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Research Note

How is the normal locomotor program modified to produce backward walking?

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Summary. The modifications occurring in the movement and muscle activity patterns of the leg when changing from forward to backward walking were studied in five healthy subjects during walking on a motor driven treadmill. Movements were recorded with a Selspot optoelectronic system and muscle activity with electromyography using surface electrodes. The movement trajectories of the leg in forward and backward walking essentially mirrored each other, even though the movements occurred in the reversed direction. The angular displacements at the hip, knee and ankle joints showed similar overall magnitude and pattern in the two situations. Most of the investigated muscles changed their pattern of activity in relation to the different movement phases. At the ankle, there was a switch between flexors and extensors with flexor activation during support in backward walking. The bursts of activity in knee extensors were prolonged and shifted to the main part of the support phase. In the hip extensors, the activity periods retained their positions relative to the leg movements, but changed function due to the reversed direction of movement. Thus, drastic changes occur in the normal locomotor program to produce a reversal of leg movements and propulsion backwards.

Key words: Human locomotion – Motor control – Movement trajectories – Motor patterns – Muscle function

Introduction

Normal undisturbed human walking at constant speed on even level ground or on a treadmill is characterized by highly reproducible movements and patterns of muscle activity (Nilsson et al. 1985a, see also Inman et al. 1981). The similarities with more detailed animal studies (cf. Grillner 1981), suggest that the basic locomotor synergy is generated by a "central program" which is under strong influence from afferent input allowing for fast adaptations to the changing demands of the environment (cf. Grillner 1981, Forssberg 1985). Characteristic adaptations to increased speed of locomotion from slow walking to fast running have been demonstrated (Nilsson et al. 1985a). In animal experiments different spinal rhythmic movements have been studied in which different muscles change phase relationships (Stein 1983). Such experiments are of importance for understanding the neural mechanisms which allow a modification of the locomotor movements from forward to, for instance, backward or sideways locomotion (cf. Grillner 1985). The pattern of coordination used when switching from forward to backward walking is practically unknown (cf. however, Miller et al. 1978; Patla 1984). Walking backwards means a reversal of leg movement trajectories and the purpose of this study is to describe these trajectories and to what an extent the normal coordination of leg muscles is modified when movements in the opposite direction are produced.

Material and methods

Five healthy subjects, 4 males (25–30 years) and one female (20 years) took part in the study. They were all accustomed to treadmill walking. Backward walking was practiced 3–4 times prior to the actual test. Forward and backward walking was performed on a motor driven treadmill (size of rubber belt 2.7 × 0.8 m) at constant speeds ranging from 1.0 to 2.0 m · s^{-1}. The direction of motion of the belt was switched between trials. The stride frequency was either spontaneous or set by a metronome. Recordings were made during 10–15 consecutive strides in each experimental situation.

Movements of the left leg were recorded in the sagittal plane with a Selspot optoelectronic system (see Halbertsma 1983;

Nilsson et al. 1985a). Infrared light emitting diodes were attached to the left shoe, on the most anterior and posterior part and at the level of the small toe, as well as over the ankle, knee and hip joints and the anterior part of the iliac crest (cf. Fig. 1). The position of each diode was sampled at a frequency of 156 Hz. Angular displacements of the ankle, knee and hip joints were calculated using common trigonometric functions. Foot contact was recorded with a pressure sensitive transducer connected to a flexible tube, which was glued onto the outer perimeter of each shoe (Nilsson et al. 1985b).

The electromyographic (EMG) activity was recorded with surface electrodes from the gluteus maximus (GM), hamstring (HAM), rectus femoris (RF), vastus lateralis (VL), lateral gastrocnemius (LG) and tibialis anterior (TA) muscles of the left leg.

All signals were recorded simultaneously and fed into a computer (HP2117F), stored on magnetic tape and later analyzed "off line". Details about data collection and processing can be found in Halbertsma (1983), Halbertsma and deBoer (1981) and Nilsson et al. (1985a).

Results

Stride characteristics

The average duration of the stride cycle, defined as the time between two consecutive touch downs of the left foot, decreased by 8–14% when changing from forward to backward walking at the same speed. The decrease occurred in all subjects and at all speeds tested. At 1.5 m · s^{-1} the decrease in stride cycle duration was from 1.03 to 0.93 s. Also the support duration was shorter in backward walking in all subjects, wheras the relative support phase duration (in % of total stride cycle time) remained approximately the same (62–66%) as did the relative duration of the swing phase in consequence.

