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Original Article

Gait analysis on the treadmill – monitoring exercise in the treatment of paraplegia

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Study design: A prospective study was performed to evaluate the gait training of seven consecutive spinal cord injured patients and 10 controls on a treadmill using instrumented gait analysis and video documentation.
Objectives: To determine whether it is possible to maintain gait motion within physiological limits during treadmill training.
Setting: Primary and secondary care unit for spinal cord injury, Heidelberg, Germany.
Methods: Treadmill training was instituted as early as possible. Gait analysis was performed when the patients were stable enough to walk without manual aid from therapists and enough endurance to allow measurements. A control group of healthy volunteers were examined as well. Video documentation and a camera system using passive markers were employed.
Results: Treadmill training started with weight reduction of 25% of bodyweight (18 (0–35) kg), maximum walking speed 0.28 (0.15–0.7) m/s and maximum walking duration 4.7 (3–7) min. At the end of the training, weight reduction decreased to 9.3 (0–20) kg, maximum walking speed increased to 0.67 (0.23–1.1) ms with a maximum walking duration of 11 (8–15) min. 3-D motion analysis of hip, knee and ankle demonstrated joint excursions almost entirely within the limits of normal gait. Exceptions were due to fixed contractures.
Conclusions: Our data suggests that it is possible to perform early gait training on a treadmill with no supportive orthoses within the physiologic range of joint motion. The risk for repetitive stress injuries or other negative effects is low.
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Keywords: locomotion training; treadmill; gait analysis; paraplegia

Introduction

The use of a treadmill in the post spinal cord injury gait training has been established over the last few years. Two basic treatment principles are employed. According to Dietz *et al*[1] and Nicol *et al*[2] it is supposed that the spinal cord has its own locomotion pattern generators which can induce basic gait motion patterns when being fed with the necessary sensory input. During treadmill training the patient is brought to an upright position supported by the use of a harness (if weight reduction is necessary). Depending on the remaining motor competence, the patient walks on the treadmill with therapists guiding gait motions manually, or, the patient moves on his/her own. It is hypothesized that the pattern generators can be activated even if there is no voluntary control of these motor segments, e.g. in a complete cervical lesion of the spinal cord.

The second treatment principle of treadmill walking is repeated exercise of gait motion to increase strength, coordination and endurance.[3,4]

Gait training is nothing new to the rehabilitation of acute spinal cord injury. It has been employed since structured treatment of these patients, as introduced by Guttmann[5], ensured survival. Physical therapists start gait training as soon as the patient recovers enough strength to balance the body with the use of long leg splints and bars or crutches. In most cases this type of therapy cannot be employed early after injury and is only possible with patients that have sufficient command of their upper extremities.

The resulting gait is often very clumsy; patients tend to use passive support of the ligaments of their joints for stabilization where muscle control is lacking. As an example, the patient services hip hyperextension in stance to purchase stability of an otherwise unstable joint (Figure 1).

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Figure 1 Conventional mobilisation to standing and walking. The patient has long leg orthoses to stabilise knee and ankle. Note hyperextension of the hip to stabilise the pelvis

Treadmill exercise departs radically from earlier practiced gait training in a very important aspect. In conventional gait training as it is described by Guttmann[5] great care is taken to use a 'step by step' approach where the patient first learns to get up and sit down, to balance his trunk while standing between parallel bars using a mirror, finally to begin with actual stepping motions trying to avoid abnormal gait patterns – when necessary by the use of carefully selected splints. Opposed to this approach, patients mobilised to walking on a treadmill are pulled into an upright position with the use of a harness at a point of time when they still do not have sufficient control of their trunk nor are orthoses (eg long calipers) applied in this stage of treadmill training.

Experienced physical therapists frequently warn against early gait exercise because they see too much damage done by the development of these 'wrong patterns' resulting eg in repetitive strain injuries to knee, ankle and hip.

In our opinion it is sensible to consider these questions seriously. While there are quite a number of indications that treadmill training is beneficial, it is by no means proven that patients who received treadmill training at these early stages after injury have a better functional outcome.

