Turning Strategies During Human Walking

K. HASE AND R. B. STEIN
Division of Neuroscience, University of Alberta, Edmonton, Alberta T6G 2S2, Canada

Hase, K. and R. B. Stein. Turning strategies during human walking. J. Neurophysiol. 81: 2914–2922, 1999. The mechanisms involved in rapidly turning during human walking were studied. Subjects were asked to walk at a comfortable speed and to turn toward the instructed direction as soon as they felt an electrical stimulus to the superficial peroneal nerve. Stimuli were presented repeatedly at random over 10- to 15-min periods of walking for turning in both directions. Electromyograms (EMGs), joint angular movements of the right leg, and forces under both feet were recorded. The step cycle was divided into 16 parts, and the responses to stimuli in each part were analyzed separately. Two turning strategies were used, depending on which leg was placed in front for braking. For example, to turn to the right when the right foot was placed in front, subjects generally altered direction by spinning the body around the right foot (spin turn). To turn left when the right foot was in front, subjects shifted weight to the right leg, externally rotated the left hip, stepped onto the left leg, and continued turning until the right leg stepped in the new direction (step turn). The step turn is easy and stable because the base of support during the turn is much wider than in the spin turn, so some subjects used it in all parts of the cycle. Initially, the deceleration of walking is similar to a rapid stopping task, which has been previously examined. The deceleration mechanism involves a sequence of distal-to-proximal activation of muscles on one side of the body (soleus, biceps femoris, and erector spinae). This pattern is similar to the “ankle strategy” used in postural control during forward sway. The control of foot placement in the swing leg and muscle activities for rotating the trunk in the stance leg occurred within a step after the cue. The action of ankle inverters and elevation of the pelvis by activity of gluteus medius may contribute to the control of trunk rotation. This activity was closely related to the timing of the opposite foot strike, independent of the part of the step cycle when the stimulus was applied. In most subjects, the turn was completed without resetting the underlying walking rhythm. This first EMG analysis of rapid turning shows how common strategies for postural sway and stopping can be combined with one of two turning strategies. This simplifies the complex task of turning at a random time in the step cycle.

INTRODUCTION

Postural control in humans depends on a relation between the body’s center of mass (COM) and the base of support. In dynamic states during locomotion, the momentum and forces caused by ongoing muscle activity must also be adjusted (Hirschfeld and Forssberg 1991; Pai and Patton 1997). Indeed a decision point depending on the phase of gait cycle is required to change the steady-state patterns (Hase and Stein 1998; Patla et al. 1991).

Patla et al. (1991) found that walking subjects could not alter the direction of locomotion if a visual cue about changing direction was given at the end of the stance phase just before the next step. The inability to change direction within the same step was not due to a limitation of reaction time but to the incapacity of muscles to rotate the body and translate it along the mediolateral axes. The authors concluded that a change in direction must be planned in the previous step to reduce the acceleration of the COM without stopping the ongoing locomotion. Lyon and Day (1997) reported that the size and direction of the initial throw of the body mass in the frontal direction must be judged in advance. They suggested that the use of a ballistic strategy might produce the different COM trajectories for stepping in different directions. During normal walking, major aspects of the swing leg trajectory are determined by the initial conditions set at the end of the stance phase coupled with the pendular dynamics of the lower extremity (Meta et al. 1981; Mochon and McMahon 1980).

In our previous study on rapid stopping subjects walking with a comfortable gait speed could stop within the same step by using decelerating mechanisms if the cue to stop was applied before the COM passed the stance foot (Hase and Stein 1998). The timing of muscle activities for producing the main braking force was controlled by when the foot was planted on the ground in front of the body. Different decelerating mechanisms were used to produce a stop, depending on the timing within the step cycle. This result suggests that the interaction between muscle tension and the mechanical demand of the task (Yang and Winter 1985) determines the decision point.

