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Attentional demands for static and dynamic equilibrium

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Abstract. Upright standing and walking tasks require the integration of several sources of sensory information. In a normal and highly predictable environment, locomotor synergies involving several muscles may take place at lower spinal levels with neural circuitry tuned by local loops of assistance or self-organizing processes generated in coordinative networks. When ongoing regulation of gait is necessary (obstacles, changes in direction) supraspinal involvement is necessary to perform movements adapted to the environment. Using a classical information processing framework and a dual-task methodology, it is possible to evaluate the attentional demands for performing static and dynamic equilibrium tasks. The present experiment evaluates whether the attentional requirements for a control sitting condition and for standing and walking conditions vary with the intrinsic balance demands of the tasks. The results show that standing and walking conditions required more attention than sitting in a chair. The attentional cost for walking was also significantly greater than for standing. For the walking task, reaction times when subjects were in single-support phase (small base of support) were significantly longer than those in double-support phase, suggesting that the attentional demands increased with an increase in the balance requirements of the task. Balance control requires a continuous regulation and integration of sensory inputs; increasing balance demands loads the higher level cognitive system.

Key words: Posture – Walking – Attentional requirements – Supraspinal control – Human

Introduction

The maintenance and control of posture and balance, whether in static or dynamic conditions, are essential requirements for daily activity. From a biomechanical standpoint, static and dynamic balance are strikingly different. In static conditions (i.e. unperturbed standing), the maintenance of balance is often modeled as an inverted pendulum with the controlled value being the projection onto the ground of the center of gravity. On the other hand, dynamic balance during gait, although still requiring control over the center of gravity, does not require the center of gravity to lie within the area delimited by the foot (Shimba 1984; Winter et al. 1990; Winter 1991). Control is achieved by reaching new positions across a given trajectory (Massion 1984).

The underlying mechanisms responsible for the automatic production of the basic rhythm responsible for locomotion have been studied extensively. Models of networks of interneurons (central pattern generators) producing rhythmical, patterned locomotor movements have been proposed (Pearson 1976; Grillner 1975, 1981; Cohen 1988). These observations, however, do not negate the importance of afferent information for locomotion (Rossignol and Drew 1985; Rossignol et al. 1988). Indeed, when afferent inputs are available, the system can modulate reflex responses (e.g. Forssberg 1979; Carter and Smith 1986). Nevertheless, there have been suggestions that in a normal and highly predictable environment, an elaborate locomotor synergy between the different muscles can take place at lower spinal levels with neural circuitry tuned by local loops of servo-assistance or self-organizing processes generated in coordinative networks (e.g. Cappozzo et al. 1976; Mochon and McMahon 1980; Grillner 1981; Turvey and Kugler 1984; Warren et al. 1986; Kelso and Schöner 1988; Rossignol et al. 1988; Schöner et al. 1990).When the locomotor task requires modification of the stereotypical pattern (e.g. changes in direction, speed, obstacle avoidance, precise foot placement), supraspinal inputs are necessary to perform movements adapted to the environmental context (e.g. Armstrong 1988; Drew 1988; Patla 1991; Dietz 1992). For example, Armstrong (1988) has shown that, compared to normal walking, the discharge rate of Purkinje cells increases when a cat is required to walk precisely on a horizontal ladder. Similarly, Drew (1988) has ob-

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served an increased discharge rate of pyramidal tract neurons in motor cortex when precise foot placement was required. Several observations of gait following brain lesions also suggest the important role of supraspinal inputs for the control of gait [see Dietz (1992) for a recent review]. Accidentally spinalized humans do not show stepping movements, and brain lesions yield characteristic changes of neuronal control of posture and locomotion. Although these observations remain phenomenological in nature, they suggest a greater dominance of supraspinal over spinal mechanisms for humans than for animals (e.g. Armstrong 1988; Patla 1991; Dietz 1992).