This is especially true for patients with lesions who do not recover beyond Frankel C. On the other hand, gait exercise for this patient population would still be feasible because it is supposed to improve circulatory and vegetative nervous sequelae of paraplegia.[5,6] Furthermore, there is evidence that very early gait training with at least some weight bearing may prevent or reduce osteoporosis.[7]

This pilot study was conducted to determine whether it is possible to achieve gait within physiological limits during treadmill training of paraplegic patients using instrumented gait analysis and video documentation.

Materials and methods

The study was started in the last quarter of 1998 as a prospective study and finished in the second quarter of 1999. Seven consecutive patients that met our inclusion criteria for treadmill training could be recruited, 10 individuals with no motion disorder served as a control group.

Inclusion criteria

Several inclusion criteria for treadmill training had to be met. First, mobilisation into the wheelchair had to be successful. The patient had to be able to sit a minimum of 2 h without signs of post spinal cord injury compromise of circulatory regulation, such as spells of dizziness or fainting. Patients were required to control their lower extremities in such a way that they could reposition their feet voluntarily while sitting in the wheelchair. These patients were then subjected to test training on the treadmill and were accepted into the program if they could walk with no more than 40% reduction of bodyweight for three training cycles of 2 min each. It has to be noted that patients did not have to be able to complete the gait cycle on their own. If necessary, manual guidance of the motion was provided by two physical therapists.

Normals had to be able-bodied with no history of chronic musculoskeletal problems or injuries.

Demographic data

The patient group included four males and three females, the average age was 37.9 (range: 18–60) years. The control group consisted of five males and five females with an average age of 31.2 (range: 19–57) years.

Patient history was obtained concerning the origin, date of onset and level of the spinal cord lesion. Also, the patients were examined for the passive range of motion of hip, knee and ankle joints to document the presence or absence of contractures. In summary, three patients had cervical lesions, and four had thoracic/lumbar lesions. Treadmill training started 8.5 weeks (range: 3 – 18 weeks; one patient 2.5 years) after injury.

Training modalities
After being accepted into the training program, patients received daily therapy (5 days a week). The amount of manual aid given, the duration of the training and the amount of weight reduction was adjusted to actual clinical situation according to the judgement of the therapist. All patients completed 9 weeks of training. Training parameters such as maximum treadmill speed and weight reduction were recorded for each session.

Measuring modalities
Instrumented gait analysis was performed as soon as the patients were able to walk a minimum of about 10 steps without the manual aid of therapists. Measurements were performed using a motion analysis system with six cameras. The measurement data were processed using Orthotrak (MotionAnalysis Systems) and proprietary software of our laboratory. Additional video documentation was performed. Figure 2 shows the typical setup of the measurement with the patient in a harness for weight reduction with the markers for the gait analysis in place. Patients were instructed to use as much aid (harness and/or handrails) as they needed during the last regular training session.

For one patient who was able to walk without weight support we performed a gait analysis with and without weight reduction.

Results

Training parameters
Overall, the patients did profit from exercise on the treadmill with a reduction of necessary support (weight reduction) and increased maximum treadmill speed during exercise. At the start of the training patients needed an average of 25% reduction of bodyweight (18 (range: 0 – 35) kg). At the end of the training cycle only 13% (9.3 (range: 0 – 20) kg) were necessary. When initially an average maximum treadmill speed of 0.28 (range: 0.15 – 0.7) m/s was possible, this speed increased to 0.67 (range: 0.23 – 1.1) m/s.

In order to compare these measurements with normal gait on a treadmill, we asked our control group to walk at leisure speed using the handrails, (0.99 (0.78 – 1.15) m/s), to walk as fast as they could without starting to run (1.84 (1.7 – 1.94) m/s) and to walk as slow as possible without making pauses between steps (0.3 (0.14 – 0.5) m/s).