A few studies on turning strategies to prevent knee injuries and disability can be found in sports medicine and orthopedics (Andrews et al. 1977; Cross et al. 1989; Shiavi et al. 1987, 1991). Andrews et al. (1977) defined two separate cutting techniques during human running as “sidestep cut” and “cross-over cut” by their kinematic analysis. The former is a way of proceeding in the direction opposite to the planting foot, and the latter is a way of proceeding in the same direction as the planting foot by crossing the opposite leg in front. Both maneuvers are required to reduce the forward momentum before changing direction. In the deceleration period, the rotation of the torso and pelvis already occurs. Therefore, by comparing muscle activities during turning and stopping, we can analyze the initial mechanisms for rotating the body.

Tinetti et al. (1986) reported that staggering when turning is a prominent characteristic of recurrent fallers. The process of turning consists of decelerating the forward motion, rotating the body, and stepping out toward the new direction. Various modulations will be required according to the phase of the movements. In none of these studies was an electromyogram (EMG) analysis performed, which is the purpose of this study. A reduced biomechanical analysis is also included, which, together with the fuller biomechanics found in previous papers (MacKinnon and Winter 1993; Soderberg and Dostal 1978;
White 1986), can suggest how the neural mechanisms lead to a complex behavior such as turning.

METHODS

Subjects and general procedure

Ten normal subjects (5 male and 5 female) with ages ranging from 26 to 57 yr participated in this experiment with informed consent. The experiment consisted of two sections to obtain data for each strategy of turning to the right and left during walking. The subjects were asked to walk on a level walkway 8 m long with a comfortable gait speed (2.3–3.5 km/h) and to go back to the starting point by turning right or left as soon as they felt a cue. The cue was an electrical stimulus to the superficial peroneal nerve. The stimulus was applied to the anterior surface of the right leg just near the crease of the ankle joint. Flexible, disposable, Electrotrace Ag/AgCl surface EMG electrodes (Jason; Huntington Beach, CA) were placed over a location where subjects reported a strong radiating paresthesia in the dorsal surface of the right foot. This is the receptive field for the superficial peroneal nerve and is activated, for example, when this part of the foot hits an obstacle. The stimulation was adjusted to the strongest intensity that was described as nonnoxious by the subjects (about twice radiating threshold). A strong stimulus was used so subjects would not miss the cue during walking. The stimulus was given irregularly by a manual switch at any one (or none) of the steps during straight walking from one end to the other of the walkway. Because the subject could not predict when or if the cue would be given to turn, the gait speed in the steady state was never changed during each trial. To assess various phases of the step cycle, data for each section were collected for 10–15 min. These experiments were performed after a rapid stopping task (Hase and Stein 1998).

Data recording and analysis

The pressure under both feet was measured during walking with force-sensitive resistors (2.5-cm diam, Interlink; Camarillo, CA) located in the insoles of the subject’s shoes. Values were linearized and converted to force with the method of Zehr et al. (1995). Three force-sensitive resistors connected with a Velcro band were adjusted to lie under the heel and the ball of the foot near the medial and lateral metatarsal joints. They were used to establish step cycle parameters, to calculate the center of pressure (COP), and to estimate the total force under the foot. Because the three sensors only measured the forces under parts of the foot (~4.9 cm each), the total force estimated from the sum of the three sensors underestimated body weight substantially but showed the typical pattern of vertical force generation observed with force plates. Angular position of hip, knee, and ankle were recorded with flexible electrogoniometers placed over each joint (Penney & Giles). Angles were defined according to the conventions in Winter (1991) with flexion angles being positive. Signals were amplified and recorded together with a stimulus trigger by using the program AXOSCOPE (Axon Instruments) on a computer system. After cleaning the skin with alcohol, disposable Ag/AgCl surface EMG electrodes were placed on the right side over the tibialis anterior (TA), soleus (SOL), biceps femoris (BF), vastus lateralis (VL), anterior segment of gluteus medius (GM), and erector spinae (ES; 30 mm lateral to L4) muscles for eight subjects. Ground electrodes were placed over electrically neutral portions such as the knee. The signals from each muscle were amplified, filtered (high pass, 30 Hz), and full-wave rectified. The rectified signals were then low-pass filtered at 30 Hz. A custom software program (SELPOS) was used to detect the step cycles in which the subjects were stimulated to turn. The unstimulated step before the stimulated one was identified as the control step. Custom software programs were also used to separate the step cycle into 16 parts, beginning with the right heel contact. Because part 1 began when an increase in force was detected under the right heel, the actual points of the right and left heel contact actually occurred in parts 16 and 8, respectively. We typically recorded data for 80 perturbed steps distributed over the step cycle and measured ~80 control steps. To obtain smoother records, stimulus artifacts were removed, and the EMG activities were filtered with a three-point digital moving average. Eight subjects were videotaped during the task in the sagittal plane, with a red flash indicating the cue to turn, and two subjects were studied in the frontal plane as well.

