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Published in:
American Journal of Physical Medicine and Rehabilitation

DOI:
10.1097/01.PHM.0000091981.41025.FC

Publication date:
2003

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0894-9115/03/8211-0825/0
American Journal of Physical Medicine & Rehabilitation

DOI: 10.1097/01.PHM.0000091981.41025.FC

Research Article

Reorganization of Gait After Limb-Saving Surgery of the Lower Limb

ABSTRACT

de Visser E, Veth RPH, Schreuder HWB, Duysens J, Mulder T: Reorganization of gait after limb-saving surgery of the lower limb. *Am J Phys Med Rehabil* 2003;82:825–831.

Objective: In this study, the concept of a cognitive dual-task performance and visual restriction during walking has been used to study the recovery of gait after limb-saving surgery in ten patients.

Design: All patients were recovering from some form of treatment to tumors of the lower limbs. Patients had to walk on a treadmill at their preferred speed. During the course of recovery, we measured normal walking, walking while performing an attention-demanding dual task, and walking during restricted vision, starting 5 mo postoperatively.

Results: Patients are able to reach an acceptable level of gait within 15 mo, especially when the basic locomotor activity (i.e., step-cycle duration, walking speed, gait symmetry) is taken into account. Nevertheless, the results showed that during the recovery, the patients were still hindered by the dual task and visual restriction while walking because they exhibited a decrease in step-cycle duration under these conditions.

Conclusions: In general, an improvement in walking speed and a decrease in asymmetry was seen. On the other hand, patients still had a basically reduced control of gait after the 15-mo recovery period. This can be attributed to a lack of gait automatism caused by an irreversible loss of somatosensory input.

Key Words: Gait, Recovery, Limb-Saving Surgery, Attention, Vision

Limb-saving surgery (LSS) is a surgical technique employed in patients with aggressive benign or malignant bone and soft-tissue tumors. In malignant tumors, the technique may be used in about 70% of the cases.[1] Patients have peripheral muscular and skeletal damage, leading to a sudden and irreversible disruption of both the efferent and afferent organization of gait. In all cases of limb-saving surgery of the lower limb, the body must adapt to a severe asymmetry of mass and muscle power and must reorganize its internal representation or body scheme. These patients experience serious balance and gait problems after limb-saving surgery.[2–4] In the first place, balance control is deteriorated under more complex conditions, such as in performing a dual task or standing with the eyes closed.[2] Furthermore, when the demands on the motor system become higher, standing becomes more difficult.[2] When gait pattern has changed from normal, patients try to gain more stability at the cost of flexibility.[4,5] Because gait is less automatic, these patients use more energy for normal walking as compared with a healthy population. The amount of energy depends on the extensiveness of the resection.[3,6–8]

Although limb-saving surgery is primarily focused on peripheral systems (e.g., limbs), a central reorganization within the sensorimotor system must take place as a reaction to the altered peripheral constraints.[3,9] Indeed, directly after the surgery, the system cannot "trust" the proprioceptive input and is largely dependent on visual input or conscious control of the movements. This concept has been used by Geurts et al.[10,11], who showed that in the early stages of rehabilitation after amputation, postural stability was guided by visual input and by controlling the output consciously. However, when the system adapted to the altered peripheral situation, these "artificial" or compensatory control strategies diminished. The authors concluded that the measurement of visual or conscious dependency could be of value for assessing the motor system during the course of recovery. Visual dependency can be determined by manipulating the perceptual input. Conscious or cognitive dependency can be measured by employing a dual-task procedure. The basic idea behind the dual-task methodology is that the performance of a difficult (e.g., nonautomated) task interferes with other simultaneously performed tasks. Hence, by employing a concurrent attention-demanding task, it is possible to use the degree of interference of this task with the primary task (e.g., walking) as a measure of the attention demands of the primary task. As long as the attention demands are high, the functional recovery is not complete. To study the visual dependency, a visual-restriction task was used. These complex conditions were compared with the single condition of normal walking. For a review of this concept, the reader is referred to Mulder et al.[12]

In the present article, this concept has been used to study recovery of gait after limb-saving surgery. We hypothesized that improvement in basic locomotor activities, derived from walking velocity, step-cycle duration, and symmetry, is seen. The improvement of functional recovery can be derived from a decrease in attention demand and a decrease in visual guidance of this basic locomotor task.