In the experiments with a constant stride frequency, set with a metronome at a comfortable pace in between the frequencies spontaneously chosen in forward and backward walking, the support phase duration was similar in the two situations. At 1.5 m · s^{-1} the stride frequency was set at 1.00 Hz (stride cycle duration: 1.00 s) for all subjects and the support duration ranged 0.64–0.66 s.

Movement trajectories

During both forward and backward walking the leg movements were very reproducible from stride to stride and virtually identical (Fig. 1) although the direction of movement was reversed. The stick figures in Fig. 1 (bottom) demonstrate striking similarities in overall leg movements and the leg traveled along essentially the same path in the two situations, but in opposite directions. The position of the leg at the start of support (heel-strike) in forward walking was similar to that at the end of support (heel-off) in backward walking. This was also true for toe-off in forward and toe-strike in backward walking.

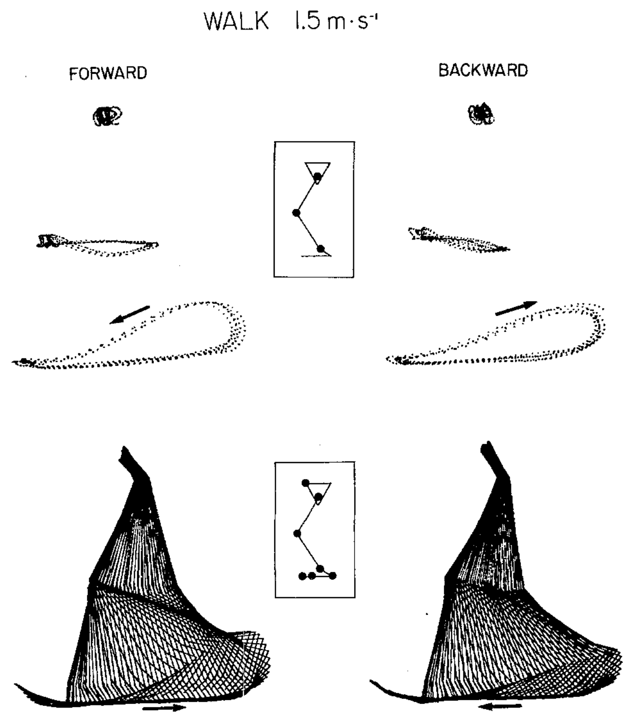

Fig. 1. Movement trajectories of the left leg during forward and backward walking on a treadmill with a constant speed of 1.5 m · s^{-1}. *Above:* Superimposed records of movements of the markers on the ankle, knee and hip during 5 consecutive strides (sampling rate 78 Hz). *Below:* Stick figures showing the movements of the whole leg during one stride of forward and backward walking (sampling rate 78 Hz). The placements of the markers are shown schematically in the boxes

Angular displacements

The characteristic pattern of angular displacement in the hip, knee and ankle joints in forward walking (Fig. 2A) was almost completely reversed in backward walking (Fig. 2B). This means that in backward walking the hip flexed during support and extended during swing, the knee extended throughout the support phase and flexed during the main part of swing, and the ankle dorsiflexed after toe-strike and then plantarflexed during the main part of the support phase. The reversal of angular motion is even more evident in Fig. 2C, where the curves from Fig. 2A and B are replotted so that forward motion starts from the left and backward motion from the right. It is clear that the hip angular displacement was identical in the two cases, although the direction was

