ORIGINAL ARTICLE

High Failure Rates When Avoiding Obstacles During Treadmill Walking in Patients With a Transtibial Amputation

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ABSTRACT. Hofstad CJ, van der Linde H, Nienhuis B, Weerdesteyn V, Duysens J, Geurts AC. High failure rates when avoiding obstacles during treadmill walking in patients with a transtibial amputation. Arch Phys Med Rehabil 2006;87:1115-22.

Objective: To investigate if and to what extent patients with a transtibial amputation are less successful in avoiding unexpected obstacles while walking than healthy adults.

Design: Experimental 2-group design.

Setting: Dutch rehabilitation center.

Participants: Eleven patients with a transtibial amputation and 14 healthy controls.

Interventions: Not applicable.

Main Outcome Measures: Subjects walked on a treadmill at .56m/s. In 2 series of 12 trials each, an obstacle was dropped in front of the prosthetic or the nonprosthetic leg of the amputation group and the left leg of the control group at different phases during the step cycle. It was noted which avoidance strategy was used (a long step strategy [LSS] or a short step strategy [SSS]) and whether the obstacle was avoided successfully or not. These data were expressed as a percentage of the total number of trials completed by each subject.

Results: With either leg, the amputation group made significantly more errors than the control subjects (prosthetic leg, 24%±17%; nonprosthetic leg, 21%±17% vs 2%±2% for the control group). Highest failure rates were in the amputation group when time pressure was high, requiring an SSS, especially on the prosthetic side. An LSS under time pressure, however, nearly always resulted in failure for both the prosthetic and nonprosthetic legs. Subjects with the longest time since amputation were most successful in avoiding unexpected obstacles.

Conclusions: Under time pressure, patients with a lower-leg prosthesis perform best when they use their nonprosthetic leg as the lead limb in an SSS. The fact that some subjects with the longest time since amputation made no errors suggests that over many years it is possible to relearn the appropriate avoidance reactions sufficiently fast.

Key Words: Artificial limbs; Gait; Leg prosthesis; Rehabilitation.

PATIENTS WITH A LOWER-LEG prosthesis due to a transtibial amputation have no muscle control about the artificial ankle and suffer from absent propriocepsis from the ankle joint and lower-leg muscles, as well as from absent exterocepsis from the foot sole. As a consequence, balance control during standing[1-3] and walking[4,5] may be impaired. In addition, stance time and single support time can be significantly shorter on the amputated side, resulting in shorter swing duration and step length on the sound side.[6,7]

Patients with a transtibial amputation may experience difficulties with unperturbed standing and walking, and especially with avoiding obstacles,[8] which increases their risk of falling. To understand why these patients fall more easily, it is appropriate to study their ability to avoid obstacles. In obstacle avoidance studies involving healthy adults, 2 possible strategies of foot placement are used to avoid stepping on a suddenly encountered obstacle. Subjects can lengthen their normal step to take a longer crossing step; this is called the long step strategy (LSS). The other strategy is to shorten their normal step and take an extra step before crossing the obstacle; this is called the short step strategy (SSS).[9]

There are few obstacle avoidance studies of patients with lower-leg amputation. We found only the studies of Hill et al,[10-12] who investigated patients with transtibial amputations as they walked along a level walkway that had an obstacle at a fixed location. Hill's focus was on whether there is a lead limb preference for avoiding obstacles and whether obstacle height (0–36cm) influences walking speed and kinematics. They found that patients had no consistent lead limb preference when negotiating obstacles.[10] Yet, the toe clearance of either leg had a higher safety margin (10cm) than that found in young healthy adults, irrespective of the obstacle height.[10] In addition, the patients disproportionally decreased their horizontal velocity of the center of mass as the obstacle height was increased.[11] Such adjustments in the walking pattern were possible because the subjects were aware of the obstacle and its position. In these circumstances, there is time to modify the walking pattern to prepare the crossing maneuver. Consequently, the subjects in Hill's study did not touch the obstacles and did not slip or fall.

In daily life, however, obstacles are often encountered suddenly, and this requires fast, somewhat automatic, responses. With this perspective, we addressed the question whether, and under what circumstances, patients with transtibial amputations are less successful in avoiding unexpected obstacles. Because of the higher fall risk in such patients,[8] we hypothesized that they would indeed be less successful than healthy adults in avoiding unexpected obstacles, particularly when under time pressure. Studies have shown that the available response time (ie, the time between obstacle detection and the estimated moment of foot contact with it) is an important predictive factor in successful avoidance reactions. In healthy adults, the success

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rate decreases with decreasing available response time,[13-15] especially in elderly subjects.[13,16] We hypothesized that with decreasing available response time, the percentage of failures of patients with transtibial amputations would increase to an even greater extent than with healthy adults. Furthermore, we investigated whether the number of failures would be dependent on which avoidance strategy was used. Finally, we examined the possible influence of various biologic characteristics on the failure rate.

