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Motor control of functional tasks: a review

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Abstract

The determinant of successful rehabilitation for patients with neurological conditions is the ability to locate the source of a particular problem and to understand the interactions of many components to ensure efficient task-oriented movement. The sensory systems gather information about the location and nature of objects in the environment and spatial position of body parts in order to plan the movement and maintain balance. The information gathered by the sensory receptors is integrated and synthesized in the frontal cortex. The premotor cortex designs the components of movement required for possible alternatives from which the basal ganglia select the most appropriate movement pattern. The cerebellum provides the timing for each component of the selected pattern that is executed by the motor cortex through the descending pathways and peripheral structures. Understanding the function of each unit of the nervous system and its contribution to motor control helps in matching physical manifestations of diseases to the area of injury and vice versa. It also helps with a problem-solving approach to rehabilitation of patients with neurological conditions.

Background

Treatment of neurological conditions and rehabilitation of survivors are dependent on identifying the source of injury or disease in the nervous system. The nervous system is a complex system with several units that interact to control the functions of the body. Control of movement is vital since it is necessary for daily activities and ensures maintenance of the quality of life. Understanding the interactions of various units that bring about movement is essential for addressing problems of patients more efficiently.

Goal-directed movement occurs through the interaction of three factors: an individual, a task to be carried out and the environment in which the task takes place [1]. To carry out a particular task, the individual gathers information from the relevant environmental features through the sensory systems; this information is used to plan appropriate movement strategies required to achieve the task. The sensory systems provide information about the state of the body (relation of body parts to each other and position of the body in space) and relationship of the body to objects in the environment that are required for the execution of the task. Integration of sensory information into meaningful information is essential for planning the movement strategy needed to perform a desired action [2]; therefore, cognitive input is crucial at this stage of movement planning. The brain utilizes the processed information to issue commands for activation of specific movement components, which linked together in the appropriate spatial and temporal sequence, make up the desired task [3, 4].

There are many functional activities that are performed frequently during daily life. Turning around to interact with the environment is an example of such functional tasks. Glaister et al [5]. filmed 11 subjects from the waist down as they walked from one office to another, from an office to a parking lot, through a convenience store and through a cafeteria. The results have shown that the steps involving turning constituted 8%, 35%, 45% and 50% of all the steps taken during each task,, respectively. This review is to explore motor control of goal-directed movement; moreover, the control of turning will be explained, whenever appropriate.

Keywords: motor control, functional tasks, goal-directed movement, environment, individual

Sensory information for the brain

For an individual to turn towards a target, the brain needs to know the alignment of the segments involved in the turn so as to compute when and to what degree each segment has to rotate to reach the target. Awareness of the position of the body in relation to the target is also valuable as it determines to what direction and angle the body needs to turn. Information on the orientation of the body and its parts is gathered by proprioceptors (6, 7) and by the vestibular system, which registers the spatial head position [8,9]. The visual system provides the brain with information about the position of the body in relation to the environment [8]. The information gathered by the sensory systems is important for planning the strategy required to initiate the movement and for feedback on whether the movement is progressing according to the plan.

Visual system

Incident light around the visual field stimulates the receptors in the retina with the image of the main object of interest falling on the central fovea [10]. This information is converted into neuronal signals in the retina and conveyed through visual pathways to the primary visual cortex of the brain where the visual information is sorted before being distributed to other cortical areas [11,12]. The visual areas are divided into two streams: a ventral stream that identifies the nature of objects and a dorsal stream that identifies the location of objects [13, 14)]. Information from the ventral stream projects directly onto the motor areas of the cerebral cortex while that from the dorsal stream projects through the cerebellum onto the cells of the motor cortex from which the descending motor tracts originate [15, 16, 17]. (Fig. 1.2) Moreover, there are cerebellar projections onto the red nucleus and brainstem areas that give rise to the descending reticulospinal and vestibulospinal tracts [18]. Thus, the visual information is important for both motor and postural purposes.