In a more general sense, several authors have recently stressed the importance of studying the links between spinal and supraspinal mechanisms (e.g. Paillard 1985, 1988; Posner and Petersen 1990; Sperry 1988). For example, Sperry (1990) has suggested that, to fully explain human movement, researchers need to account for emergent and previously unknown properties interacting at their own higher level and also exerting causal control from above downward. If higher cognitive systems are necessary for controlling and regulating gait, a less stable postural position could require more attention than a stable postural position. When an unstable position is identified or achieved (whether for an upright standing or a walking condition), a corrective response needs to be subsequently organized at a supraspinal level (Stelmach and Worringham 1985; Teasdale et al. 1992, 1993). Dual-task methodology has been used to assess the attentional demands necessary for performing a primary task. Briefly, this methodology has three basic underlying assumptions: (1) there is a limited central processing capacity, (2) performing a task requires part of the limited processing capacity within the central nervous system and (3) if two tasks both share the processing capacity, the performance in one or both tasks can be disturbed if the limited central processing capacity is exceeded (Kahneman 1973; Parasuraman 1981). Using this general approach, several authors have demonstrated that maintaining an upright posture requires some attention. For example, Stelmach et al. (1990) reported that, when simple single-digit additions were performed concurrently with an arm-swinging task, postural recovery following the arm-swinging task yielded a larger sway range for elderly than for younger subjects. Kerr et al. (1985) showed that young adults' performance on a memory task decreased when they were asked to maintain a difficult standing position (tandem Romberg stance). More recently, Geurts et al. (1991, 1992) observed that postural stability of lower limb amputees was greatly affected by a concurrent attention demanding task (Stroop task). Finally, Teasdale et al. (1993) reported that elderly persons responded with greater delay to an unpredictable auditory stimulus when their center of foot pressure was in an eccentric position than when it was near a central, and presumably more stable, postural position. These findings suggest that the mechanisms responsible for regulating postural stability interact with high-level cognitive systems and share similar attentional resources.

Using similar methodology, Bardy and Laurent (1991) demonstrated that walking requires more cognitive processing than simple sitting or upright standing posture (see also Girouard 1980). Moreover, walking towards a small target required more attention than walking towards a large target (located at eye level). Their results are reminiscent of similar observations made by Posner and Keele (1969) for wrist movements made at small and large targets. Bardy and Laurent's (1991) findings are important because, even though walking is a highly practiced task that is performed in a constant and predictable environment, it still requires some cognitive processing. Overall, the above experiments clearly demonstrate that balance control, both in static and dynamic conditions, may require cognitive processing. Despite mechanical distinctions, it is possible that static and dynamic balance evaluation share similar neural mechanisms – whether the frame of reference is constructed through evaluations of the position of the center of gravity or through head stabilization, as suggested by Pozzo et al. (1990). For both tasks, visual, vestibular and proprioceptive inputs are integrated to establish appropriate egocentric and exocentric frames of reference, and the distinction between static and dynamic balance may correspond to two different context-dependent strategies for preserving equilibrium (Paillard 1988). The aim of this experiment was to determine whether the attentional demands for a control sitting condition and for standing and walking conditions vary with the intrinsic balance requirements of the task. For standing upright, the attentional requirements were evaluated when subjects adopted a narrow or a broad base of support. For walking, the attentional requirements were evaluated when subjects were in single support and double support phase. The single support phase involves limb oscillation and requires adequate foot trajectory and placement; these specific requirements may demand more attention than the double support period liable to serve as a restabilizing phase.

Preliminary data were presented at the International Symposium on Gait and Posture, Portland, May 1992.

Materials and methods

Subjects

Six healthy subjects, five men and one woman, age 20–30 years (mean 26 years), participated in the experiment. None of them was familiar with the purpose of the experiment. They all gave informed consent to participate.

Tasks and apparatus

All subjects performed four tasks: (1) sitting, (2) standing upright with a broad base of support (shoulder width apart), (3) standing upright with a narrow base of support (feet together) and (4) walking. The four tasks were randomly presented to subjects to avoid any learning and task effects. The walking condition was performed on an 8-m long pathway covered with aluminum wire netting. Shoe covers were set with conductive material fixed under the heel and toes of each foot. Contacts with the wire netting were coded digitally to provide accurate temporal values corresponding to the onset and offset of right and left single-support and double-support phases. The left foot displacement was recorded with a 3D Selspot two-camera system. The sampling rate was 500 Hz and cameras were positioned on the left side of subjects [20 feet (6.1–m) from the subjects, 27 feet (8.2–m) apart]. This camera placement allowed the recording of a little more than one complete walking cycle. To insure stable gait, only results of the third walking cycle among the seven cycles that the walking platform permitted, were kept for analysis. For all tasks, subjects wore a helmet equipped with a microphone. The analog signal from the microphone was used to detect the onset of the verbal responses. Signals from foot contacts and the microphone were sampled at 500 Hz and temporally synchronized with the kinematics data.