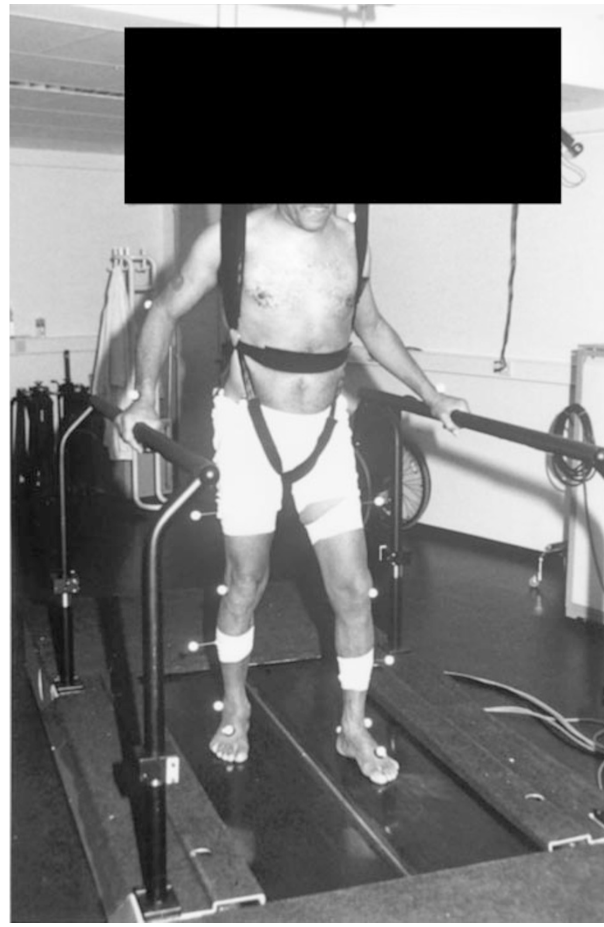

Figure 2 Setup for treadmill gait analysis under weight reduction

Physical examination
The examination of the passive range of motion (ROM) showed no abnormal findings except for one patient who had a bilateral fixed *pes equinus* of 15 degrees.

Instrumented gait analysis
Three dimensional motion data was obtained for hip, knee and foot motions. In all subsequent figures the shaded area represents the standard deviation for the averaged mean motion curve obtained by the 10 members of the control group.

The motion curves obtained for the hip were checked for signs of exaggerated ab- and adduction during stance as a signal of insufficient strength and control of the gluteus muscles. Figure 3a,b demonstrate the effect of weight reduction by a harness to an unstable hip in ab- and adduction. The abnormal movement pattern is greatly reduced, the joint motions occur almost entirely within the normal range of motion. Flexion and extension of the hip (Figure 4a,b) also stay well within normal limits.

