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RESEARCH NOTE

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Online steering: coordination and control of body center of mass, head and body reorientation

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Abstract Steering is an integral component of adaptive locomotor behavior. Along with reorientation of gaze and body in the direction of intended travel, body center of mass must be controlled in the mediolateral plane. In this study we examine how these subtasks are sequenced when steering is planned early or initiated under time constraints. Whole body kinematics were monitored as individuals were required to change their direction of travel by varying amounts when visually cued either at the beginning of the walk or one stride before. The analyses focused on the transition stride from one travel direction to another. Timing of changes (with respect to first right foot contact) in trunk roll angle, head and trunk yaw angle, and right foot displacement in the mediolateral plane were analyzed. The magnitude of these measures along with right and left foot placement at the beginning and right foot placement at the end of the transition stride were also analyzed. The results show the CNS uses two mechanisms, foot placement and trunk roll motion (piking action about the hip joint in the frontal plane), to move the center of mass towards the new direction of travel in the transition stride, preferring to use the first option when planning can be done early. Control of body center of mass precedes all other changes and is followed by initiation of head reorientation. Only then is the rest of the body reorientation initiated.

Key words Steering control · Human locomotion · Center of mass · Head orientation · Body orientation

Introduction

Steering is an integral component of the locomotor control system. Steering around an obstacle or an undesirable surface preserves dynamic stability, and provides for goal-directed locomotion. Unlike other adaptive strategies such as step length and step width regulation which are successfully implemented within a step cycle, direction change must be planned and initiated in the step before (Patla et al. 1991). Steering at its most basic level requires reorientation of the body in the direction of intended travel. Online control of steering (without termination of ongoing locomotion) will require the control of body reorientation embedded within other modifications of the structure of the ongoing step cycle.

Among the other modifications are step width regulation, requiring movement of body center of mass (COM) in the direction of travel and possibly independent control of head orientation to see where you are going (Gibson 1958; Grasso et al. 1996) before initiating body reorientation. Since a large proportion of the body mass is concentrated in the upper body, control of trunk yaw motion will dominate body reorientation. As expected, steering involves control of axial moment and modulation of the mediolateral component of the ground reaction force under the stance foot (Patla et al. 1991). Therefore steering represents a challenging task for the locomotor control system and our objective is to explore how these various subgoals are coordinated and controlled to successfully steer under different planning time constraints. Once effects of available response time on the emergent movement strategies are determined, effects of additional constraints such as risk of potential threat to stability and/or additional visual search of the new travel path can be evaluated.

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Materials and methods

Participants

Six healthy male adults (age 22.5±2.1 years, height 182.1±5.9 cm, weight 77.6±5.5 kg) volunteered for the study. The experimental protocol was approved by the University of Waterloo Ethics Committee and informed consent was given by all participants. Exclusion criteria included any self-reported neurological, musculoskeletal or visual impairment.

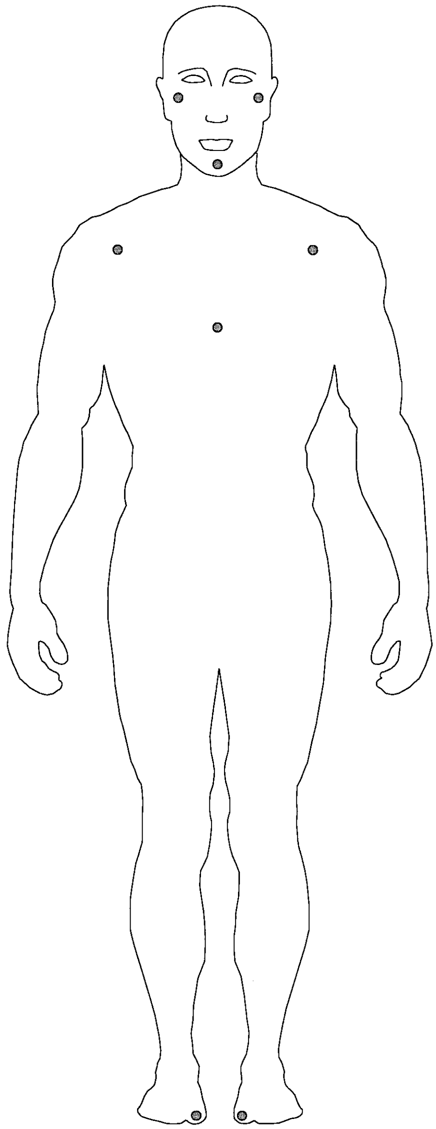


Fig. 1 Placement of the infrared diodes on the participant are shown. Note three non co-linear markers were placed on the head and trunk to model the segment as a rigid body

