful aid for the patient to count repetitions.

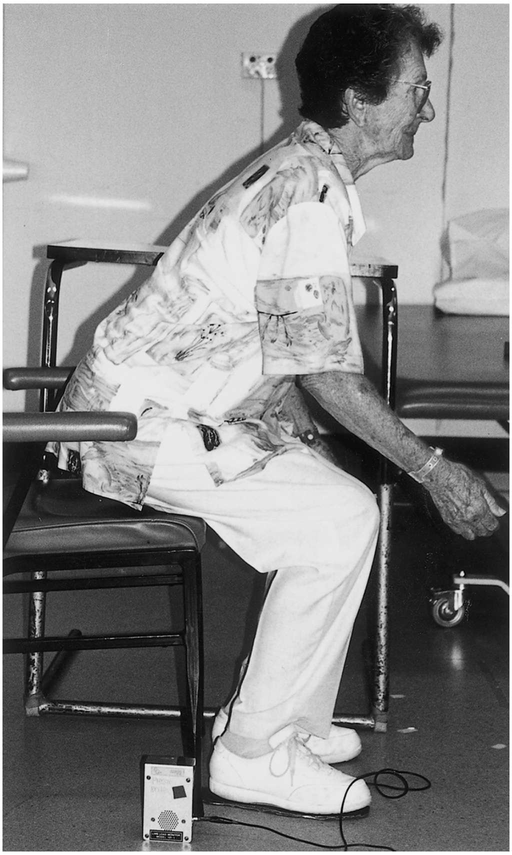

**Fig. 5.19** Semi-supervised repetitive standing up and sitting down practice. The patient gets feedback from a pressure-sensitive device under the foot and records the number of repetitions on a counter in her left hand to compare with how many repetitions she did yesterday.

## Nonweightbearing Exercises

In these exercises, resistance is provided by free weights, weight machines (e.g., dynamometer), and elastic bands (**Fig. 5.20**). With the goal of increasing the ability of a muscle or group of muscles to generate and control force, these exercises can be practiced independently and as part of circuit training. Although concurrent task practice is necessary for neural adaptation (Rutherford 1988) and learning to occur, in very weak patients small changes in lower limb strength gained by nonweightbearing exercises may produce relatively large changes in motor performance (Buchner et al. 1996).

**Guidelines for Strength Training**

- Encourage patient to exercise as intensively as possible.
- Grade the amount of resistance and number of repetitions to the individual's ability.
- Utilize resistance from body weight, free weights, elastic bands, isokinetic dynamometry, exercise machines, or inclined treadmill.
- Vary body weight resistance, step height, chair height, weight of object being lifted.
- As a general rule, a maximum number of repetitions should be performed (up to 10) without a rest and repeated in three sets, with a short break between sets.
- In progressive resistance weight training the patient attempts 10 repetitions of 60%–80% of the maximum possible load that can be lifted in one attempt.
- For endurance, a high number of repetitions is practiced at low levels of load; exercises can include stationary cycling, arm cycling, and treadmill walking.
- For very weak muscles, use methods which facilitate muscle activation and force generation, and include simple exercises, biofeedback, mental practice, and functional electrical stimulation.

Strength training is designed not only to improve force generation but also sustainability of muscle contraction and speed of force buildup (power). To be effective, strength training should transfer into functional improvement. Sharp and Brouwer (1997) found a correlation between increases in strength and in gait speed after a strength training

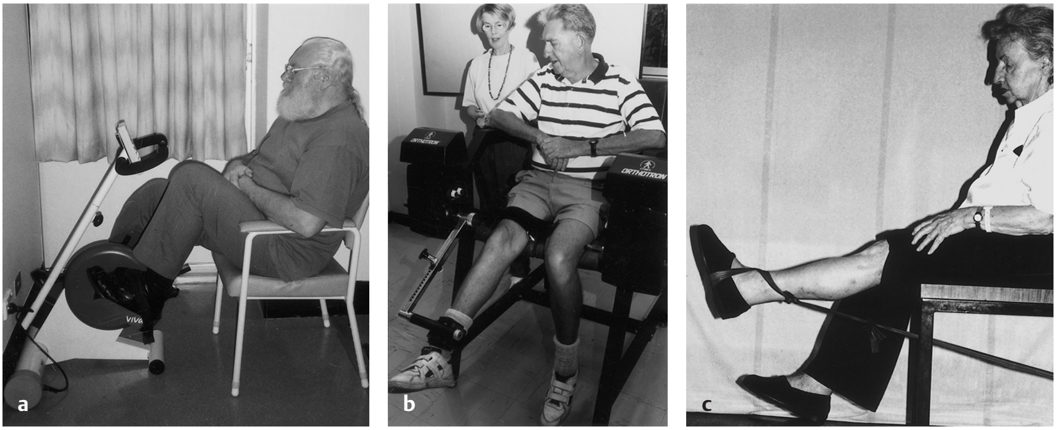

**Fig. 5.20 a–c** Circuit training stations:
**a** The MOTOmed provides resistance or assistance in response to the individual's performance *(Reck, Betzenweiler, Germany.)*
**b** Exercising on a dynamometer strengthens knee extensor muscles concentrically and eccentrically, or isometrically. This patient's target is to exercise his quadriceps at 60% of his 1RM load. He is getting feedback from the monitor. Muscles that act as stabilizers are also being exercised. *(Reprinted with kind permission from PRO-ED Inc, Austin Tx, USA.)*
**c** The elastic band should be under tension throughout the movement.