Possibly, improvement in basic locomotor activities is observed when gait is studied under optimal conditions (flat floor, no distracting circumstances, optimal lighting conditions). For functional recovery, however, it is necessary that patients are able to walk while performing a secondary task and that they are able to walk without the need of continuous visual guidance of every step. In this study, we evaluated patients with limb-saving surgery to determine to what extent they reached this status of functional recovery.

METHODS

Subjects. A total of 11 patients (seven men and four women) were included in the study. The age at date of operation ranged between 19 and 66 yr, with a mean age of 43 yr. All patients were treated at the Department of Orthopedics, University Hospital Nijmegen, for malignant osteosarcoma, Ewing sarcoma, or chondrosarcoma in the bone of the lower limb. Four patients were treated with a distal femoral knee prosthesis, four patients were treated with a proximal femoral hip prosthesis, and three were treated with a saddle prosthesis. Gait analysis began 5 mo postoperatively. These measurements were repeated 7, 9, 12, and 15 mo postoperatively. During the rehabilitation period, the patients received a physical therapy program. This program was primarily focused on the mobilization of the operated joint, whereas in a later stage, the focus shifted toward improvement of functional gait. Note that all therapists were allowed to follow their own program. The local medical ethics committee approved the study.

Procedure. Details of the procedure used were described by de Visser et al.,[3] so we will give only a brief account here. Before the experiment was started, patients practiced an auditory Stroop task once in a standing position. This task consists of a voice pronouncing the words "high" and "low" either in a high or low pitch. The subjects had to indicate immediately whether the pitch was low or high and to suppress the tendency to repeat the spoken word. After this, the subjects were allowed to walk on the treadmill to get used to the peculiarities of treadmill walking. The patient could change the walking speed with the speed button on the tread-