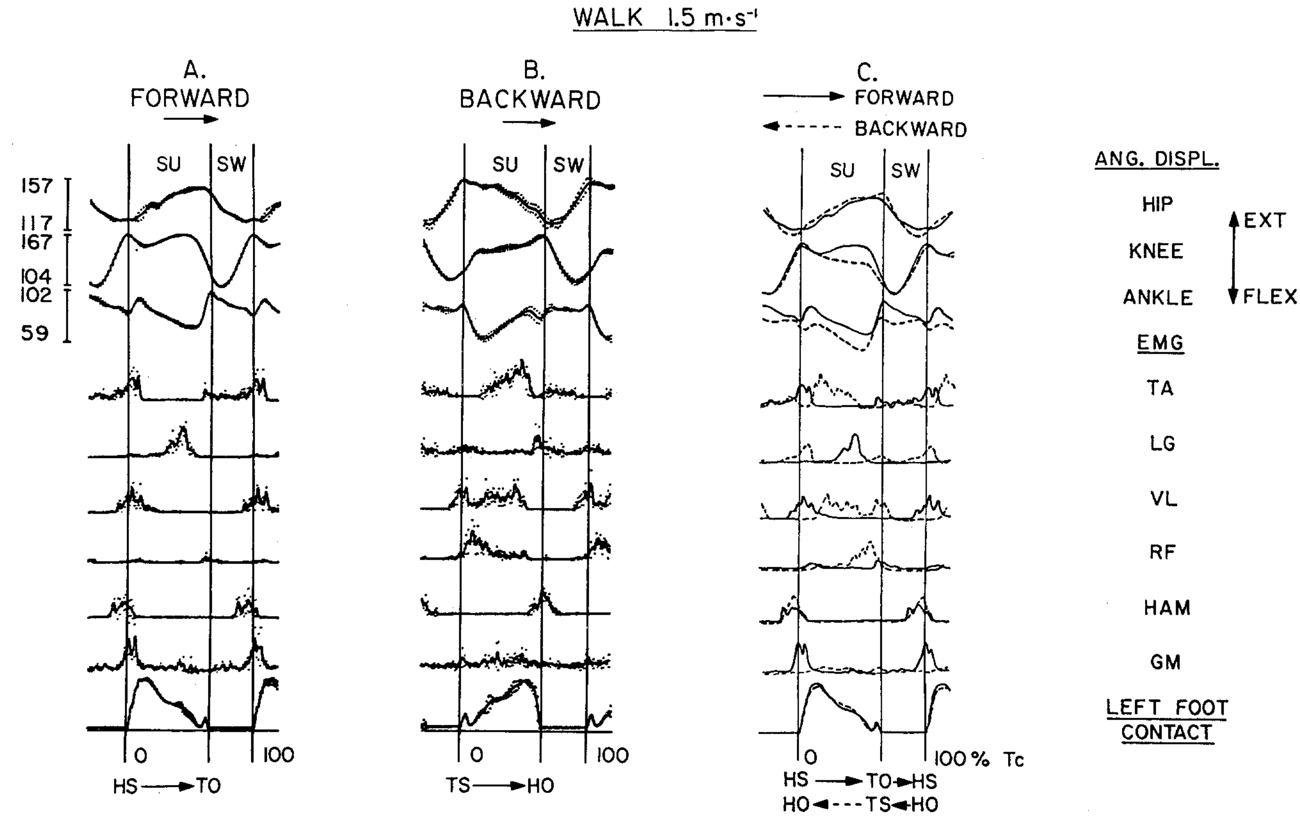

Fig. 2A–C. Angular displacements and rectified and filtered EMG signals of the left leg during forward and backward walking at 1.5 m · s^{-1}. In **A** and **B** the curves are means of 5 normalized stride cycles (points denote ±1 standard deviation). The strides were normalized with respect to the onsets of support (su) for the left leg during consecutive strides (heel-strike, HS, in forward and toe-strike, TS, in backward walking), which are illustrated with vertical lines at 0 and 100% of Tc (stride cycle duration). The middle vertical line in each graph represents end of left foot support (= start of swing, sw), i.e., toe-off (TO) in forward and heel-off (HO) in backward walking (cf. the lowermost graph indicating left foot contact). In **C** the contours of the mean curves have been traced, and the backward graph turned over and superimposed on the forward one, so that the leg movements correspond. (Note that movements occur in the opposite directions.) The muscles recorded from were: tibialis anterior (TA), lateral gastrocnemius (LG), vastus lateralis (VL), rectus femoris (RF), hamstrings (HAM) and gluteus maximus (GM). The amplitude scales are the same for corresponding traces in both situations. Calibration bars for angular displacements are given to the upper left

reversed. One conspicuous difference was the absence of knee flexion during support in backward walking. It is striking that the angular movement in the knee during swing as well as the knee angle in the most forward leg position coincided in the two situations. Also the angular motion of the ankle joint in the reversed direction was very similar, although the movements occurred around a more flexed ankle position in backward walking (Fig. 2C). A difference was present during swing, where the dorsiflexion of the ankle in forward walking was not reversed to a plantarflexion. The overall amplitude of angular displacement in each of the three joints was similar in the two forms of walking.

Pattern and amplitude of muscle activity and its relation to leg movements

Figure 2 also shows the filtered and rectified EMG from six leg muscles during walking forwards and backwards at the same speed. Some of the most noticeable changes in muscle activity pattern and amplitude when changing direction of progression are pointed out below.

The hip extensor *gluteus maximus* (GM) muscle had a burst of activity starting at touch down in forward walking, but in backward walking the activity was of much lower amplitude or often totally absent, particularly at low walking speeds. When present, GM bursts occurred at the end of support. For the *hamstring* group (HAM), which can act as knee flexors and hip extensors, a relatively good correspondence was seen between forward and backward walking when cycles were 'superimposed' (Fig. 2C), which means that the bursts occurred at the transition from swing to support in one case, but from support to swing in the other. The function of HAM was consequently changed from being one of braking knee extension during late swing and assisting in hip extension during early support in forward walking to mainly initiating hip extension and/or knee flexion during early swing in backward walking.