Statistics

ANOVA and Tukey post hoc analysis were used to test significant differences in the observed frequency of turning strategies for each part of the step cycle. Statistics were based on average values of the frequency of turning strategies used by each subject. The level of probability selected as significant was $P < 0.05$.

RESULTS

Turning strategies

For consistency and ease of understanding, all data (except for Fig. 3B) are presented for turns to the right. Similar results were seen with left turns. Figure 1 shows the mean forces (—) and SEs (—) under both feet just before and after a cue to turn right (time 0) for one subject. The cues in Fig. 1, A and B, were given near the times of left heel contact and right heel contact, respectively. Figure 1, dotted line, represents the average for control steps in which no cues were given. The control cycles lasted 990 ms on average for this subject. A typical foot placement pattern, taken from the videotape, is schematically displayed above the traces. The foot is indicated by a dashed line when it is in the air at a given time. When only the heel is off the ground, the back of the foot is dashed, and when the toe is off the ground (heel strike) the toe is dashed.

In Fig. 1A the stimulus was given near the time the left heel struck the ground (referred to as part 8 of 16 parts of the step cycle, which begins with the right heel strike). Approximately 200 ms later the force begins to come off the heel and onto the ball of the left foot, as indicated by the force changes under the lateral and medial surfaces of the left foot. The force on the lateral surface is stronger than under the medial surface and will push the body to the right. Note that the force also comes off the ball of the left foot sooner than in the control steps and is assumed by the right foot. In effect, the step cycle is initially speeded up by the cue rather than slowed down. However, there is little or no force on the right heel because the subject lands on the ball of the right foot, which is then used as the axis on which to turn (indicated as a horizontal dotted line through the foot placement patterns).

The force remains on the ball of the right foot for a longer than usual period while the body rotates around the right leg; this leg is referred to as the axial leg as it supports the weight during the change in direction. Eventually, the left foot is placed on the ground either in front of or to the side of the right foot. The right leg is now free to step in the new direction. Eventually, the left foot is placed on the ground either in front of or to the side of the right foot. The right leg is now free to step in the new direction of movement. We refer to this as a spin turn because the body spins around the ball of one foot, which serves as an axis for the turn. This maneuver to make a U-turn corresponds to the crossover cut for turning 90° during human running, which was named and described by Andrews et al. (1977).

Figure 1B shows the corresponding sequence, when the cue
was given at the right heel contact (part 16 of the step cycle). Now the force comes off the heel and onto the ball of the right foot shortly after it is placed on the ground. Again the weight comes off the ball of the foot quickly and is assumed by the other (left) foot. However, rather than a prolonged period of weight support, while the body spins around this foot, another step is initiated quickly. Note also that most of the weight is on the medial surface of the left foot at this time to balance the body weight during the quick step with the right foot. Thus the forward leg that produces a braking force works as the main axis for changing direction, but both feet are rotated to some extent during this step so that they face diagonally to the new direction for walking. Finally, the left leg steps and lands normally on the heel pointing in the new direction. We refer to this as a step turn, corresponding to the sidestep cut by Andrews et al. (1977). It differs from the spin turn in that both feet continue to step, and each can serve as the axis for part of the turn (Fig. 1B, 2 horizontal dotted lines in the foot placement diagram). This provides a broader base of support for the turn and is therefore easier for the subject.