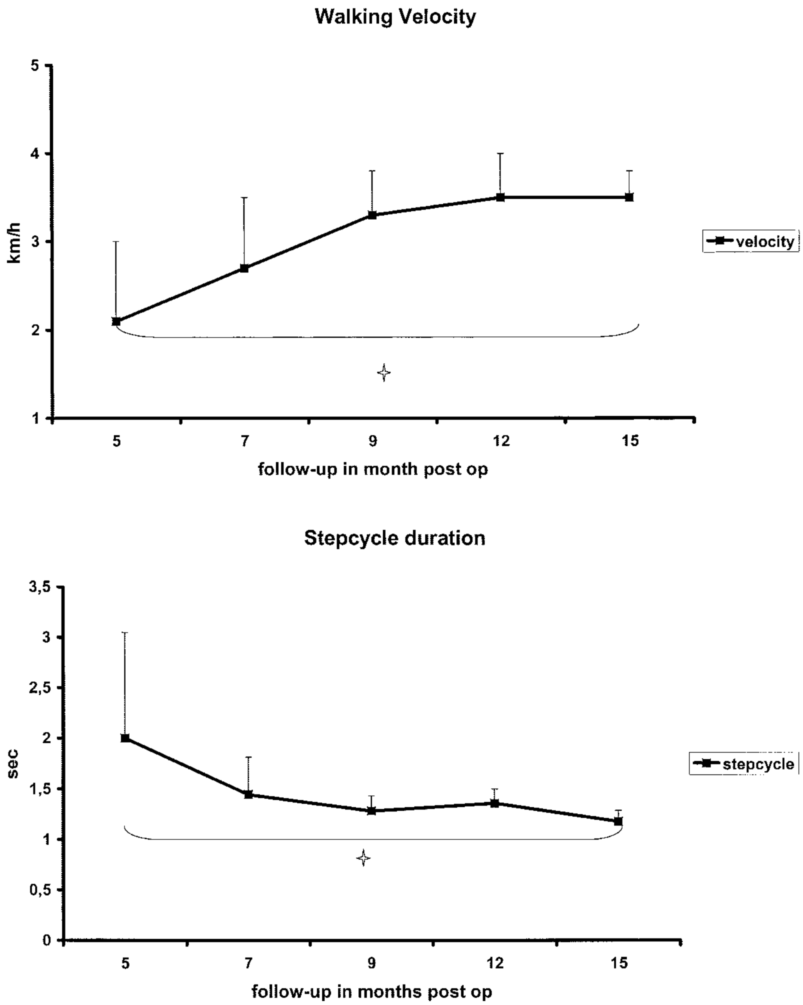


Figure 1: *Top panel*, mean preferred walking velocity and standard deviation of the patient group during the follow-up. ☆Significance between 5 and 15 mo follow-up. *Bottom panel*, mean stride time and standard deviation of the patient group during the follow-up. ☆Significance between 5 and 15 mo follow-up; *post op*, postoperative.

mill; in this way, they find there preferred speed for the experiment. All subsequent trials were performed at the same initial self-selected speed. Patients were allowed to use canes when needed. In the first condition, the subjects walked under optimal and unconstrained circumstances. This condition was necessary to facilitate the collection of reference values. In the second condition, subjects had to walk (with the same walking velocity) while performing an attention-demanding concurrent task (i.e., the auditory Stroop task). In the third condition, the walking took place while vision was restricted by using special glasses with the lower half of both lenses covered so that it was impossible to observe the feet while walking. The fourth condition was identical to the first. This condition was to check whether fatigue or other time-related factors had to be excluded as being responsible for the observed difference in gait performance between the first and second and first and third conditions. Note that during the experiment the patients were allowed to rest when needed.

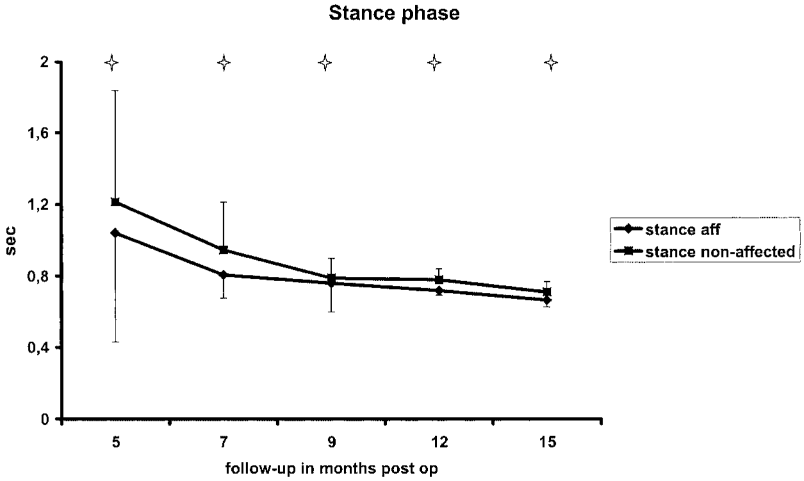
Equipment and Data Sampling. Measurements were made during a time interval of 100 sec while subjects walked on a treadmill (ERGO EL2, Woodway, Bonn, Germany). Very thin, custom-made insole foot switches, placed in shoes, were used to detect heel strikes and toe off. To avoid masking of important features of individual responses, all individual trials and subjects' data were examined before averaging. Each measurement consisted of at least 20 strides (heel strike to heel strike). The variables were averaged over the complete strides. In each condition, the following gait variables were determined: preferred walking velocity, stance duration, swing duration, and stride time. Step variables were calculated and averaged from the foot-switch data.

Statistical Analysis. For the stance phase and swing phase duration, Wilcoxon's test was used to compare the differences between the affected and nonaffected leg in each measurement. Wilcoxon's test was also used to compare the first measurement of velocity and step-cycle duration with the 15-mo postoperative measurement.

Statistical analysis was conducted on the average value of three consecutive identical experiments to reduce intrasubject variability. For each individual, the stride times were analyzed during each follow-up experiment using Wilcoxon's test with normal gait as the first factor and constraints as the second factor (dual task, visual restriction).