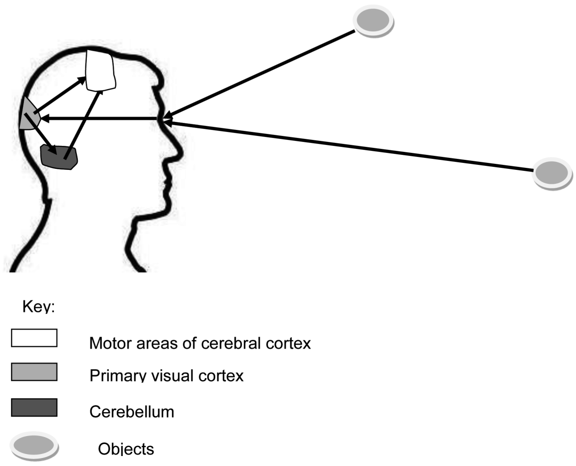


Fig. 1.2. Connection of visual and motor system

The location of the target to turn to in relation to the individual is therefore sent to the cerebellum through the pathway described above. The cerebellum utilizes the information to produce the appropriate timing of motor activations that is sent to the motor cortex for execution. The visual information is also important for maintenance of balance during the turn.

Vestibular system

The vestibular system gathers information about the position and movement of the head in space which is used to control eye and head movements and to provide postural adjustments to the body for maintenance of balance [19]. The vestibular system detects two components of head movement (rotation and translation). Rotational movements, such as shaking or nodding the head, are detected by three semicircular canals while translational movements, such as forward/backward or sideward movement of the head, are detected by two otholith receptors (utricle and saccule) [20]. The receptor cells of the semicircular canals and otholiths (vestibular apparatus) send signals to the vestibular nuclei which project onto the eye for fixation of the eye on objects during head motion and onto the spinal cord to produce reflexes to stabilize posture [20] (Fig. 1.3).

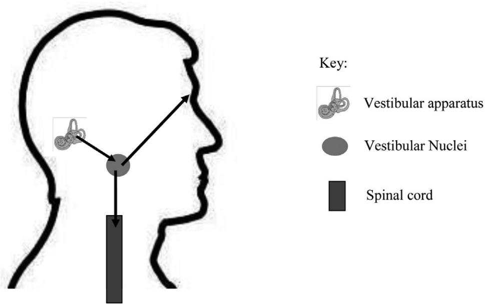


Fig. 1.3. Vestibular system

For an individual to turn successfully from one target to another, the eyes need to be properly controlled in relation to movement of the head. During a turn the eye often reaches the object of interest before the head [21], probably because of the inertia the head encounters due to its weight. When the eye is fixed on an object, the continuous head movement can alter the stability of the eye on the object. A reflex called the vestibulo-ocular reflex helps in stabilizing the eye on the object by counter-rotating the eye against the movement of the head until the head reaches the object [22]. Another important task for a successful turn from one point to another is the ability to keep vertical orientation with respect to gravity during the turn. If the head and body start to tilt, the vestibular nuclei will automatically compensate by initiating the correct postural adjustments that bring back the body to its vertical position.

Proprioceptive system

Proprioception is the information provided to the CNS by sensory receptors in muscles, tendons, joints or skin about the position of the body or its parts and of the force, direction and range of movement of the joints [23, 24, 25]. The information is carried by primary afferent fibres and conveyed through the thalamus and sensory cortex to the motor areas of the frontal lobe for the guidance of motor activity [8, 26]. The information is also conveyed to other brainstem areas where it is integrated with the information from the visual and vestibular systems for posture control [8] (Fig. 1.4)

The proprioceptive information to the cerebral cortex helps in updating the central motor system about the position of body segments so that muscle activation during the turn is adapted to the actual positions of segments. On the other hand, the proprioceptive information to the cerebellum is essential for maintaining the body balance while the turn is executed.