Figure 2 shows all the recordings from the medial force sensors (under the ball of the foot near the first metatarsal joints) for stimuli applied at each of the 16 parts of the step cycle (same subject as in Fig. 1). The slight variations in timing that are seen near time 0 arise partly from the fact that each part of the cycle had stimuli occurring over a period of 990/16 = 62 ms. In part 5 (~30% of the step cycle) two responses occurred with an earlier onset (~500 ms after the cue) and a longer duration on the ball of the right foot after the first peak of weight support. These responses correspond to ones with shorter duration on the ball of the left foot in part 5. This means that part 5 represents a transition between two kinds of turning strategies, as described previously for stopping strategies (Hase and Stein 1998). Another transition period, in which a quick step was sometime taken with the left foot, occurs in parts 11 and 12 of the step cycle. Around these periods there is a variation in the timing, but a fully formed strategy (either a step turn or a spin turn) was evident by 500–600 ms. During parts 6–10 this subject turned to the right with a “spin turn” (Fig. 1A). However, at the end of one cycle (parts 13–16) and the beginning of the next (parts 1–4) he used a “step turn” (Fig. 1B).

In 7 of 10 subjects, the turning strategies could be divided into these two common styles. Figure 3 shows the frequency with which a spin turn was used in each part of the cycle by the seven subjects. ANOVA and Tukey HSD post hoc analyses were used to estimate which strategy was used by the subjects at the different cue times. In turning to the right, the spin turn was mainly used during parts 6–11, and the step turn was mainly used during parts 13–16; 1–4 (Fig. 3A, P < 0.005). In
turning to the left, subjects used the spin turn during parts 14–16; 1–3 and step turn during parts 6–12 (Fig. 3B, P < 0.005). Note that the spin turn was not used exclusively in any part of the cycle and was used over less of the cycle (6 parts) than the step turn (8 parts). Generally, when the spin turn was used, the time to step in the new direction varied depending on the duration of rotating the body on the axial leg. In the step turn, just after the leg was placed in front for braking, some subjects rotated both legs at the same time. These differences in the mechanisms for rotating the body contributed to a variation among individuals in the time required for turning. However, both strategies were almost complete within one step cycle.

The other three subjects used a stepping strategy in all parts of the cycle. To turn right, the ball of the left leg was used initially as the axis in part 8 (Fig. 4). There was no strong push-off on the lateral side of the left foot to rotate the body for a spin turn. Instead one more step was taken, which required a longer distance to turn than that shown in Fig. 1. In the step turn, just after the leg was placed in front for braking, some subjects rotated both legs at the same time. These differences in the mechanisms for rotating the body contributed to a variation among individuals in the time required for turning. However, both strategies were almost complete within one step cycle.

The other three subjects used a stepping strategy in all parts of the cycle. To turn right, the ball of the left leg was used initially as the axis in part 8 (Fig. 4). There was no strong push-off on the lateral side of the left foot to rotate the body for a spin turn. Instead one more step was taken, which required a longer distance to turn than that shown in Fig. 1. By using the step turn throughout the step cycle, the subject needed only one transition period (parts 4 and 5) and could turn with a constant rhythm except for this period (Fig. 5). Note that there is a prolonged period of pressure on the ball of the left foot, irrespective of where in the cycle the cue was given. We do not know the reasons that some subjects used both strategies and others used only the step turn. However, both groups walked with similar gait speeds, so speed was not a major factor.

The turning strategy was basically determined by which leg was placed in front for braking. In the spin turn, the axial foot was placed toward the midline with external rotation of the hip, probably by muscle activities in hip adductors and external rotators. The initial responses for turning combined decelerations and rotations of the body (Fig. 1A). Also in the step turn an action for rotating the pelvis toward the turning side was added to a decelerating mechanism similar to that used in the rapid stopping task. These initial responses, from the time of the cue until the foot placement for producing the main braking force, were common to all subjects, despite some variations in actions for rotating the body on the axial leg, as described previously. Around the transition periods, however, the subjects could not decelerate and turn simultaneously, so they came almost to a stop and then turned.