METHODS

Participants

Patients with a unilateral transtibial amputation who had a high activity level (K3 level[17]) were eligible for the study. A patient with a lower-limb extremity with a functional K3 level has the ability or potential for ambulation with variable cadence. This is typical of the community ambulator who can traverse most environmental barriers and may have vocational, therapeutic, or exercise activity that requires prosthetic utilization beyond simple locomotion. We included only patients who could walk independently on a treadmill without a walking aid, who had had their prosthesis for at least 2 years, who had good visual acuity (if necessary with correction), and perceived good health. Patients with stump problems or morbidity of the nervous or musculoskeletal system were excluded. Power analysis revealed that at least 10 subjects per subgroup should be included. The 7 men and 4 women who participated in the study underwent the same prosthetic gait training at the same rehabilitation clinic both during their rehabilitation after the amputation and each time after a new prosthesis was prescribed. They wore their prosthesis the entire day (see table 1 for subject and prosthetic characteristics). The 14 control subjects (healthy people without lower-extremity amputations) included 5 men and 9 women with a mean age ± standard deviation (SD) of 28.6±11.3 years. Their mean body weight was 68.4±9.9kg and their mean height was 176.7±10.7cm. All subjects gave their informed consent to participate in this study. The experiments were approved by the local Central Committee on Research Involving Human Subjects.

Experimental Setup

Subjects walked on a motor driven treadmill[a] with a walking surface of 2.0m (length) by 0.7m (width). They wore comfortable shoes and a safety harness, which was attached to the ceiling by a spring suspension. At the front of the treadmill a wooden obstacle (40cm [length]×30cm [width]×1.5cm [height]) was attached to an electromagnet (similar to the setup described by Schillings et al[18]). The height of the obstacle was only slightly larger than the minimal toe clearance during unobstructed gait,[19] so that adaptations in stride length were required in combination with minor vertical adaptations. After the electromagnet was switched off, the obstacle fell on the treadmill in front of the prosthetic or nonprosthetic leg of the amputee subjects and in front of the left leg of controls. The latter were tested on the left side only, because obstacle avoidance reactions are similar for both their legs.

Lightweight reflective markers, with a diameter of 3cm, were placed on the most posterior and most anterior end of the foot used to avoid the obstacle (heel marker and toe marker, respectively). A third marker was attached to the closest end of the obstacle. A 6-infrared camera 3-dimensional motion analysis system[b] recorded the position of the markers at a sample rate of 100Hz and these data were stored on hard disk using WinRead data acquisition software.[c] With the heel marker signal, the moment and location of the heel strike could be determined for several successive unperturbed steps, and subsequently we calculated the average stride length. By extrapolating the stride length into the following stride, the computer could predict the moment of the next heel strike and the correct moment for obstacle release was determined.

Protocol

Before the actual experiment was started, subjects were given the opportunity to become accustomed to walking on the treadmill and to become familiar with the experimental proce-

Table 1: Characteristics of the Patients With Transtibial Amputation and Control Subjects

	Sex	Age (y)	Weight (kg)	Height (cm)	Cause of Amputation	Side of Amputation	Time Since Amputation (y)	Prosthetic Socket	Prosthetic Foot
1	F	37	61	162	Traumatic	Left	21	Tec liner	Variflex
2	F	26	53	167	Traumatic	Left	5	Alpha liner	Multiaxial
3	M	48	120	185	Diabetic	Right	3	Alpha liner + sleeve	DER foot
4	M	33	95	188	Traumatic	Right	11	Alpha liner	Multiaxial
5	M	50	105	176	Vascular	Left	3	Alpha liner + sleeve	Multiaxial
6	F	23	55	156	Congenital	Left	7	KBM, Tec liner	Single axis
7	M	44	102	178	Traumatic	Left	25	KBM, Tec liner	Multiaxial
8	M	59	80	192	Traumatic	Right	34	KBM	DER foot
9	M	45	82	186	Traumatic	Right	23	KBM, Tec liner	Multiaxial
10	F	46	62	166	Traumatic	Left	11	KBM, Tec, cord	Variflex
11	M	45	84	177	Traumatic	Right	39	PTB, roll-on socket	SACH
Mean ± SD		41.4±10.7	81.7±22.3	175.7±11.7			16.7±13.0		
Median		45.0	82.0	177.0			11.0		
Control group									
Median		28.3	68.5	176.5					