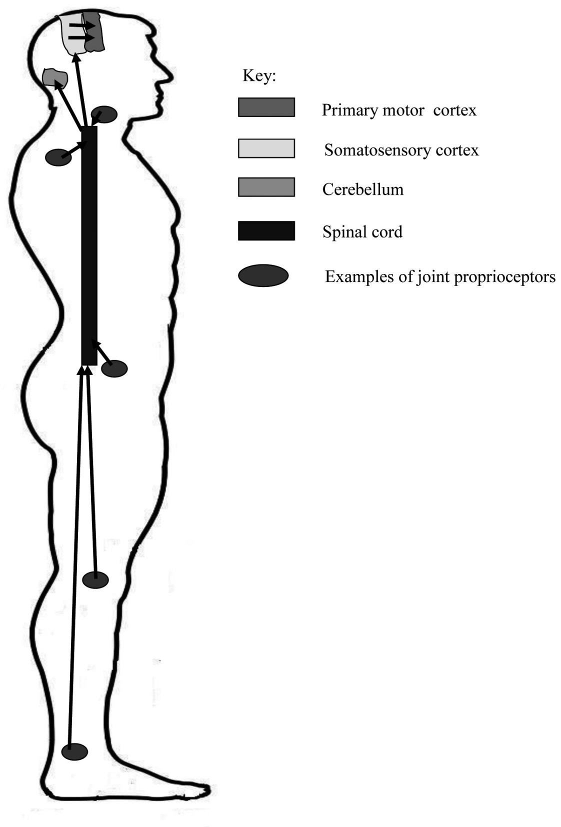
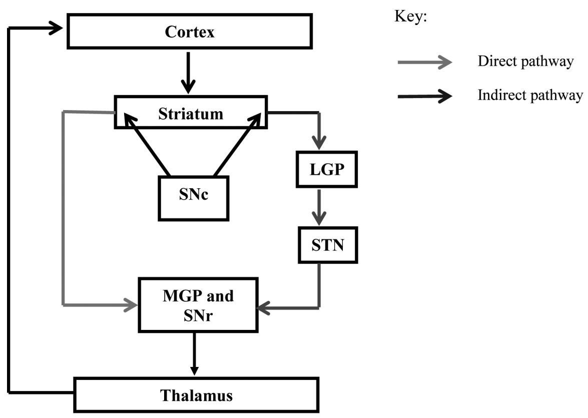


Fig. 1.4. Proprioceptive system

Central control of movement

The parietal lobes that gather the sensory information (Fig. 1.3) are closely interconnected with the prefrontal areas (Fig. 1.6), and together these two regions represent the highest level of the motor control hierarchy [27, 28]. It is at this level that the decisions are made about what action to take to achieve the task at hand. The prefrontal cortex is central in the integration of the sensory information into meaningful information by providing the background for synthesizing a diverse range of information that lays the foundation for deciding what action to take to achieve the task [29]. This is termed information processing and forms the core of the cognitive system. Stored memory is also essential for the guidance of purposeful movement [30]. The memory structures are necessary for recognizing signals in the environment and for recalling prior movement plans. The prefrontal area sends its axons to the premotor cortex (Area 6) which, having been informed of the kind of action to take, helps to determine the basic components of the movement for this purpose [27]. This area of the cortex devises a plan for the movement and passes this information to the motor cortex (M1) for implementation [27].

After setting a strategic movement plan for the desired goal by the premotor cortex, it is necessary to ensure that only the required movements are executed. The basal ganglia act as a filter, blocking the execution of movements that are not required to achieve the task. Inputs from the cortex reach the striatum and the output of the striatum is sent to the globus pallidus (GPi) and the substantia nigra pars reticulate (SNr) through direct and indirect pathways [31]. Dopamine from the substantia nigra pars compacta (SNc) facilitates the striatal neurons in the direct pathway and inhibits those in the indirect pathway [24]. Activation of the direct pathway leads to reduced neuronal firing in the GPi and SNr and movement facilitation, while activation of the indirect pathway increases neuronal firing in the GPi and SNr and suppresses movements [24]. In this way the required components of the movement are facilitated while the unwanted movement components are inhibited. The GPi and SNr give descending outputs to certain brainstem nuclei, such as superior colliculus, which are probably of importance for the control of coordinated head and eye movements [32] as well as outputs to the thalamus. The outputs to the thalamus have widespread ascending projections onto the motor cortex, completing a complex cortico- striato-thalamo-cortical loop [33] (Fig. 1.5).