Figure 6 shows the average force on the medial surface of the ball of the left foot for two subjects on an even slower time scale. From the timing of the peak force before the cue future peaks can be predicted. The agreement is remarkably good for

![Graph showing frequency of spin turns in each part for 7 subjects who used both strategies for turning. A: right turn; B: left turn.](http://jn.physiology.org/)

![Graph showing average forces in the same format as in Fig. 1 are shown for a cue at left heel contact while turning right (average of 10 responses). This subject always used a step turn, as shown in the schematic diagrams of foot placements.](http://jn.physiology.org/

![Graph showing forces under the balls of the right and left feet before and after a cue to turn right. Same subject as in Fig. 4; format as in Fig. 2.](http://jn.physiology.org/)
subject 1, although the observed peaks are delayed slightly on average. This was the most common pattern, although sometimes the observed peaks were at or even before the predicted time. Thus these subjects maintained an ongoing rhythm and fitted the various corrections into this rhythm. A different pattern is seen for subject 2, who is the one shown in Figs. 1 and 2. In parts 1–11 of the cycle the peaks lag the predictions, whereas the peaks lead the predictions in most of the later parts of the cycle.

An alternative hypothesis is that the cue resets the walking rhythm. If this hypothesis is true, the peaks should line up with the average cycle time of control steps. Further details in the text.

subject 1, although the observed peaks are delayed slightly on average. This was the most common pattern, although sometimes the observed peaks were at or even before the predicted time. Thus these subjects maintained an ongoing rhythm and fitted the various corrections into this rhythm. A different pattern is seen for subject 2, who is the one shown in Figs. 1 and 2. In parts 1–11 of the cycle the peaks lag the predictions, whereas the peaks lead the predictions in most of the later parts of the cycle.

An alternative hypothesis is that the cue resets the walking rhythm. If this hypothesis is true, the peaks should line up with the average cycle time of control steps. Further details in the text.

Figure 7A shows data for a spin turn elicited by a stimulus applied in part 8 together with the corresponding schematic diagrams from video. The EMGs of relevant muscles from the right leg are shown together with the kinematics from the same leg. After the cue was applied, there was a small burst of activity in TA, presumably so that the toe can clear the ground. Then BF was activated during the right swing phase and could contribute to an early right foot strike, external rotation of the hip, and movement of the right leg toward the axis for turning. SOL and VL were activated just before the foot contact, which could extend the ankle and knee joints, as in the rapid stopping task. The activation of these muscles should contribute to the decrease in forward momentum that is required to turn.

The continuous activity of ES may be associated with holding the torso back, despite the forward momentum acting about the hip from the rapid deceleration. Continuous activity in the spinal muscles as well as in BF helps to stabilize the right leg while the body is spinning on the ball of the right foot. After right foot strike, there were two peaks of activation in GM that could stabilize the hip for rapid weight bearing and elevate the opposite pelvis during rotation of the body, respectively. The three subjects who used a stepping strategy for turning right in part 8 of the step cycle did not have the second peak of GM or the continuous SOL activity. All subjects had the same sequence of EMG activities until the time of right foot contact.

The left leg in part 8 of the step cycle (not shown) had a small SOL activity coupled with BF activity for decelerating the forward movement (Hase and Stein 1998). ES activity followed, so the sequence of EMG has the same pattern as the right leg in part 16 during turning right (see Figs. 7B and 8B). Two subjects who used the spin turn had a BF burst at 100–150 ms after the cue. An acceleration of hip extension in the stance phase may be associated with the rotation power. The short activation in SOL could produce push-off power to spin the body.