The pattern of activity of the hip flexor – knee extensor *rectus femoris* muscle (RF) was markedly changed in backward walking (Fig. 2C). RF was active almost the whole support phase as compared to short periods of activity at heel-strike and toe-off in forward walking. Note that in backward walking there was a simultaneous knee extension and hip flexion during support (Fig. 2B), both of which could be accomplished by a shortening contraction of RF. The RF activity was markedly increased in backward as compared to forward walking.

The pure knee extensor *vastus lateralis* (VL) muscle had a burst of activity starting before touch down in forward walking lasting through the initial phase of support (Fig. 2A). During this period there was a flexion of the knee, i.e. VL underwent a lengthening contraction. Also in backward walking VL was active at touch down, but in this case the initial peak of activity was followed by a large activity period lasting through the main part of support (Fig. 2B). During the whole support phase there was an extension in the knee, although at different velocities (Fig. 2B), and thus only a shortening contraction occurred in VL.

At the ankle there was almost a complete shift in the activation pattern of flexors and extensors. In forward walking the *lateral gastrocnemius* muscle (LG) was active during the second half of the support phase and the *tibialis anterior* muscle (TA) mainly during the swing phase, with peaks in activity just after touch down and at toe-off (Fig. 2A). In backward walking, on the other hand, LG showed only minor peaks of activity at the beginning and end of support, whereas TA had a large burst of activity during the support phase with a peak during the second half (Fig. 2B). During the swing phase there was some activity in ankle flexors both in forward and backward walking.

Discussion

Changing direction of locomotion from the normal forward progression to backward is done rather readily by all people. However, it poses an interesting problem from a control point of view. The pattern of muscle activation has to be changed to produce a reversal of leg movements and a propulsion in the backward direction. The present study has shown that the leg not only reverses its direction of movement, but it travels in the opposite direction along virtually the same movement path in the two situations, and that the reversal is accomplished by modifications of the normal motor program to varying degrees depending on which joint is involved.

At the hip joint the angular movements were almost identical in the two situations. This was also the case for the activity period of hip extensors in relation to the position of the leg. Both hamstrings and gluteus maximus (at high walking speeds) were activated in conjunction with the switch from hip flexion to extension in the two cases. However, due to the reversed direction of movement the period of muscle activity was completely shifted in relation to the stride cycle phases, from the start of support (heel-strike) in forward walking to the end of support (heel-off) in backward walking. Thus, the hip extensors could act to brake hip flexion (lengthening contraction) and initiate hip extension (shortening contraction) in both forms of walking, but the functional implications of the contraction became quite different depending on the change in direction of motion. Similar conclusions could be drawn concerning the potential flexor function of the hamstring muscles at the knee joint.

In forward walking the muscles at the hip and knee joints exhibited relatively short bursts in conjunction with touch down. In backward walking this was entirely changed for the knee extensors vastus lateralis and rectus femoris, which showed a massive activation throughout most of the support phase. It is worth noticing that during this period there was simultaneous knee extension and hip flexion. Thus, both muscles contract during shortening and there is no possibility to utilize elastic energy stored in muscle during a stretch-shortening cycle as in forward walking (cf. Cavagna 1977).

At the ankle there was a reciprocal activation of flexors and extensors in both situations. However, there was almost a complete switch between the two in relation to the stride cycle. Lateral gastrocnemius was active during support in forward and tibialis anterior in backward walking. Interestingly, both muscles underwent a lengthening contraction during the main part of the support phase in the two conditions. This allows for storage of elastic energy, which could contribute to force production during push off. Forward propulsion is mainly caused by the ankle extensor muscles undergoing a stretch-shortening cycle and producing an extensor torque around the ankle joint. Backward propulsion seems to be accomplished by ankle flexors creating a reversed torque around the ankle joint. Thus, a similar strategy is used, although the mechanical conditions, such as the lever arms for flexors and extensors, differ in the two situations.

Figures 1 and 2C show that the limb essentially follows the same trajectory in forward and backward locomotion, but in opposite directions. To accomplish this dramatic and very specific change, most muscles change their pattern of activity in relation to the different movement phases. Provided that the same neural circuitry is used in both cases (see Grillner 1985, Stein et al. 1986), these findings suggest a marked and specific modifiability within the network generating locomotion.

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