SNc = Substantia nigra pars compacta; MGP = Medial globus pallidus; SNr = Substantia nigra pars reticulata; LGP = Lateral globus pallidus; STN = Subthalamic nuclues

Fig. 1.5 Cortico-striato-thalamo-cortical loop

The appropriate movement components selected by the basal ganglia are executed by the primary motor cortex (M1). However, the arrangement of muscle contractions in space and time needs to be specified by the cerebellum. The M1 and cerebellum make up the middle level of the motor control hierarchy [27]. The cerebellum regulates the duration and sequence of movements of body segments. It first receives information from the sensory and motor areas and then sends information to M1 (Figure 1.6) about the required timing of each movement.[5] M1 sends the information to the relevant parts of the body for implementation (Figure 1.6). Within a particular region of M1, a pyramidal tract neuron innervates more than one muscle and therefore can control more than one joint at a time [8]. A particular movement is achieved by the activity of many neurons, each innervating a number of muscles across joints, thus initiation of purposeful movement involves several joints, rather than an isolated, single join [8], i.e. the motor cortex is organized to ensure the performance of tasks rather than to control individual joints. M1 issues commands to lower motor neurons via the nuclei and interneurons of the brainstem and spinal cord.

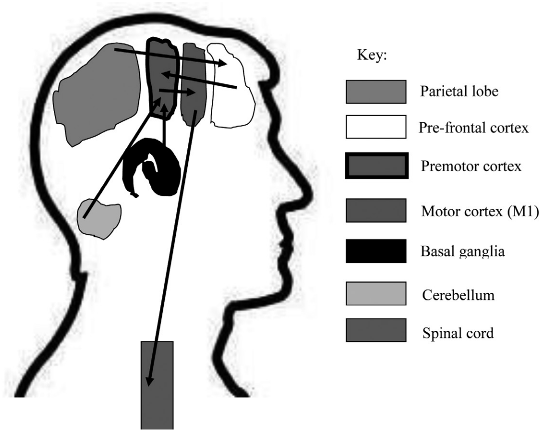


Fig. 1.6. Central control of movement

Command to lower level of motor system

The CNS gathers information needed for constructing a blueprint required for achieving a particular task. This blueprint is sent to the muscles for implementation through various tracts in the brainstem and spinal cord [8]. Each tract conveys specific information that is required for initiating and maintaining the movement or for stabilizing the body during the movement. This represents the lowest level of the motor control hierarchy [27], which is concerned with execution, i.e. activation of the motor neuron and interneuron pools that generate the goal-directed movement and make any necessary adjustments of posture.

The corticospinal tract is the main pathway through which execution of voluntary movement occurs. The reticulospinal, tectospinal and vestibulospinal tracts serve as alternative pathways for the activation of voluntary movements in addition to providing postural adjustments during tasks. However, these are mostly automatic, reflex movements that are relatively independent of descending connections from the cerebral cortex such as movements that orient the body toward external stimuli [8].

Peripheral control of movement

The axons of lower motor neurons leave the CNS in ventral roots and divide into terminal branches distributed to the muscles [27]. Each branch ends at the neuromuscular junction of a muscle fibre. Each motor neuron and the muscle fibres it innervates form a motor unit, which is the smallest functional unit in motor control. The force produced by a normal muscle contraction depends on the number and type of motor units recruited and the characteristics of the motor unit discharge [34, 35]. Muscle force or tension is increased when the absolute number of active motor units is increased and/or the firing rates of already active motor units are increased [34].

In many situations individual segments that control separate groups of muscles need to be coordinated to smoothly achieve a particular task. Coordination is defined as "the ability of a given subject to activate appropriate muscles for the execution of a purposeful movement in an accurate and effective manner" [36]. A coordinated movement is the net result of activity in several muscles, including agonist, antagonist and synergist, that share a precise temporal (i.e. when a muscle turns on) and spatial (i.e. which muscle turns on) pattern of onset [36]. Interneurons (propriospinal neurons) enhance cooperation of various spinal segments. They establish synaptic contacts between many neurons in the cord, within the segment in which the cell body is located, and in segments above and below [8].

Coordination of movement and posture

It is very important to maintain a stable body position while at the same time allowing body parts to move freely during functional activities. Failure to achieve any of the two could lead to either instability or inefficiency in carrying out functional tasks. Postural control is organised to build up and update body orientation and ensure that balance is maintained [37, 38] during movement. Pollock et al. [39] described postural control as "the act of maintaining, achieving or restoring a state of balance during any posture or activity".

Postural control occurs simultaneously with functional tasks and plays a role in controlling the movement of the COM within the base of support of an individual to allow safe and efficient performance of movement. Frank and Earl [40] have postulated that there are three strategies that could be adopted to maintain upright stance during voluntary movement.