RESULTS

Normal Gait. During treadmill walking, the patients used at least one crane, but after 12 mo, none of the patients needed a crane anymore. Figure 1, *top panel,* shows that the patients walked with a preferred walking velocity of 2.1 ± 0.9 km/hr during the first measurement. During the recovery time, their walking speeds increased significantly till the end of the rehabilitation and reached a mean preferred walking velocity of 3.5 ± 0.3 km/hr at 15 mo after surgery. The step-cycle duration changed accordingly, as



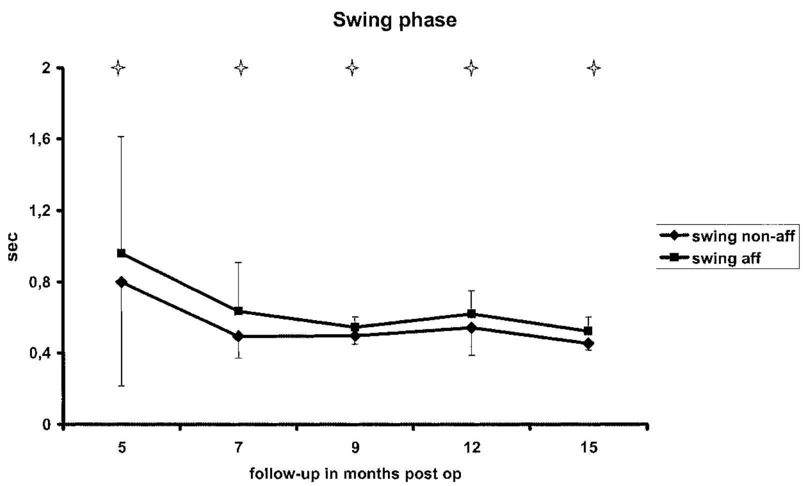


Figure 2: *Top panel*, stance phase of the affected (*aff*) and nonaffected leg and standard deviation of the patient group during follow-up. ☆Significance. *Bottom panel*, swing phase of the affected and nonaffected leg and standard deviation of the patients group during follow-up. ☆Significance; *post op*, postoperative.

can be seen from Figure 1, *bottom panel*. In the first measurement, the step-cycle duration was 2 ± 1.04 sec. At the end of the rehabilitation process, it was significantly decreased to 1.18 ± 0.106 sec. When we take the different treatment modalities into account, the patients with a knee prosthesis walked with a walking speed of 3.9 (SD, 0.15) km/hr and a stride time of 1.15 (SD, 0.05) sec. Patients with a hip prosthesis walked with a preferred speed of 3.4 (SD, 0.23) km/hr and a step-cycle duration of 1.21 (SD, 0.07) sec after 15 mo. Patients with a saddle prosthesis had a walking speed of 2.2 (SD, 1.1) km/hr and a stride time of 1.50 (SD, 0.33) sec.

During the course of rehabilitation, a slight improvement of symmetry was seen; however, some asymmetry persisted after 15 mo in all the patients (Fig. 2). Indeed, all patients showed a shorter stance of the affected leg as compared with the nonaffected leg in all measurements, but the difference decreased over time. For the swing phase, a reversed situation was seen. In all measurements, the swing phase lasted longer on the affected side as compared with the nonaffected side.

Gait Under Constraints. In the fourth measurement (i.e., the normal walking), no significant decrease in step-cycle duration was observed as compared with the normal walking in the first measurement. In contrast with this, the data for each individual in the dual task and restricted-vision condition demonstrated that the stride time decreased under these constraints. This can be seen in Figure 3, *top panel*, in which the stride time in normal walking and walking with the dual task is depicted. This figure makes it clear that this difference persisted during the rehabilitation period but became smaller over time. The decrease in step-cycle duration caused by the dual task was significant in all the measurements ($P < 0.001$ for the first measurement and $P < 0.05$ for the last measurements). Figure 3, *bottom panel*, shows the data of the stride time during normal walking and during the restricted vision condition. The results are similar to the situation seen under dual task involvement. Visual feedback proved a powerful aid during walking, as indicated by the decrease in step-cycle duration under the visual-restricted condition ($P < 0.001$ for all the measurements).

DISCUSSION

We measured a heterogeneous group of patients who were recovering from a resection of a bone tumor and reconstruction with a megaprosthesis at the pelvis, hip, or knee level. Because the surgery changed the peripheral constraints in a rather dramatic way, a reorganization of the central motor control mechanism was necessary. It was hypothesized that as long as this reorganization process is not complete, the system is forced to shift to other strategies, such as conscious control of gait (attention demanding) or visual control of gait. Whether these patients have a central disorder caused by chemotherapy is unknown in this group.