The turning strategy toward the right after a stimulus in part 16 of the step cycle is characterized by early activities of SOL, BF, and usually ES followed by activities of GM and TA of the right leg (Fig. 7B). Similar to the rapid stopping task, there were early activities in SOL and BF that could produce a braking force. Just before the force came off the heel, ES was activated. Because the right leg was kept behind the body and the weight was on the ball of the foot, the activation in TA and the inhibition of SOL activity for push-off should reduce the forward momentum. The inversion action of TA may provide a lateral shift of the knee and assist the pelvis in rotating toward the right. Additionally, a larger and longer discharge of TA should keep the right ankle in dorsiflexion during an external rotation of the right hip for changing direction. A larger burst of GM occurred after the weight shifted to the ball of the right foot. This suggests that having the right hip joint in extension is necessary for the effective action of GM to elevate the pelvis. While the opposite pelvis is elevated on the supporting hip, GM as well as TA activities can initiate the lateral shift of the knee required to rotate the body. To facilitate this shift,
knee flexion with an eccentric contraction of VL will be required.

The left leg in part 16 during turning right (not shown) plays the main role in decelerating the body and works as the axis for turning. There was an extensor synergy as well as activities of GM and ES for decelerating gait speed, as seen in rapid stopping. Following the action for deceleration, the forward leg supported the weight during the change in direction. With rotation of head and trunk, the opposite leg was externally rotated on the hip and stepped out toward the new direction. In Fig. 1B, a continuous increase of the medial force under the ball of the forward foot (left leg) represents push-off power. At this time, BF and GM activities should produce extension and abduction of the hip (not shown) and help to shift the weight onto the stepping leg. However, during the initial responses involved in rotating the body, muscle activities measured in this experiment were not very different from those in the stopping task.

**Comparison between responses during turning and stopping strategies**

The stepping strategy for turning was common to all subjects at some phases of the cycle. With rotation of the trunk and pelvis to the turning side, the forward leg was placed on the ground with toe inward, except around the transition periods as described previously. In this respect, the initial responses during the turning task are different from those in the corresponding parts of the step cycle during rapid stopping. By comparing turning and stopping, we can see some of the muscles that participate in rotating the body.

Figure 8 shows data on early responses for stopping (Fig. 8A) and turning right (Fig. 8B) in which the cue was applied in part 16 of the step cycle. During the swing phase of the left leg, there is an additional GM activity in the right leg (period 1). This second activation in GM follows the first peak just after the right foot contact was seen in all subjects during parts 15–16; 1–4 in the task of turning right. Thus this activity may play a crucial role in rotating the body by elevating the pelvis. Throughout parts 15–16; 1–4, the time from the second GM peak to foot strike in the opposite leg was <15% of the control stride time (not shown). The first activation in GM occurred at almost the same time during the stopping and turning tasks. This means that the GM has one peak for stopping and a second peak for rotating the body. Intervals between the first and second peaks of GM activity in parts 15 and 16 were significantly shorter than in parts 1–4, respectively (according to t-test at the 5% level of confidence, not shown). Because the foot placement for producing a braking force is faster in parts 15 and 16, as in the rapid stopping task, the peak-to-peak latency of GM activity must be shortened to work effectively. Moreover, even when the cue was applied
after the right foot strike, the interval between both peaks tended to be decreased. Thus the timing of GM activity for rotating the body was closely related to the placement of the opposite foot.

DISCUSSION

In this section we will first contrast the mechanisms used in the two turning strategies. Then we will summarize the relation between the biomechanics and the EMG activity for stopping and turning. Finally, we consider the functional significance of our observations. In the rapid stopping task, subjects stopped with the right foot in front of the left or vice versa, depending on when the cue to stop was applied in the step cycle (Hase and Stein 1998). To turn rapidly during walking, the leg that was placed forward to produce a braking force was generally used as the axial leg for rotating the body. An exception occurred in those parts of the step cycle for three subjects who took one more step to turn instead of using a spin turn. Figure 9 schematically illustrates the turning mechanisms for a spin turn and a step turn. Although we have no data on the interaction among the trajectories of the COM, the COP, and the exact foot placement, the forces and kinematic findings from electromyographs and video helped us to understand the relations of the trunk and legs during turning. By carefully relating these data to the observed EMG responses, we hope to clarify each turning strategy in relation to the expected COM trajectory from biomechanical studies.