Protocol

Eight infrared diodes were placed on the following anatomical landmarks: lateral border of each eye, the chin, each acromion, the xiphoid process, and each toe (anterior border of the first metatarsal) (see Fig. 1). These active markers were tracked using the Optotrak motion analysis system (Northern Digital Inc., Canada). Participants walked at their natural self-selected pace along a 9-m straight travel path. Stride duration nevertheless was similar across all participants with variability of less than 7% (standard deviation/mean). Randomly during 50% of the trials, they were visually cued to alter their direction of travel at the midpoint of the travel path. The magnitude of direction change was either 20°, 40°, or 60° to the right. Path direction was specified through appropriately positioned light cues on a board placed at eye level at the end of the straight travel path. Light cues were activated when the participant stepped on a pressure-sensitive mat. One mat was positioned at the start such that the visual cue about a direction change was available when the participant started walking; while the second mat was positioned one step length before the midpoint of the straight travel path such that the participant had one stride duration (two steps) to plan and implement a direction change. Five trials for each experimental condition were collected along with 30 trials for the straight path condition. All trials were randomized. The experimental setup is shown in the left panel of Fig. 2.

Data analysis

The stride from right foot contact before direction change (first right foot contact, RFC1) to the subsequent right foot contact after direction change (second right foot contact, RFC2), subsequently referred to as the transition stride, was clipped and several kinematic measures were obtained. Pitch, roll and yaw angular displacement profiles of the trunk and the head in the global reference frame were determined from the three non-co-linear markers placed on the trunk and the head. The three markers define the rigid body of the trunk and the head, making it possible to determine their orientation with respect to gravito-inertial frame. From these profiles (Fig. 1) the following measures were determined: onset of change in the head and trunk yaw motion (referenced to RFC1); head and trunk initial and final (at RFC1 and RFC2 respectively) roll and yaw angles. From toe displacement profiles, the following measures were extracted: onset of change in the right foot displacement along the mediolateral axis (referenced to RFC1), right foot placement (RFC1), subsequent left foot contact, and initial and final step width (at RFC1 and RFC2 respectively). A repeated measures ANOVA was performed on each measure with the significance level set at 0.005 (adjusted for the number of measures analyzed). Depending on the measure the number of levels in the ANOVA varied; the levels are described in “Results.”

Results

Before we describe the results in detail, it would be worthwhile to explain typical profiles of the head and trunk yaw, trunk roll and right foot displacement in the mediolateral direction (Fig. 1). During normal straight path locomotion, head and trunk yaw displacement are minimal, and right foot trajectory has minimal deviations in the mediolateral plane (see thin solid lines in Fig. 1). Trunk roll movements show a cyclical pattern during normal straight path locomotion (less than ±3°): trunk deviates to the right during the right stance phase and to the left during the left stance phase. When participants are required to change direction to the right, as expected head and trunk rotate to the right (yaw angle deviations in the clockwise directions) to reorient the body in the direction of travel, and the right foot trajectory shows displacement to the right during the swing phase to control foot placement on the new travel path. In addition we see trunk movements to the left (roll angle deviations to the left). Because of the nature of the task, no significant changes in the sagittal plane were expected; therefore the pitch profiles are not included in Fig. 1. The following significant results were obtained.

Sequencing of the changes in various parameters showed an interaction effect of parameter by visual cue time ($F_{(3,15)}$=8.90, P=0.0012) and parameter by direction change magnitude ($F_{(6,30)}$=9.58, P=0.0001). These effects seen in the time profiles of Fig. 3 are summarized in Fig. 4 and show that for the late cue condition trunk roll change precedes all other changes. For both cue conditions, change in head yaw is followed by change in