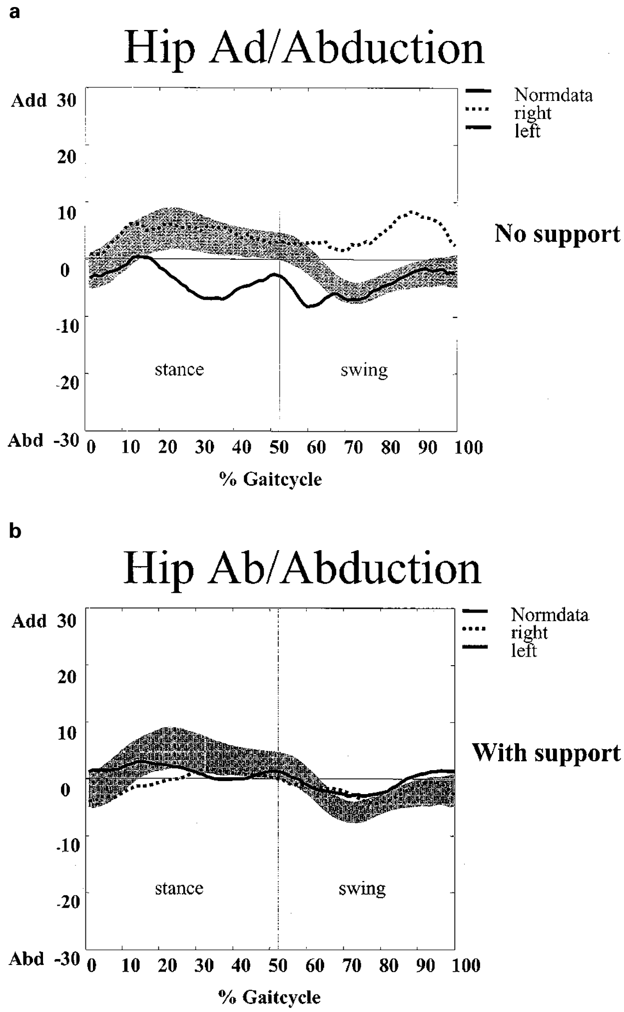

Figure 3 (**a**) and (**b**) All signs of a very unstable left hip with loss of *M. gluteus medius* and *maximus* function with normal strength of *M. psoas* are shown. Soon after initial contact, after some weight has to be carried by the left leg, the trunk moves to the left side in order to centre the weight over the hip minimising the force needed by the gluteal muscles. This manoeuver results in excessive hip abduction during mid stance (Duchenne type gait). In swing the gait pattern normalises and the hip is moving most of the time within normal limits. During swing the right hip shows too much adduction. This is due to the oblique pelvis as described above. With adequate support (**b**) the motion almost normalises

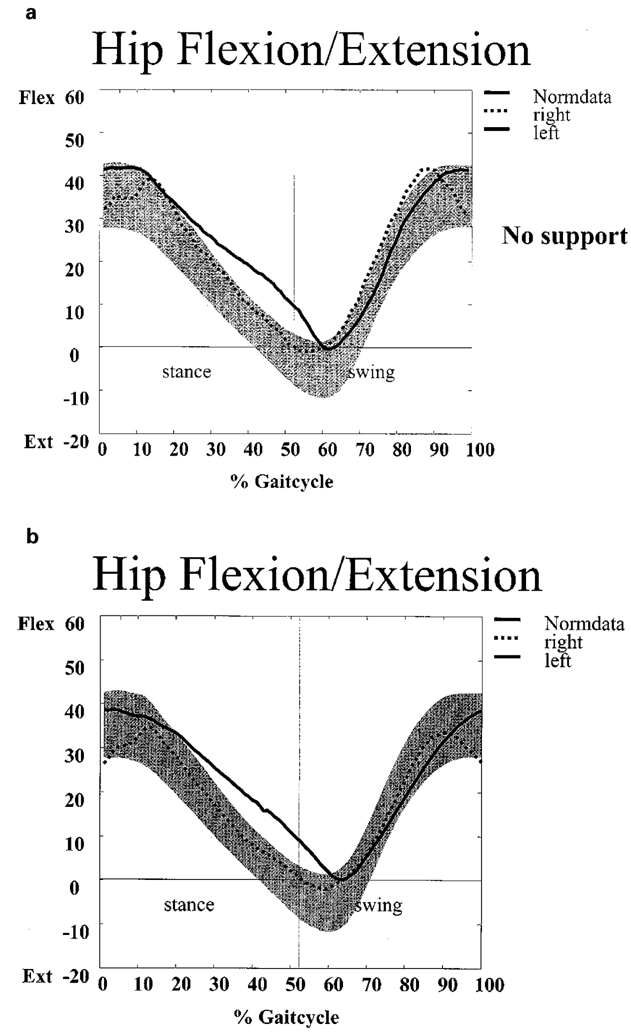

Figure 4 (**a**) and (**b**) The graphs for hip flexion and extension as function of the strong *M. psoas* do not show significant changes (**a**: no weight support; **b**: with weight support)

Hip flexion and extension for all participants are within the normal range except for the patient with fixed bilateral equinus deformity. In this case, we found excessive hip flexion during swing to clear the foot. Two patients did not reach the threshold of normals concerning extension, but not one demonstrated hyperextension of the hip to stabilise the joint during stance in the absence of sufficient motor control. Figure 5 demonstrates the averaged motion curves for the right hip of all seven patients.