Firstly, preserving upright stance during movement may involve postural preparations engaged well before movement [40, 41]. An individual preparing to turn around may increase the base of support by widening the distance of the feet and/or stiffening the joints through muscle contractions to set a more stable posture.

Secondly, maintaining upright posture can be achieved by postural adjustments that occur simultaneously with, or just before, the initiation of voluntary movement [40, 42] in a strategy referred to as the postural accompaniment. The general mechanism of postural accompaniments involves anticipating the effect of the movement on posture and coordinating the activation of both the postural adjustments and the intended movement to minimize the postural disturbance [40] in a feed-forward control. Alexandrov et al. [43] have shown that forward bending is performed by flexion in the hip and extension in the knee and ankle joints, a movement synergy that maintains equilibrium during the movement by stabilizing the COM within the base of support. According to them, the coordinated movement of the joints is centrally controlled in a feed-forward manner as supported by the findings of Massion et al. [44] demonstrating that a similar interjoint coordination is preserved even in microgravity. This implies that if there is a problem with central control of movement, the coordination of posture and movement during bending tasks may be jeopardized, which was indeed shown in the study of Alexandrov et al. [45]; according to them, people with Parkinson's disease present with increased COM shift due to incoordination of joint angles.

The coordination of posture and movement using the postural accompaniment strategy has also been shown during changing direction (turning) while walking in healthy adults. Young healthy adults reoriented their head followed by the trunk, then movement of the COM in the medio-lateral plane which was accompanied by trunk roll (movement of the trunk in the frontal plane) and finally foot displacement in the medio-lateral plane [46]. The control of the COM towards the new direction is shown to be affected by the predictability of the target to turn to [47]. Participants used medio-lateral foot displacement when the position of target was predictable (cue for direction of turn given early) while they used trunk roll motion when the position of the target was unpredictable (cue for direction of turn given one stride before the turn). The effect of damage to the CNS in coordination of movement and posture during turning has not been investigated; however, older adults have been demonstrated to have different sequence of movement and posture parameters, as manifested in a delay in the medio-lateral displacement of the COM [46].