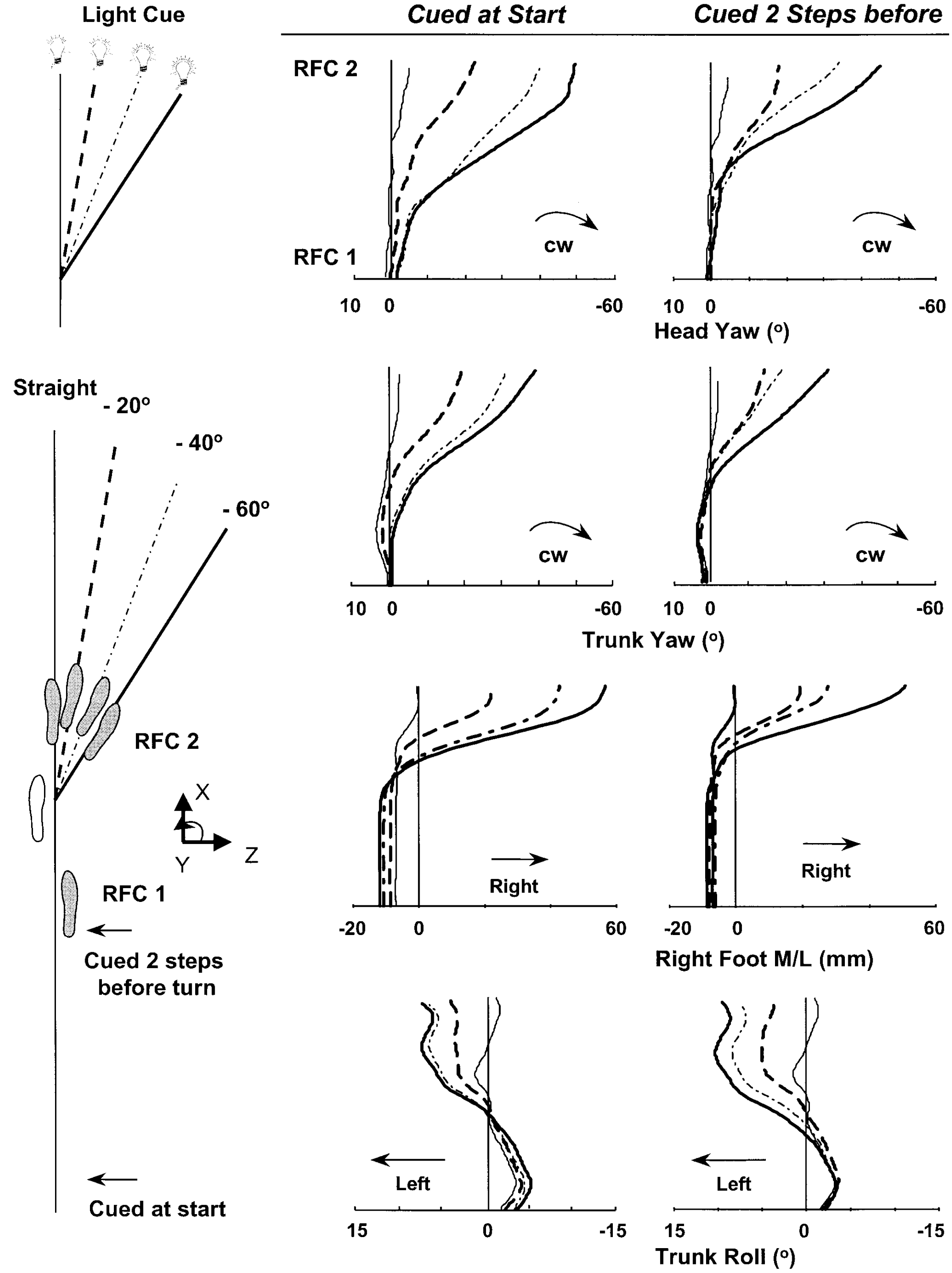


Fig. 2 Time-normalized ensemble profiles over the five trials of head yaw, trunk yaw, trunk roll and right foot displacement in the mediolateral plane for the transition stride [first right foot contact (*RFC1*) to the second right foot contact (*RFC2*)] are shown for one individual for various experimental conditions. *The left panel* shows a schematic diagram of the experimental setup (*CW* clockwise rotation). The reference coordinate system is shown: note yaw angle in the CW direction, roll to the left and pitch forward result in a negative angular displacement

trunk yaw and a change in foot displacement which always occurred at right toe-off. For larger direction change magnitude, the sequencing of trunk roll and head yaw is similar to late cue condition.