In this study, the patients were required to perform the same motor task, namely, walking at their pre-

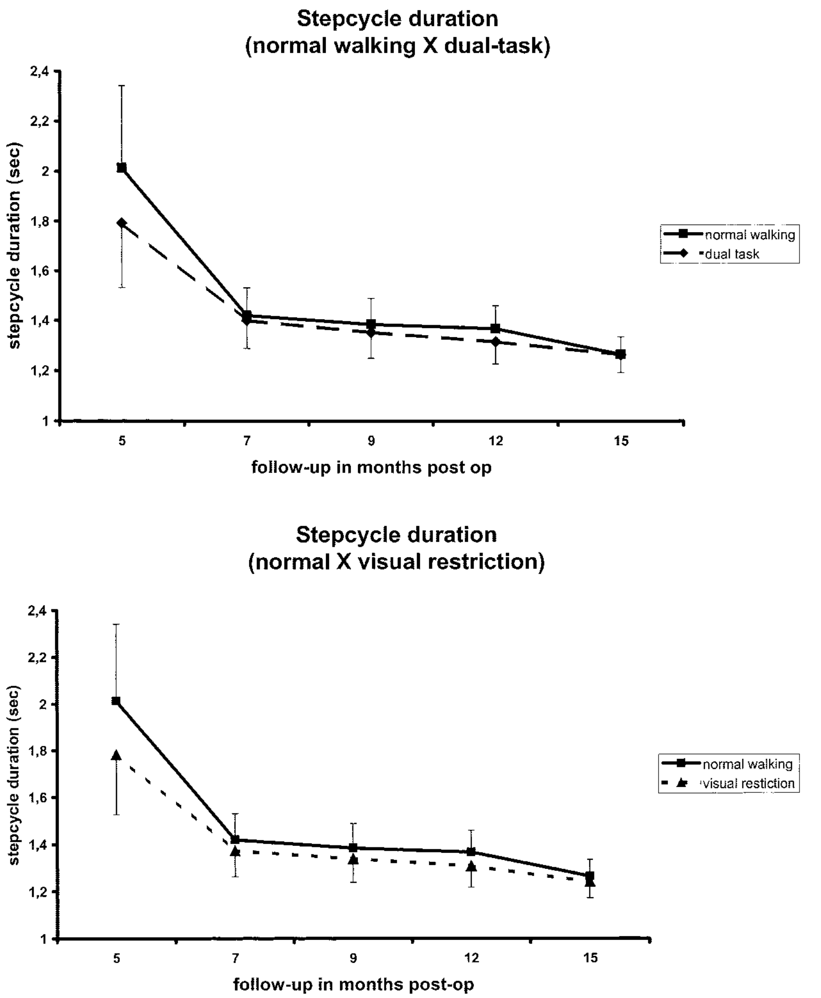


Figure 3: *Top panel*, mean stride time and standard deviation during normal walking and under dual-task are depicted for all the patients during follow-up. *Bottom panel*, mean stride time and standard deviation during normal walking and during visual restriction are depicted for all the patients during follow-up. *post op*, postoperative.

ferred speed, under different conditions of cognitive load and visual restriction during their course of recovery. These conditions enable us to assess the importance of compensatory strategies across time. In other words, it enabled the investigator to estimate the degree of cognitive and visual involvement in the control of gait and to study whether this involvement changed across recovery time.

In general, the patients had reached a relatively high functional level of performance after 15 mo. This means that they were able to walk with a rather smooth stride. This improved functionality can also be derived from the increment in preferred walking speed and the increase in stride time. Although the numbers are small, it seems that knee endoprosthesis patients were able to walk with a higher preferred walking speed and a lower step-cycle duration than hip endoprosthesis patients. The patients having a pelvic saddle prosthesis had the lowest preferred walking velocity. This could be because of the limited motion at hip level. After the course of rehabilitation, the preferred walking speed is rather low when compared with a normal healthy population (in which it is expected to be around 4.0 km/hr). This is a result of decreases in both cadence and stride length.[7]