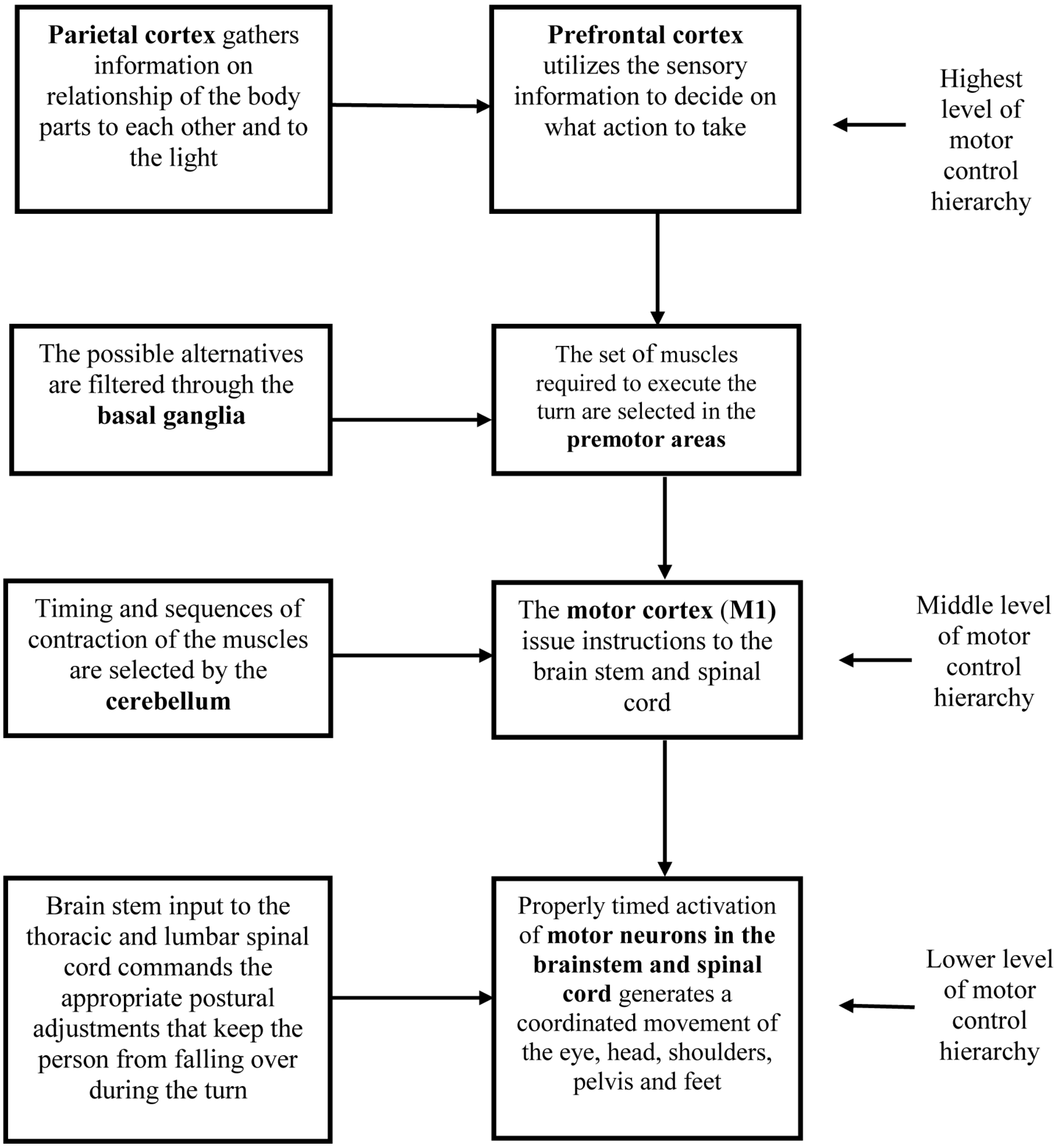
Finally, postural disturbances imposed by movement can be counteracted by sensory-based feedback strategies called postural reactions [40]. The general mechanism of feedback strategies consists of excitation of sensory receptors that trigger automatic postural adjustments. This strategy is the primary defence against unexpected external perturbations. An individual may select one or another of these strategies, depending on the perceived need for safe regulation of the body's COM and timing of the movement. Postural preparations arrive well before movement initiation; postural accompaniments arrive within about 100ms of movement initiation and postural reactions arrive about 100ms or more after movement initiation [40].

It is now clear that performance of efficient goal-directed movements occurs through the coordination of posture and movement. When the mechanism that controls the movement is intact but the postural adjustments that ensure stability during the movement is faulty, the balance of an individual could be compromised and vice versa. Many questions could therefore be raised with regard to the consequences of the disruption of the CNS control of movement and posture during goal-directed movement. Firstly, does damage to the CNS lead to in-coordination of the movement itself? Does it affect the development of appropriate postural adjustments that keep the body upright during the movement? Could these changes lead to instability and subsequent falls? This paper has therefore raised questions that need to be addressed in order to identify the source of motor and postural impairments in people with neurological conditions.

Summary of motor control

Goal-directed movement depends on information about where the body is in space, where it intends to go, and selection of a plan to get there. Once a plan has been selected, instructions to implement the plan have to be issued. To some extent, these different aspects of motor control are carried out by different regions of the brain.

To appreciate the different contributions of the three hierarchical levels of motor control to movement, consider the actions of an individual standing preparing to turn the whole body on-the-spot towards a light placed in a particular location. The parietal cortex has information about where precisely the body is in space and its position in relation to the light based on vision, vestibular information and proprioception. Strategies have to be devised to move the body from the current state to one in which the body is facing the target light. The set of muscles required to execute the turn are selected in the premotor areas, and the possible alternatives are filtered through the basal ganglia and back to the cortex until a decision is made, based predominantly on experience. The motor areas of the cortex and the cerebellum then make the decision about sequences of muscle contractions and issue instructions to the brain stem and spinal cord. Activation of neurons in the brainstem and spinal cord then causes the movement to be executed. Properly timed activation of motor neurons in the brainstem and spinal cord generates a coordinated movement of the eye, head, shoulders, pelvis and feet. Simultaneously, brain stem input to the thoracic and lumbar spinal cord commands the appropriate postural adjustments that keep the person from falling over during the turn (Fig. 1. 7).



Fig, 1.7. Summary of motor control during turning

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