Sagittal plane recordings of knee motion were analyzed, since one of the common compensation mechanisms of insufficient knee stability is hyperextension throughout weight bearing in stance. We found that overall motion stayed within the limits of normal. Except for the patient with fixed *pes equinus*, no potentially damaging hyperextension of the knee was observed. We also saw that the dynamic reaction to loading (loading response) was diminished. Less than the expected flexion – extension movement during stance was seen. Figure 6 depicts a summary of the curves obtained for right knee flexion and extension for all patients. Differences in the timing of peak knee flexion were due to different walking speeds.

In order to compensate for weak dorsiflexion, three patients required taping of the foot to secure sufficient

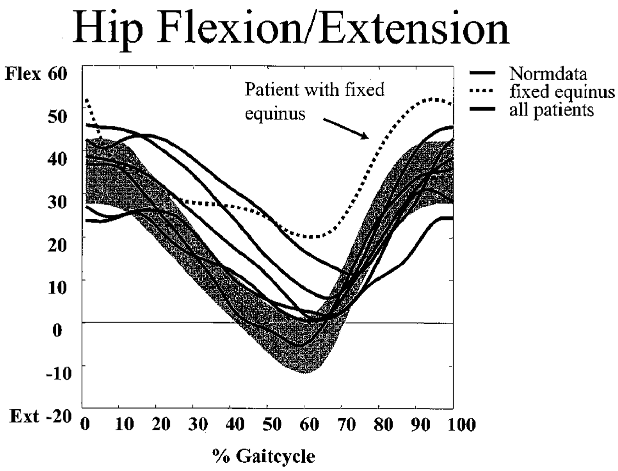

Figure 5 Layered graphs of hip flexion and extension (right hips) show that the dynamic range of hip motion is reduced in some patients. These patients do not reach sufficient hip extension in mid and terminal stance. But except for the patient with the fixed equinus deformity no patient shows abnormal motions patterns

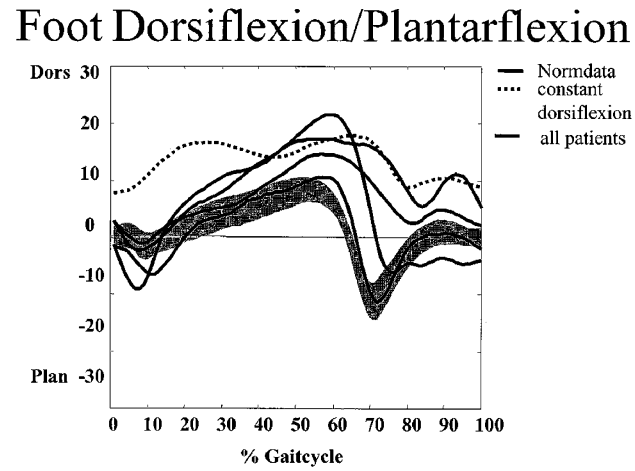

Figure 7 All patients show increased dorsiflexion in stance as a result of slow gait and weak calf muscles. One patient maintains increased dorsiflexion throughout the full motion cycle. This was due to an almost complete lack of deep sensory function. He vigorously dorsiflexed his feet, including his toes, during the whole gait cycle to avoid tumbling

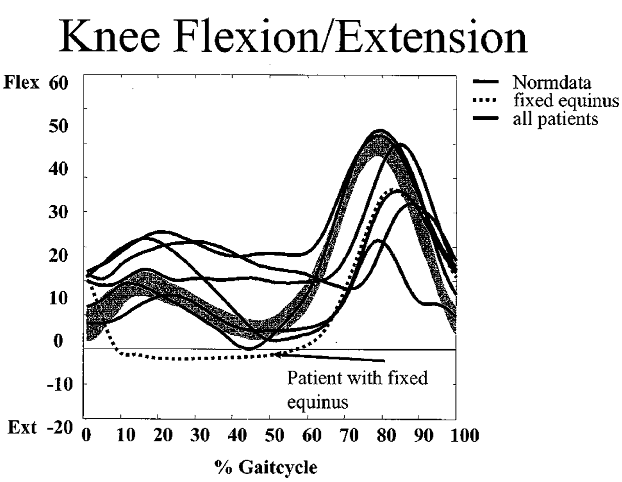

Figure 6 Summary of the flexion extension curves of right side knee motion. Reduced dynamic range of motion and diminished loading response but no gross changes in the motion pattern except for the patient with the fixed equinus deformity