Spin turn (Fig. 9A)

This strategy allows the body to spin on the forward leg while producing a braking force (axial leg). The torso is kept behind the axial leg presumably to balance the centrifugal force caused by rotating the body and to step toward the new direction. As a result the subjects could not use this strategy after the COM passed the stance foot. The existence of push-off power is also advantageous to put spin on the body so the spin turn is restricted to less of the cycle than the step turn. BF activity of the swing leg initiates hip extension and external rotation. The action of BF and the hip adductor muscles should move the swing leg toward the midline with toe outward (Fig. 1A). This foot placement reduces the COM displacement in the frontal plane needed to change direction. As the extensor synergy of the forward leg supports the weight, push-off by the opposite leg produces a spin force. While changing direction,

FIG. 8. Comparison between responses after right heel contact during (A) stopping and (B) turning right. Time scale is different from Fig. 7. The flat sections in some EMG traces (near time 0) were created by removing the stimulus artifacts digitally. There are extra activities of GM (1) and ES (2) in turning, which are discussed, respectively, in RESULTS and DISCUSSION (DECCELERATION MECHANISMS FOR TURNING). The second BF activity in stopping (3) is to keep the backward leg behind the body in the termination style (Hase and Stein 1998).

FIG. 9. Schematic diagrams of (A) spin turns and (B) step turns, when the cue was applied near heel strike during turning right. ⋯⋯ left leg. In each part the first diagram shows the time of stimulation, the second shows the deceleration phase, and the third shows the turning mechanisms.
GM activity in the stance leg should help to elevate the opposite side of the pelvis. Hip flexor muscles in the swing leg may produce a rotating power, as in running (Montgomery et al. 1994). The duration of rotating the body on the axial leg varied even within the same part (e.g., part 8 in Fig. 2), so the relation between the inertia and the propelling forces was presumably less stable in the spin turn. Therefore it is not always used, unlike the step turn (Fig. 3).

Step turn (Fig. 9B)

This strategy is easier and more stable for the subject because of the base of support while changing direction is much wider than for the spin turn. We can see a constant step rhythm during changing direction in the subjects who always used the step turn (e.g., part 8 in Fig. 4). The activity of SOL after BF and ES provides a deceleration force at first. As a result, the trunk should remain in a more posterior position. Elevation of the opposite side of the pelvis by GM as well as inversion of the ankle by TA can contribute to moving the COM toward the turning direction. GM activity reaches a peak just before the opposite foot strike. When the extensor synergy provides a braking force, the knee of the trailing leg is flexed so the hip can easily rotate externally to change direction. TA activity keeps the ankle in dorsiflexion. The extension of the knee and ankle as well as abduction of the hip in the forward leg produce a step toward the new direction.

Recently, Patla et al. (1999) reported that changing direction during ongoing locomotion primarily required control of the COM. Two mechanisms, foot placement and trunk roll motion, were used for moving the COM, and head reorientation followed. They pointed out that the COM trajectory for changing direction is controlled either through appropriate foot placement, when the cue to alter the direction is given at the beginning of gait, and/or by using the hip strategy described by Horak and Nashner (1986). By decelerating the forward momentum, the subject can use all the strategies for changing direction within one step, in spite of an additional demand to control deceleration. The very similar patterns in initial EMG responses indicate the close relation between the motor control mechanisms for stopping and turning (Fig. 8). Therefore by comparing them the neural mechanisms for the turning strategy can be clarified.