Abbreviations: DER, dynamic elastic response; F, female; KBM, Kondylen Bettung Münster; M, men; PTB, patellar tendon bearing; SACH, solid ankle cushioned heel; SD, standard deviation.

dure. The walking speed was set at .56m/s for all subjects. This speed is lower than the mean comfortable overground walking speed in patients with leg amputation (range, 0.81±0.33m/s for dysvascular patients to 1.25±0.08m/s for traumatic patients[20-23]). In preliminary experiments, we tested various walking speeds and found that when walking speed was low (.28m/s) it was difficult to maintain a natural walking pattern. When walking at 0.83m/s or 1.11m/s, however, it was difficult to perform all trials without becoming exhausted and to maintain balance after avoiding the obstacle. Therefore, we chose an intermediate speed of .56m/s for our experiments. After the familiarization period, heel and toe markers were placed on both feet. Subjects then walked on the treadmill for at least 2 minutes, during which the position of the markers was recorded to determine relevant stride characteristics. Thereafter, the markers on 1 foot were removed and the actual experiment began. Subjects were told to look at the obstacle and to avoid it by stepping over it after it was released. A regular walking pattern was achieved when the difference in stride duration between 2 consecutive strides was less than 50ms. After 5 regular unperturbed strides the obstacle was dropped in the following stride. In this way, 1 trial consisted of minimally 5 unperturbed strides and 1 perturbed stride in which the obstacle was released. Subjects were told that stepping beside the obstacle would be classified as a failure. They were encouraged to walk unsupported. In the case of balance loss after stepping over the obstacle, however, they were allowed to briefly hold on to a rail at the front of the treadmill. Immediately after they recovered their balance, they walked unsupported again and therefore holding the rail did not interfere with the next trial. This rail was adjusted to each subject's pelvis height. Subjects were instructed to maintain their walking position on the treadmill, that is, prior to release of the obstacle they had to maintain a constant distance between the toes at initial contact and the closest end of the obstacle (≈10cm). In this way, the obstacle could be released at the intended moments in the gait cycle.

The obstacle was dropped in 6 different phases during the step cycle, varying from mid stance to mid swing. These moments were repeated 4 times and randomly divided over 2 series of 12 trials. For the amputee patients, the obstacle was first dropped in front of the prosthetic leg in 2 series of 12 trials each. Subsequently, the same protocol was completed for the nonprosthetic leg. Hence, in the patient group, stepping over the obstacle was examined on both sides of the body. With the control subjects, the obstacle was only dropped in front of the left leg in 2 series of 12 trials.

Data Sampling and Analysis

During the experiment the observer noted which strategy was used (LSS or SSS) and whether the obstacle was avoided successfully (success) or not (failure). The obstacle was successfully avoided if the subject's foot did not touch the obstacle and the subject did not step beside the object. In addition, if the obstacle was touched, we recorded the strategy the subject used. These observations were verified offline by analyzing the changes in marker positions. Using the recorded position of the markers, the phase of the gait cycle in which the obstacle was dropped and the position of the foot were determined. When the foot was placed in front of the obstacle prior to the actual crossing step, the trial was classified as an SSS; it was classified as an LSS if the step in which the obstacle was presented was lengthened to cross the obstacle. The individual failure rates and strategy choices were expressed as a percentage of the total number of trials completed by each subject.

The available response time is an indication of how much time a person has to react after the obstacle is dropped. To calculate that time, we calculated the moment that the toes of the leading limb would have crossed the front of the obstacle if there had been no avoidance reaction. This was done by extrapolating the trajectory of the toe marker. The available response time was defined as the time between this moment and the moment of obstacle presentation (fig 1). The available response times were divided into categories with a range of 50ms each.