Despite the increase in preferred velocity, there were several factors indicating that gait was still not ideal after 15 mo. In these patients, the stance phase of the affected leg was shortened as compared with the nonaffected leg. Tsuboyama et al. studied a similar patient group and showed that asymmetry was caused by a shortened contact phase, decreased peak pressure, and reduced force-time integral during gait on the affected side.[5] Furthermore, a positive correlation was found between load under the foot and isokinetically measured knee extension strength. de Visser et al.[4] found that the stance phase of the affected leg was similar to the stance phase of a normal population and that the stance phase of the nonaffected leg was lengthened. They argued that the nonaffected leg must provide support that lasted long enough to allow the ipsilateral swing to be made. Another important finding was that patients with less asymmetry had more quadriceps muscle mass and higher extension strength.[13] Otis et al. found that asymmetry in the gait pattern after limb-saving surgery leads to a higher net energy cost.[8]

Patients with knee, hip, or pelvis replacements are likely to have different problems and probably require different times to rehabilitate. However, in this study, we showed that all the patients were substantially affected by the dual task. This was reflected in a decreased stride time. These data cannot be explained by fatigue or other time-related factors because repeating the normal walking condition failed to show any change. Furthermore, de Visser et al.[3] showed that normal controls did not change their stride when walking with a dual task or restricted vision. This means that the used dual task and the restricted vision did not cause alteration in the gait of any individual. The fact that attention is involved in motor performance, particularly when the performance is not automated, is suggested in several studies.[3,11,14,15] The results provide

an argument for an influential role of attention-demanding processes during the course of rehabilitation. Dual-task interference may be seen as the result of some competition that takes place within a "general purpose central processing system" that is limited in capacity. An adequate performance of the Stroop task requires the allocation of attention. However, the same is true for the control of gait in the beginning of the rehabilitation period. Later, when walking becomes automated again, the dual-task interference can be expected to diminish. The fact that our results show dual-task interference during the total recovery period indicates that total re-automation did not take place and that the system remains vulnerable.

During the visual-restriction condition, the patients were also unable to walk in the same manner as during normal walking condition. This implies that visual control mechanisms are important to safely maintain gait during the early phase of the reorganization process. These patients need full vision to be able to compensate for their abnormal gait control. Such extra reliance on visual input may be needed to detect body disturbances that are insufficiently compensated by automatic responses because of the lack of somatosensory cues and the loss of output structures on the operated side. Previous studies with respect to the role of vision in human walking showed that there is an important influence of the visual system.[16] Indeed, vision provides the only direct measure of self-motion that is useful for regulating speed of locomotion and steering. In patients with pathology influencing gait, the visual system is necessary to maintain a certain level of gait performance.[3]

In general, the divided attention or the restricted vision resulted in a shorter step duration. If this occurred during ground walking, the gait speed would likely increase. The fact that we see this is based on the constant walking velocity due to treadmill walking. When we perform this experiment on a walkway, the data of the shorter step duration will be lost and changed in both a shorter step duration and a lower walking speed. It is argued here that both values will lose their significance. Its is remarkable that these finding were seen under more complex, real-life conditions, without any awareness of the patients. Under these complex conditions, the patients make shorter steps, with an increased cadence, which leads to more safety during walking. The findings as reported in the present study suggest that patients after limb-saving surgery rely substantially on their visual system and on an attention process to modulate their walking patterns.[3,9] Despite the fact that these adaptive shifts permit the system to remain active and to generate motor activities in a leg with a changed architecture caused by limb-saving surgery, they never are as efficient as the premorbid strategies. The patient had to pay a price to keep the output optimal. Limb-saving surgery creates novel constraints, and these constraints will lead to a breakdown of automaticity because they are unknown to the central nervous system. However, the cost of compensations decrease with time.[12] Our point is that the compensations in the patients last for a certain time and that, in this time, the central nervous system adapts to the novel flow of afferent information from the affected leg. After this, the patient can perform on a higher level, reflected in the higher walking speed. However, because there is dual-task involvement and visual restriction, optimum gait pattern had not been properly relearned, and there is no return to the premorbid automated level of performance. It may be that in these patients, the irreversible damage to the proprioceptive system caused by the joint/bone replacement by a prosthesis and to the muscle resection prevents complete recovery and the return to a normal gait pattern.

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