program. They reported significant increases in concentric muscle strength and motor performance after concentric strength training in chronic stroke. Weightbearing and nonweightbearing exercises such as those described above can result in significant increases in:

- Gait speed (Dean et al. 2000, Eng et al. 2003, Teixeira-Salmela et al. 1999, 2001)
- Muscle power and function (Foldvari et al. 2000)
- Walking endurance and the step test (Dean et al. 2000)
- Ability to balance, speed of standing up and muscle strength (Weiss et al. 2000)
- Ability to balance while moving, reduction in falls (Lord et al. 2007, Sherrington and Lord 1997, Sherrington et al. 2008)
- Number of stand-ups during the day and loading of paretic limb when standing up (Britton et al. 2008)

## Active Muscle Stretching

Due to weakness and subsequent inactivity, the natural tendency is for soft tissues to become stiffer and shorter. Increased stiffness in the paretic plantar flexors has been reported to occur as early as 2 months (Malouin et al. 1997), although it is likely to occur much earlier as shown in both animal and able-bodied human research. Slow-twitch muscles, such as the soleus, seem particularly vulnerable if they are rarely exposed to active and passive stretch.

Preservation of functional length of muscles, in particular of soleus muscle and hip flexors, requires active stretch during practice of exercises that make similar length demands to those of functional activities. It is particularly important to practice repetitive standing up and sitting down with feet placed behind knees as early as possible after stroke as means of preserving length of the soleus muscle. This muscle shortens rapidly if the person is inactive, and once it is short many actions such as standing up may become compromised. It is natural for muscle length, stiffness, and strength to adapt to an individual's needs, and when our needs change, it is typical for us to stretch and exercise to improve our flexibility when we plan to play an unaccustomed sport. There is evidence that active stretch during repetitive exercise can increase range of motion (Miller and Light 1997, Teixeira-Salmela et al. 1999).

Repetitive practice of functional actions is not only necessary for regaining skill but also preserves the necessary muscle length for performance of the skill. However, passive methods of length preservation in the very early stages may be necessary for some patients. If practice of standing up modified by a raised seat height is not possible, standing on a tilt table with the foot on a wedge for 20–30 minutes will maintain a passive stretch on the soleus muscle (**Fig. 5.21**). It is active stretch, however, that is necessary for preserving functional length.

Increased range of motion after stretching involves biomechanical, neurophysiological, and molecular mechanisms. Tension in muscle consists of active and passive components. Stretch can affect the active component by altering neural activity (Hummelsheim and Mauritz 1993) and the passive mechanical component by affecting viscous and elastic properties of the muscle. The mechanisms of increasing muscle length and range of motion are not well understood, but may possibly be found in the cellular and adaptive mechanisms of a muscle fiber (De Deyne 2001). One characteristic of viscoelasticity is that tissues respond to stretch and to being held at a constant length with a decrease in tension; this is known as stress relaxation. During stretch, soft tissues also undergo progressive deformation and can be progressively extended with a constant force. This is called creep (Herbert 2005).

**Fig. 5.21** Passive stretch to the calf muscle on a tilt table. Positioning the nonparetic limb on a stool ensures that the paretic calf is being stretched. This position is held for 20–30 minutes.

## Maximizing Muscle Endurance and Physical Fitness

The extent and time course of change in exercise capacity during rehabilitation has not been studied extensively in the early poststroke period. Similarly, the intensity of exercise and the extent of cardiovascular stress induced during rehabilitation have received little attention (Kilbreath and Davis 2005). The results available suggest that contemporary stroke rehabilitation programs may not be sufficiently vigorous to prevent physical deconditioning. Sustained physical inactivity induces a reduction in aerobic capacity (aerobic capacity is the product of the capacity of the cardiorespiratory system to supply oxygen, i.e., cardiac output, and the capacity of the skeletal muscle to utilize oxygen; Pang et al 2006a), limiting the performance of activities of daily living, and increasing the risk of falls and dependence on others.

Deconditioning may to some extent be a consequence of the relatively static nature of typical rehabilitation programs (Kelly et al. 2003, MacKay-Lyons and Howlett 2005). MacKay-Lyons and Makrides (2002) investigated the aerobic component of physical and occupational therapy for stroke patients by monitoring heart rate (using heart rate monitors) and therapeutic activities biweekly over a 14-week period without influencing the content. The major finding was that therapy sessions involved low-intensity exercise and activity that did not provide adequate metabolic stress to induce a training effect. A disproportionate amount of time was spent inactive. When present, the aerobic component of a typical physical therapy session took less than 3 minutes. Although one might expect progressively higher exercise intensities over time as functional status improves, any increase in hear rate ($HR_{mean}$ and $HR_{peak}$) did not reach statistical significance.

Implementation of a goal to improve cardiorespiratory fitness by increasing the aerobic component of training during the early rehabilitation