clearance in swing. In these cases, ankle motion could not be assessed. Three of the remaining patients showed rapid increase of ankle dorsiflexion in stance. All of these patients showed peak dorsiflexion with normal timing, but two reached excessive peak values. All of these graphs show a rapid motion into plantarflexion in terminal stance. One patient did not follow this pattern; he showed continuous dorsiflexion throughout stance and swing (Figure 7). Clinical observation and videotaping revealed that this was due to an almost complete lack of deep sensory function. He vigorously dorsiflexed his feet, including his toes, to avoid tumbling during the whole gait cycle.

Discussion

We started this study to determine whether it is possible to perform gait training for paraplegic patients without exceeding the physiological boundaries of joint movement. We were concerned about this problem because, according to our own clinical experience, conventional mobilisation using handrails or bars often resulted in such overuse when the training was begun too early. A similar mechanism is well described for polio patients.[8] Locomotion training on a treadmill has been advertised to be possible in a very early phase of the rehabilitation process.[4,9–13] This is a major change from the standard of careful 'step by step' of mobilising a patient towards walking, compared to the traditional standard described by Guttmann.[5]

We do not think that problems will occur in the phase of mobilisation when therapists manually guide the motions because their control of the motion is very effective and they will block abnormal or potentially harmful motion. Furthermore it is not technically possible to perform a kinematic study while a therapist guides the motion, because the body of the therapist inevitably blocks the view of the camera system

The interesting phase of locomotion training on a treadmill is the time when patients perform the motions on their own. This was the reasoning for us to perform the kinematic analysis at this point. This point was usually reached in the third week of training.

Overall, our data suggests that patients exercise with gait patterns that are not normal, as compared to normal gait of healthy volunteers, but are sufficiently well within normal limits of joint motion during the entire gait cycle. We therefore show that the joints are not loaded in abnormal positions, a finding that implies that the potential risk for overuse during training is very limited.

This finding also supports the claim that this form of locomotion training helps to feed the nervous system with regular sensory input of walking. This again, might facilitate the activation of postulated 'spinal pattern generators'.[1,2,14–18] Also, the pre- and post training walking ability as expressed in increased speed and reduced need for support represents quite an improvement of function. We can reproduce the reported positive effects of treadmill training.

For hip, knee and ankle joint motion we found that most patients maintained too much hip flexion in stance and did not reach normal extension. This causes gait to be more inefficient but it does not cause harm to the hip joint. We did not see any patients using forced hyperextension to stabilise the pelvis in stance. We furthermore did not see hyperextension of the knee as a stabilisation mechanism in stance. We, therefore, are confident to reduce the possibility of repetitive stress injury problems.[8]

This finding is especially important, because the use of the harness allowed us to train the patients without protecting orthoses. This is quite a change to the usual mobilisation towards walking using handrails. Here, orthoses are almost always necessary. Training without orthoses helps to avoid a time-consuming weaning process and saves a considerable amount of money.

The patient with the fixed bilateral equinus contracture was the one that showed motion curves with markedly abnormal pattern and exceeded the normal range of motion in a significant way. The findings corresponded to the clinical problems seen. In the future we will consider a more aggressive approach to correct such contractures before starting gait training.

Finally our findings imply some interesting questions about the necessity of 'coordination training'. Mere weight reduction by the use of a harness obviously enables patients to maintain stepping patterns with reasonable normal patterns. Furthermore all of this is happening at a point of time when the patient would probably just be standing and turning between bars. Does this leave room for the idea that the patient needs to train coordination or is only strength missing? It will be the task of further studies to find answers to these questions which will greatly affect the concepts behind the physical therapy offered.

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