Stride length showed a main effect of direction change magnitude ($F_{(2,10)}$=124.69, P=0.0001) with stride length reduced as the magnitude of direction change increases (0°: 148 cm; 20°: 138 cm; 40°: 128 cm; 60°: 115 cm). Head and trunk pitch angle at RFC1 and RFC2 were not significantly affected by the available response time. Only the trunk pitch angle at RFC2 was significantly modulated as a function of the magnitude of the direction change ($F_{(2,10)}$=46.24 P<0.0001; 20°: –17.7°; 40°: –14.93°; 60° –12.3°). Because the task does not require any large changes in the body movements in the sagittal plane, these results are understandable. Trunk roll displacement at the end of the stride (RFC2) also showed a significant main effect of direction change magnitude ($F_{(2,10)}$=29.92, P=0.0001); the trunk angular displacement towards the left increased as a function of direction change magnitude (0°: 1.62°; 20° ~4.24°; 40° –7.91°; 60° –10.9°). Head yaw and trunk yaw deviations from the actual magnitude of direction change (angular displacement achieved minus the desired direction change level) at the end of the stride showed a significant main efrect of direction change magnitude

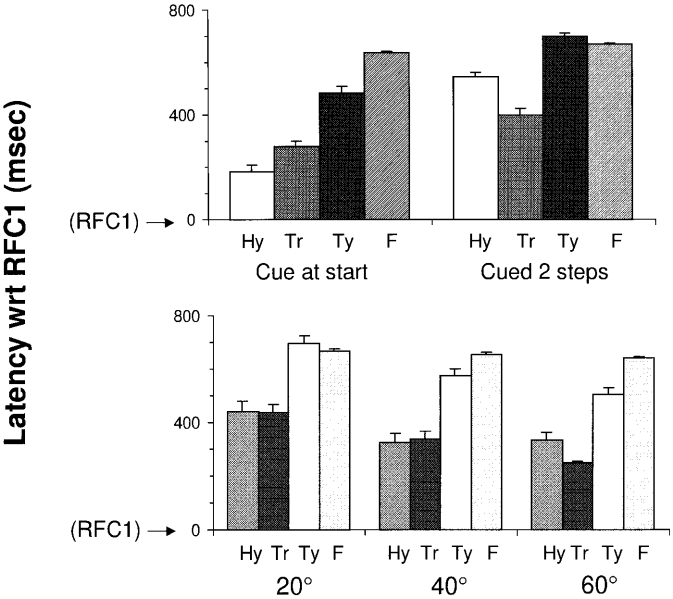


Fig. 3 Initiation of head yaw (*Hy*), trunk roll (*Tr*), trunk yaw (*Ty*) and foot mediolateral displacement (*F*) with respect to initiation of the transition stride (*RFC1*) is summarized as a function of visual cue time (*top panel*) and direction change magnitude (*bottom panel*). The average value across participants plus one standard error is shown

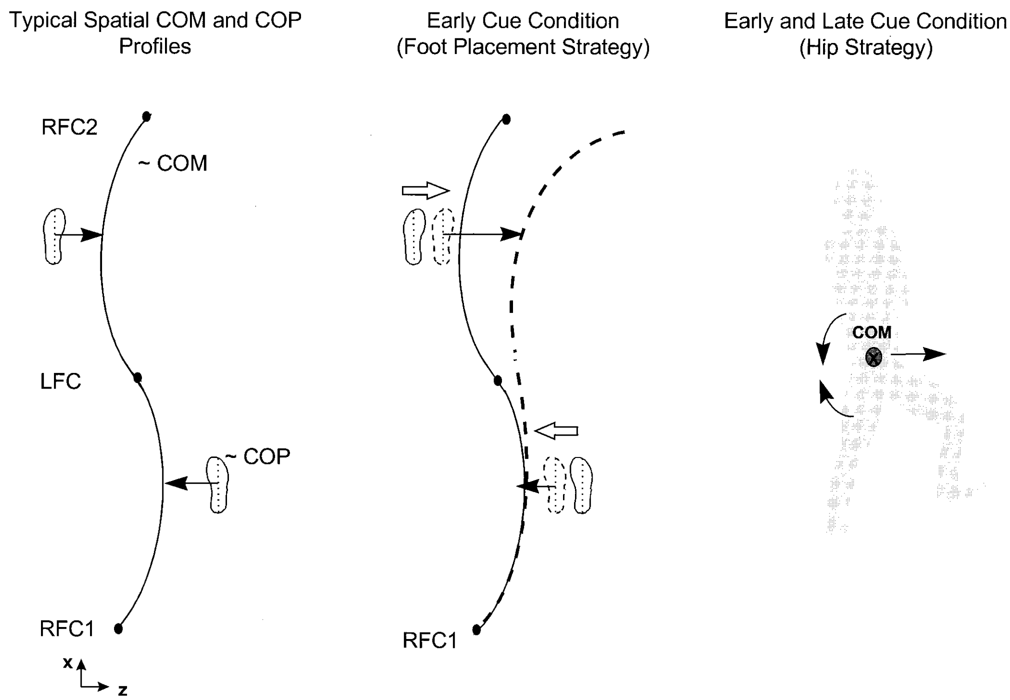
($F_{(2,10)}$=79.40, P=0.0001). These results show that yaw angular deviations are smaller for the smaller direction change magnitude (20°: +3.65°; 40°: 1.04°; 60° –8.02°).