Procedures

In addition to sitting, standing and walking, subjects were asked to give a verbal response ("top") to an unpredictable auditory stimulus. A verbal warning preceded each trial. Reaction time (RT) was defined as the temporal interval between the presentation of the auditory stimulus and the onset of the verbal response (detected from the analog signal). For the sitting and standing tasks, 20 stimuli were given following one of five randomly presented preparatory periods: 3, 3.5, 4, 4.5 and 5 s. A chair without an armrest was used for the sitting task. Subjects adopted their preferred position for the broad-support task and kept their feet together for the narrow-support task. For the walking task, subjects selected their preferred pace and were allowed to familiarize themselves with the walking environment (five to ten practice trials). After these trials, ten trials (control condition) were presented at the beginning of the experiment. For these trials, subjects were aware that no stimulus would be given. These trials served to establish the subjects' normal walking behavior. Furthermore, subjects performed 56 additional walking trials (i.e. eight trials × three cycles × two stance conditions and eight catch trials); stimuli were presented randomly in the second, third or fourth walking cycle on left foot toe off (i.e. at the onset of the single support condition) or on left foot heel contact (i.e. at the onset of the double support condition). The eight catch trials (i.e. without stimulus) were presented randomly to prevent any anticipation. As for the sitting and standing tasks, the stimuli were given 3–5 s after walking onset.

Results

Gait characteristics for the control trials and the Probe-RT trials

An essential prerequisite of the double-task methodology was to make sure that the addition of the Probe-RT procedure (i.e. the verbal response to the auditory stimulus) does not affect the walking behaviour (primary task). When the primary task is unaffected, it is assumed that an increased RT reflects an increased attentional load (Abernethy 1988). Table 1 presents cycle length and cycle duration and Table 2 presents average speed and cadence for the walking cycles obtained for the control condition and when probes were given in single support and double support. The different dependent variables were submitted to a one-way analysis of variance (ANOVA) with repeated measures (control, single stance, and double-stance conditions). No difference was observed across conditions ($F_{2,10}$ = 3.24, 0.02, 2.23, and 0.93, $P > 0.05$, for cycle length, duration, speed and cadence, respectively). These data compare well with those reported by Winter (1991) for a similar population (e.g. cycle length of 1.54 m, speed of 1.40 m/s, cadence of 109.0 steps/min, compared with Winter's cycle length of 1.56 m, speed of 1.43 m/s, and cadence of 110.5 steps/min). The heel displacement in the direction of progression (anterior-posterior plane) also was examined for the third walking cycles. Figure 1 illustrates for one representative subject the heel displacements of the left foot obtained (a) without probe (control condition) and when probes were given in (b) single stance and (c) double stance conditions. For all subjects, no difference was observed between conditions, suggesting that the Probe-RT procedure did not affect the gait pattern of our subjects. Therefore, the RT data

Table 1. Cycle length and cycle duration for the different experimental conditions

Subject	Cycle length (mm)			Cycle duration (ms)		
	SS	DS	Control	SS	DS	Control
1	1501	1484	1484	1114	1127	1129
2	1606	1605	1598	1108	1098	1095
3	1298	1299	1282	1037	1032	1044
4	1797	1789	1799	1084	1084	1094
5	1590	1600	1594	1124	1127	1128
6	1486	1484	1473	1128	1141	1119
Average	1546.3	1543.5	1538.3	1099.2	1101.5	1101.5

SS, single-limb support stance phase; DS, double-limb support stance phase

Table 2. Speed and cadence for the different experimental conditions

Subject	Speed (m/s)			Cadence (step/min)		
	SS	DS	Control	SS	DS	Control
1	1.35	1.31	1.31	107.7	106.5	106.3
2	1.45	1.46	1.46	108.3	109.2	109.6
3	1.25	1.26	1.23	115.7	116.3	114.9
4	1.66	1.65	1.64	110.7	110.7	109.6
5	1.41	1.42	1.41	106.8	106.5	106.4
6	1.32	1.30	1.32	106.4	105.2	107.2
Average	1.41	1.40	1.39	109.3	109.1	109.0