Deceleration mechanisms for turning

Basically, the initial process of decelerating gait speed for turning is similar to rapid stopping (Hase and Stein 1998), although subjects did not come to a full stop. Also, to facilitate a step toward the new direction, another deceleration mechanism must be initiated for keeping the COM in a more posterior position than in stopping. In the stopping task, the trunk muscles only work to prevent the torso from falling forward, so they are activated just before the opposite foot strike to produce a braking force (Fig. 8A). On the other hand, in turning there is another peak of ES during the stance phase (Fig. 8B). This activity may help to stabilize the trunk (including head and arms) over the supporting hip to control the COM. The activation pattern from SOL to BF to ES agrees with the so-called ankle strategy in postural control during forward sway (Horak and Nashner 1986). This deceleration mechanism may play a crucial role in making the following foot placement and trunk rotation easier (Fig. 9).

Foot placement for turning

In the spin turn, BF activity of the swing leg may initiate hip extension and abduction and so quicken the foot placement. In the late swing phase, the hip/knee moment arm of biarticular hamstring muscles in the swinging leg can effectively reduce the forward momentum of the body (White 1986). Other hip extensor muscles such as gluteus maximus and hip adductor muscles are also activated at the same time. As a result the foot is placed toward the midline in a toe-out position (Fig. 1A). This foot placement would result in a reduction in acceleration of the COM toward the direction opposite to the turn (Patla et al. 1999). Also, this strategy is available for stepping, when the cue is given during the midswing phase of the trailing leg (e.g., part 13 of right turn).

Trunk rotation for turning

In addition to positioning the foot, the control of the COM in the frontal plane during walking is achieved through appropriate action of the ankle inverters/evertors and by balancing the trunk and swing leg over the supporting hip (MacKinnon and Winter 1993). The action of the former is not very effective in the frontal balance control during walking because of the large moment of inertia of the body about the ankle and the limited force capability of the ankle muscles. In the turning task, they may work more effectively in synergy with hip abductor muscles because the forward movement is already slowed by the ankle strategy, as described previously. In the stepping strategy, the ankle inversion by TA, with the hip abduction by GM, may provide a lateral shift of the knee as well as a braking effect and an initiation of a pelvic rotation. Additionally, hip abductor muscles in the stance leg control the duration for swing of the opposite leg. We found that GM activity was closely related to the timing of the opposite foot strike. Because the moment arm of the anterior segment of GM for hip abduction is decreased, when the hip flexion angle is increased (Soderberg and Dostal 1978), it has little potential for abduction during early stance phase. Therefore GM activity in the late stance phase is more effective for hip abduction. A burst of BF preceding GM may provide a quick hip extension and help the action of GM. Similarly, in the spin turn, the action of hip abductor muscles is used for rotating the body.

Significance

The task of quickly turning the body, once a cue occurs at a random point in the step cycle, while still maintaining balance and some momentum is extremely complex. The body appears to use a number of simplifications to solve this complex problem. First, a series of responses for turning is initiated by a deceleration mechanism that was previously described for the rapid stopping task (Hase and Stein 1998). The leg that ends up in front rapidly initiates a broad extensor synergy to brake the forward momentum, and the trailing leg shows a flexor synergy, which reduces the push-off power. Second, while braking is occurring, human subjects quickly choose one of two general turning mechanisms (the spin turn or the step turn). The forward leg then assumes a role as the axis of rotation. Rotation
is already initiated, whereas some momentum remains to assist turning rather than stopping and then turning. Thus, within a few tenths of a second, braking flows into a turning strategy that is essentially complete within a single step cycle. Finally, the process is so smooth that walking continues in the opposite direction for many subjects with little or no change in the timing that would have occurred in the absence of a cue to turn. Grafting these triggered EMG patterns or synergies on the walking rhythm allows the body to be turned quickly and safely whenever the cue occurs in the cycle.

This research was supported by the Neuroscience Network of Centers of Excellence and the Medical Research Council of Canada.

Address for reprint requests: R. B. Stein, Division of Neuroscience, University of Alberta, 513 Heritage Medical Research Centre, Edmonton, Alberta T6G 2S2, Canada.

Received 28 September 1998; accepted in final form 10 February 1999.

REFERENCES