Right foot placement at the beginning of the stride showed a main effect of visual cue time ($F_{(1,5)}$=33.0, P=0.0022). The right foot was placed further to the left when the cue was given at the start (see Fig. 1; 0: –92.5 mm; early cue: –120 mm; late cue: –93.6 mm), while the foot placement for the late cue condition was not different from the control condition as expected. Trunk roll displacement at the end of the stride also showed a significant main effect of direction change magnitude ($F_{(2,10)}$=29.92, P=0.0001); the trunk angular displacement towards the left increased as a function of direction change magnitude (0°: 1.62°; 20°: –4.24°; 40°: –7.91°; 60°: –10.9°). The step width (right foot placement at the end of the transition stride minus right foot placement at the beginning of the transition stride) showed a main effect of visual cue time ($F_{(1,5)}$=23.92, P=0.0045) and direction change magnitude ($F_{(2,10)}$=177.14, P=0.0001); stride width was larger for the early cue condition (536 mm vs 474 mm) and was as expected increased as a function of the direction change magnitude (20°: 314 mm; 40°: 525 mm; 60°: 676 mm).

Discussion

A new direction of travel can be achieved by coming to a stop, reorienting your body to the new direction and proceeding to walk. This strategy involves no changes in step width. During normal travel, this discretization of the movement components is not the norm but an exception. Instead, as observed in this study, reorientation of the body is carried out online during the transition from one direction to another without interruption in walking. All changes are primarily initiated within one stride. We classified the changes made to the whole body kinematics into three broad categories related to control of body COM in the mediolateral plane, orientation of the visual system and orientation of the body. How these components are sequenced and achieved is discussed next.

Fig. 4 The two mechanisms foot placement and hip strategy to control COM in the direction of travel (*to the right*) are described. The vector connecting COP (*under the foot*) and corresponding COM determines magnitude and direction of COM acceleration. Key temporal events in a stride (right and left foot contact, *RFC* and *LFC*) are superimposed on the spatial trajectory of the COP and COM



Control of body center of mass in the new direction of travel is initiated first through appropriate foot placement and/or trunk roll motion: The body COM in the mediolateral plane can be regulated by controlling foot placement (in swing phase) and control of the body pendulum through appropriate action of ankle inverters/evertors and hip and trunk musculature (in stance phase) (McKinnon and Winter 1993; Winter 1995).

Consider first the foot placement at initiation of the transition stride. Foot placement is the primary determinant of the position of the center of pressure (COP); difference between the COP and COM dictates the center of mass acceleration magnitude and direction (Winter 1995). Typical COP and COM spatial profiles are shown in Fig. 3a. When the right foot makes contact the acceleration in the mediolateral direction is towards the left shown by the vector connecting the COP with the COM. If the right foot is placed to the right of normal foot placement through appropriate control during the swing phase, then the acceleration towards the left can be increased and vice versa. As expected when the cue is given two steps before (at right foot contact), the right foot placement is not different from the straight path condition. But for the early cue condition, individuals can and do alter the right foot placement; the foot is placed to the left of the normal foot placement thereby reducing the acceleration of the COM towards the left (see Fig. 3b). This reduction in acceleration towards the left will alter the center of mass trajectory and move it more towards the right. Since the direction change is to the right, this strategy is appropriate. Subsequent left foot contact can also be altered to modulate COM acceleration. But if the left foot is placed further to the left to increase the acceleration of the COM to the right, subsequent left swing phase will be compromised. Therefore, this strategy is not used in either cue conditions.