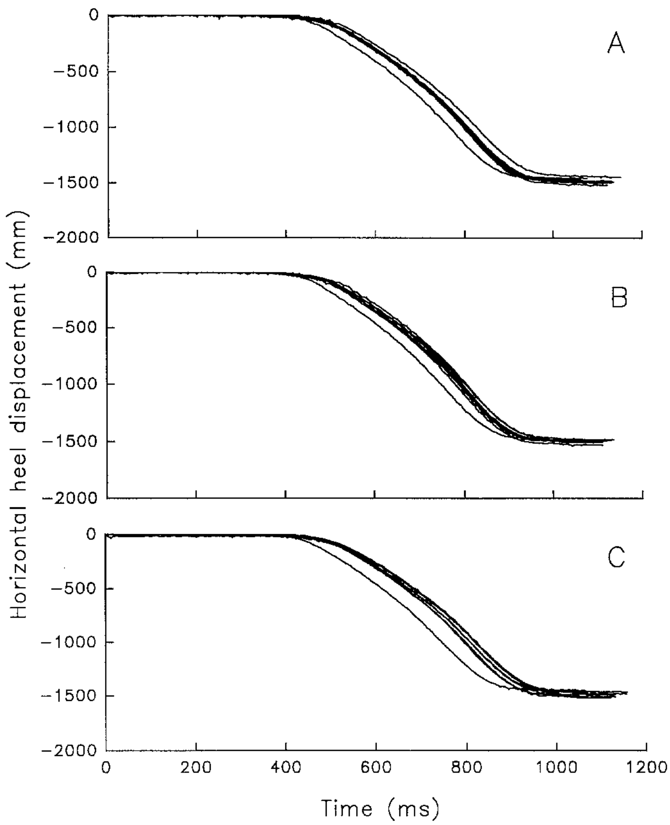

Fig. 1. Horizontal heel displacement when probes were presented to subjects in (**A**) single-limb support phase, (**B**) double-limb support phase and (**C**) control condition

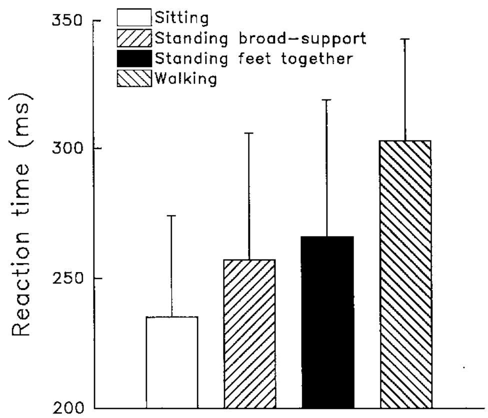

Fig. 2. Average reaction times and standard deviation for the sitting, broad-support standing, standing with feet together and walking conditions

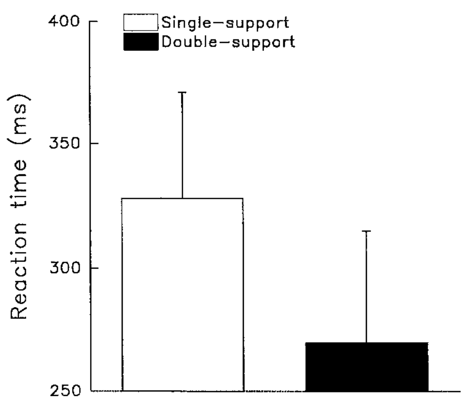

Fig. 3. Average reaction times and standard deviations recorded when probes were presented to subjects in single-support and double-support phases

are a valid index of the attentional demands required by the walking task.

Attentional requirements

The average RTs for the four tasks are illustrated in Fig. 2. The mean RTs for the sitting, broad-support standing, standing with feet together, and walking tasks were 235, 257, 266 and 303 ms, respectively. A one-way analysis of variance (ANOVA) with repeated measures showed a significant effect of task ($F_{3,15} = 17.05$, $P < 0.005$). Duncan post-hoc analysis showed that the RTs for the sitting task were shorter than those obtained for the standing and walking tasks ($P < 0.05$). The RTs for both standing tasks were also significantly shorter than those obtained for the walking task ($P < 0.005$). No significant difference was found between the two standing tasks ($P > 0.05$). Clearly, walking required more attention than the more static tasks.

Attentional requirements while walking

When walking, the alternating leg movements yield a single-limb support phase (SS) and a double-limb support phase (DS). The base of support is smaller for the SS than for the DS phase. Furthermore, and contrary to what is observed for the DS phase, the center of gravity for the SS phase does not lie over the base of support. Thus, we wanted to examine whether the attentional requirements for the SS phase were more important than for the DS phase. Figure 3 illustrates that the attentional demands were more important when subjects were in SS (328 ms) than when they were in DS (270 ms). An ANOVA with repeated measures showed that this difference was statistically significant ($F_{1,11} = 6.19$, $P < 0.05$).

Discussion

Maintaining an upright (and unperturbed) standing position requires more attention than sitting in a chair; walking requires more attention than both maintaining an upright standing position or sitting in a chair. Clearly, these results suggest that the attentional demands of a postural task increase with an increase in the balance requirements.