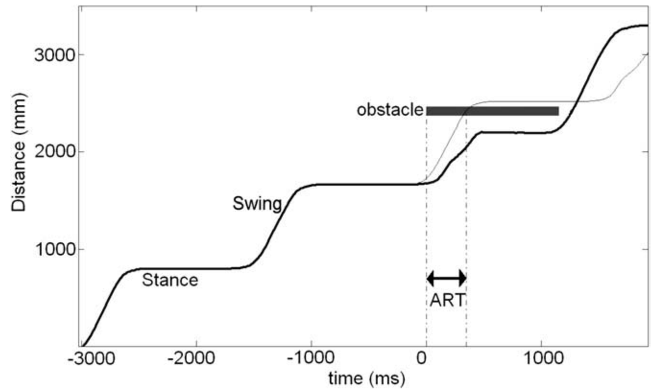

Fig 1. The positions of the toe marker and the obstacle are shown after transformation from treadmill walking to overground walking. The bold line illustrates the actual trajectory of the toe marker; the thin line illustrates the extrapolated trajectory of the toe marker that would have occurred without an avoidance reaction. The grey rectangle represents the obstacle, which started to fall at 0ms. The duration between this moment and the moment at which the *extrapolated toe* would have crossed the front of the obstacle is defined as the available response time. In this trial, the available response time was 350ms and a short step strategy was used to avoid the obstacle. Abbreviation: ART, available response time.

Furthermore, by analyzing the data of the 2 minutes of unperturbed walking, stride characteristics such as step length, stance time, and maximum vertical heel displacement were calculated for both sides of the body.

Statistical Analyses

Three group results were identified in this study, that is, the prosthetic leg and the nonprosthetic leg of the amputee patients and the left leg of the control group. To test for group differences in stride characteristics we used a 1-way analysis of variance. If there was a significant test result, we made post hoc comparisons with the unpaired *t* test. To find an effect of the factor group on failure rates and selected strategies, we used the Kruskal-Wallis test. We used the Mann-Whitney *U* test for pairwise comparisons to show in what way the groups differed. Differences were considered significant when *P* was less than .05.

We used the Spearman correlation coefficient to assess the relation between the available response time and the failure rate, as well as to find any effect of age, height, weight, and (for the amputation group) time since amputation on the failure rate.

RESULTS

Every subject performed all trials safely without becoming exhausted. There were no missing values.

Stride Characteristics During Unperturbed Walking

Because there were no significant differences in the values of the left and right leg in control subjects, only the data of the left

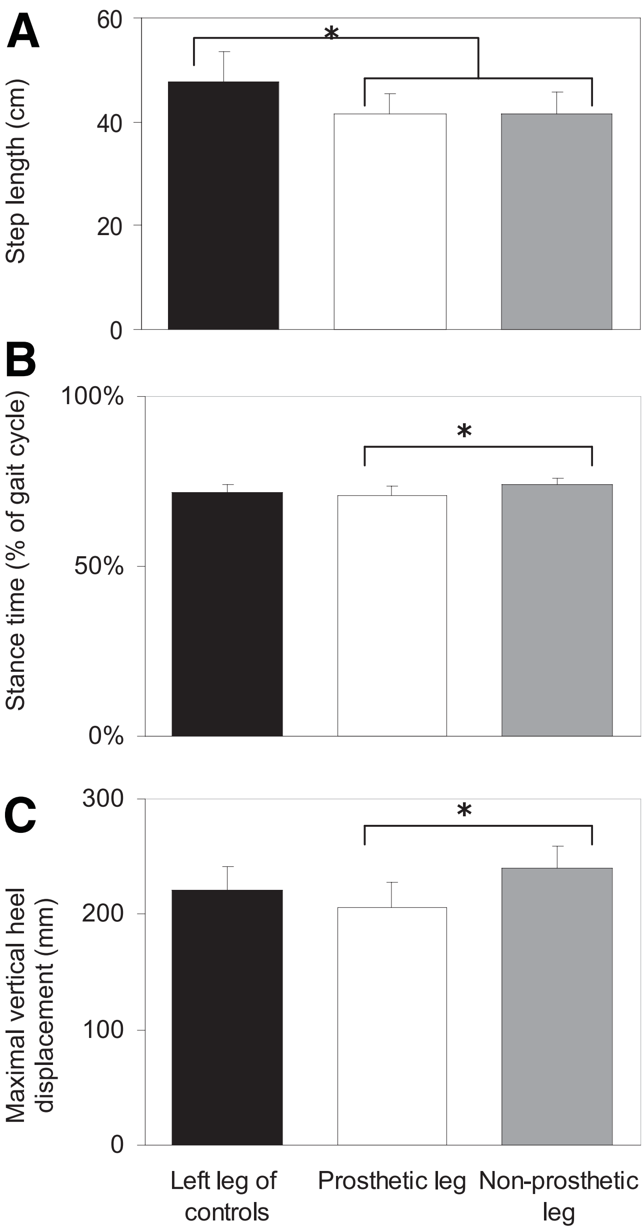

Fig 2. Mean ± SD (A) step length, (B) relative stance time, and (C) maximum vertical heel displacement for the left leg of the control group, and for the prosthetic and nonprosthetic legs of the amputation group. *P<.05.

leg are presented and compared with either leg of the patients using a prosthesis.