A second strategy for moving the COM towards the right in the transition stride is by controlling the body pendulum in the stance phase. This can be done by controlling the inverted pendulum in the frontal plane through the activity of the ankle inverters/everters; since these muscles are relatively weak and the inertia of the pendulum is large, this strategy is not very effective (Winter 1995). Rather individuals move the body COM through muscle action at the hip and trunk, the so-called hip strategy (see Horak and Nashner 1986). The body is controlled as a double pendulum with the lower limbs and the upper body moving in opposite directions (see Fig. 3c), resulting in the COM moving towards the right. This strategy is captured in the trunk roll motion. For both visual cue conditions, the trunk was displaced to the left with the action initiated at the end of the right stance phase (see Fig. 1) and continuing in the left stance phase. This hip strategy initiated during the right stance phase is completed in the left stance phase while the right foot is in the swing phase. The trunk roll displacement at the end of the transition stride (RFC2) is towards the left. The only difference between the two visual cue conditions is that trunk roll is initiated earlier for the early cue condition; since the amplitude changes are identical, this would result in smaller displacement velocity (same amplitude over longer duration) of the COM. Thus the hip strategy contributes less to the COM displacement for the early cue condition since foot placement strategy is available and is used to control the COM.

Therefore, the control of COM towards the new direction of travel is initiated first either through foot placement when possible (early cue) or through trunk roll motion (late cue).

Turning the head in the direction of travel is initiated next: Seeing where you are going is obviously an important and necessary component of steering control (Gibson 1958; Grasso et al. 1996). Orienting the visual system to the new direction of travel can be accomplished by rotating the eyes, and/or the head and/or the trunk. In this study we only monitored head and trunk movements. Eye movements rather than head movements are used to redirect gaze only when body orientation is not altered (Patla and Vickers 1997). If only eye movements are used to redirect gaze during direction change, then further scanning of the travel path will be compromised by the eccentric position of the eye within the head. Head movements are therefore important when gaze orientation has to be altered along with whole body orientation as in steering. Besides gaze orientation, turning the head in the direction of travel shifts the frame of reference for subsequent sensorimotor transformation (visual to motor and vestibular motor).

Head reorientation can simply be a consequence of whole body reorientation. That the head yaw motion is initiated before trunk yaw motion suggests that reorientation of gaze takes precedence (Fig. 2). This is similar to the findings by Grasso et al. (1996), who found that anticipatory head movements were initiated about 200 ms prior to direction change. Head rotation preceding trunk rotation can simply result from different inertial characteristics of the head and trunk (Biguer et al. 1982). The different onset times for the head yaw motion and similar onset times for the trunk roll motion for the two cue conditions and the differential effects of direction change magnitude on head and trunk yaw motion onset (Fig. 2) suggest a more active control by the CNS to reorient the head first (see also Carnahan and Marteniuk 1991).

Orientation of the whole body is initiated last by trunk orientation in the direction of travel: Trunk yaw rotation is initiated close to right toe-off (see Figs. 1, 3) and the reorientation completed during the right swing phase. Torsional moment which produces this trunk rotation has been documented (Patla et al. 1991). The whole body reorientation follows changes that control body COM and orientation of the visual system.

Conclusions

The complex sequence of changes involved in online control of steering during locomotion show that control of COM in the mediolateral plane takes precedence over all other changes. This control is achieved either through appropriate foot placement when cue is available early and/or through the use of hip strategy to move the COM in the direction of travel. Head reorientation follows the center of mass changes, and only then is body reorientation initiated.

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References

Biguer B, Jeannerod M, Prablanc C (1982) The coordination of eye, head and arm movements during reaching at a single visual target. Exp Brain Res 46:301–304

Carnahan H, Marteniuk RG (1991) The temporal organization of hand, eye, and head movements during reaching and pointing. J Motor Behav 23:109–119

Gibson JJ (1958) Visually controlled locomotion and visual orientation in animals. Br J Psychol 49:182–189

Grasso R, Glasaver S, Takei Y, Berthoz A (1996) The predictive brain: anticipatory control of head direction for the steering of locomotion. Neuroreport 7:1170–1174

Horak FB, Nashner LM (1986) Central programming of postural movements: adaptation to altered support surface configurations. J Neurophysiol 55:1369–1381

MacKinnon CD, Winter DA (1993) Control of whole body balance in the frontal plane during human walking. J Biomech 26:633–644

Patla AE, Vickers J (1997) Where and when do we look as we approach and step over obstacles in the travel path. Neuroreport 8:3661–3665

Patla AE, Prentice S, Robinson C, Neufeld J (1991) Visual control of locomotion: strategies for changing direction and for going over obstacles. J Exp Psychol: Hum Percept Perform 17: 603–634

Winter DA (1995) Anatomy, biomechanics and control of balance during standing and walking. Waterloo Biomechanics, Waterloo, Ontario