Using interference protocols, several authors have recently demonstrated that the control and regulation of posture require attention. Kerr et al. (1985) have observed that the performance at a memory task decreased when subjects were asked to maintain a difficult stance position (tandem Romberg stance versus sitting task). In the study of Stelmach et al. (1990), the balance recovery following a simple arm-swinging task was affected by the addition of simple, single-digit mental calculations. In the present experiment, decreasing the base of support yielded a small increase in RT. This difference, however, did not reach significance level. It is possible that the equilibrium demands of the small base of support were not sufficient to overload the cognitive system. Geurts et al. (1991, 1992) have made a similar observation. In their experiments, lower-limb amputees' postural performance was affected greatly when they had to stand upright and perform concurrently a Stroop task (the Stroop task requires the identification of colored words that are presented in a different color). The performance of control subjects, however, was not affected by the introduction of the secondary task. Through rehabilitation, the amputees improved their postural stability (decreased sway range and velocity). Similarly, Teasdale et al. (1992, 1993) reported that young and elderly persons, when asked to maintain an upright stable posture, had slower reaction times to an auditory stimulus when the sensory information was decreased (by withdrawing vision and/or altering the reliability of the somatosensory information by adding an open-cell polyurethane foam surface). These observations suggest that the maintenance and the regulation of balance require a substantial amount of the information processing capacity, and that a more difficult balance task can demand a greater amount of the available resources.

From a biomechanical perspective, the postural and balance requirements for walking are different and more challenging than those for upright standing. Walking is a highly practiced and repetitive action. It is characterized by a single-limb support phase (swing phase) and a double-limb support phase (stance phase). Although a safe placement of the swing foot is essential to avoid destabilization, the duration of the swing phase is approximately constant for different speeds (McMahon 1984; Winter 1991). Several authors have reported that, under normal conditions, the swing phase is conducted passively with non-muscular forces (Cappozzo et al. 1976; Mochon and McMahon 1980) and suggested that the swing phase is "ballistic" and as such does not require on-line regulations. In the present experiment, walking was performed in a stable and predictable environment. The greater attentional demands observed for the walking task suggest that, from an information processing viewpoint, walking cannot be considered as an automated task requiring no (or hardly any) cognitive processing. The increased reaction time from the sitting condition to the walking condition replicates earlier anecdotal observations, e.g. Kahneman (1973), and the empirical findings of Girouard (1980) and Bardy and Laurent (1991).

More important, the slower RTs observed for the single support phase suggest that the attentional demands varied within a cycle. When walking is goal oriented (i.e. pointing at a target), Bardy and Laurent (1991) reported that the attentional demands start increasing three steps before target contact and are more important when subjects point at a small target than when they point at a large target. In the present experiment, however, the walking task had no specific accuracy or pointing requirements. Further, the stimuli were always given three steps after walking onset and at least four steps before the end of the trial. Thus, subjects were walking at a stable cadence when stimuli were given and the slower reaction times observed when the stimuli were given in the single support phase cannot be attributed to specific accuracy or pointing requirements and/or cadence regulation processes. Our results are in variance with Sajiki et al. (1989) who observed no difference in RTs between the two stance phases. However, their data are difficult to interpret, since they reported no reaction time difference between a seated control condition and the walking conditions. In the study of Sajiki et al. (1989), the stimuli were given always within the first walking cycle and it is likely that subjects were anticipating the stimulus.

There is also neurophysiological evidence of supraspinal contribution on the peripheral muscular system during the walking cycle. Both Armstrong and Edgley (1984) – see Armstrong (1988) and Dietz (1992) for recent reviews – and Drew (1988) have reported cortical activity varying within the walking cycle. For example, Armstrong and Edgley (1984) observed that the discharge of nucleus interpositus neurons was greater during the swing than during the stance phase. They suggested that nucleus interpositus (through interposito-rubral and rubro-spinal projections) may help the spinal central pattern generators to regulate the levels of flexor muscle contraction that initiate and sustain the swing phase. Although it is hazardous to compare animal and human gait, our observations suggest an alternative hypothesis for the contribution of nucleus interpositus. The slower RTs observed during the single-support phase (swing phase) raise the possibility that the programming and dynamic control of balance over the alternating leg movements are cognitively expensive. Ongoing balance regulations may occur at a high level within a walking cycle with the double support phase serving to restabilize balance. Thus, nucleus interpositus activity could also reflect high-level balance evaluation and regulation required by the walking cycle.

Overall, our results emphasize that balance control within the gait cycle is not automatic and loads differentially on the higher level cognitive system. Balance control may require a continuous regulation and integration of sensory inputs; the rapidity and efficiency of these high-level processes may depend upon the integrity of the peripheral systems and the balance requirements. We believe these observations pose fundamental questions regarding the interdependence between the different levels of organization necessary for an adaptable and optimal gait pattern.

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