Step length was significantly larger for the controls (47.7±5.8cm) compared with the amputation group (41.5±4.2cm and 41.5±4.1cm for the prosthetic and nonprosthetic leg, respectively) ($F_{2,33}$=4.9, P<.05) (see fig 2A). Relative stance time in the control group was 72%±2% of the stride duration. Relative stance time, that is, the percentage of the gait cycle that the foot was in stance phase, was significantly longer with the nonprosthetic leg (74%±2%) than with the prosthetic leg (71%±3%) ($F_{2,33}$=4.04, P<.05) in the amputee patients (see fig 2B). Maximum vertical heel displacement was 221±20mm in the control group (see fig 2C). The maximum vertical heel displacement of the prosthetic leg (206±21.7mm) was significantly smaller than that of the nonprosthetic leg (240.5±19.0mm) ($F_{2,33}$=7.86, P<.01). There were no significant differences between the control group and the amputation group in relative stance time and vertical heel displacement.

Failures

The mean percentage of failures during the obstacle task was 2%±2% in control subjects (fig 3A), whereas it was significantly higher in the amputation group. For the nonprosthetic leg it was 21%±17% (z=−3.57, P<.001) and for the prosthetic leg 24%±17% (z=−2.69, P<.01).

Failure rate in the amputation group was dependent on the available response time, shown in figure 3B. As available response time was increased, the percentage of failure trials decreased significantly, both for the nonprosthetic leg (ρ=−.97, P<.001) and the prosthetic leg (ρ=−.86, P<.001). In contrast, failure rates in the control group were low in all available response time categories (ρ=−.38, P<.10).

On average, the amputee patients clearly preferred the LSS with their prosthetic leg (58.3%±23.3%), but not with their nonprosthetic leg (48.5%±22.7%), whereas controls used the LSS in only 43.9%±21.1% of the trials (fig 4A). This group effect, however, did not reach significance. For either leg of the amputee patients, both strategies showed significantly

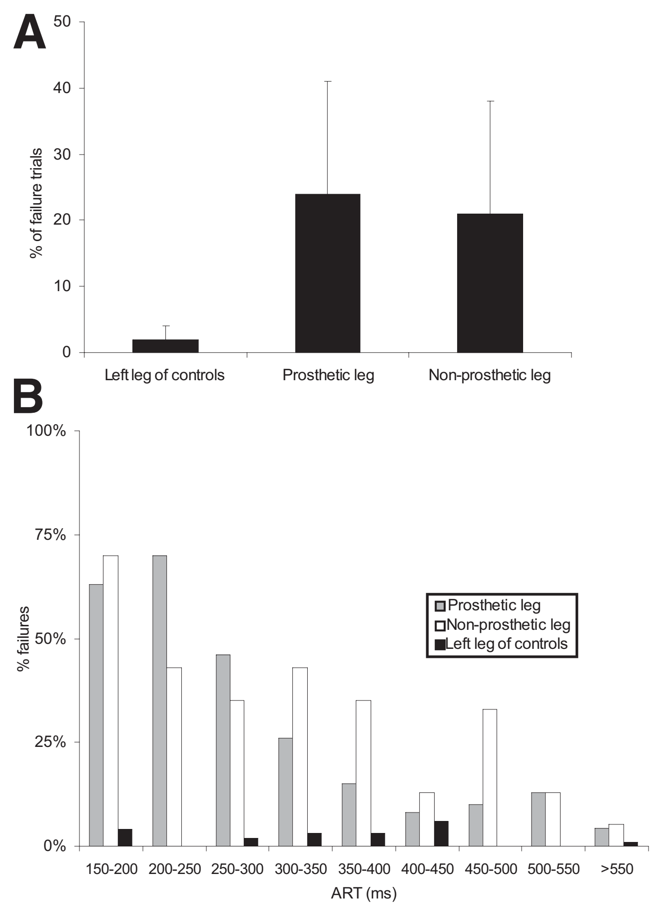

Fig 3. (A) Mean ± SD percentage of failures for the left leg of the control group and for the nonprosthetic and prosthetic legs of the amputation group. (B) Failure rates per available response time category for the left leg of the control group and for the 2 legs of the amputation group.

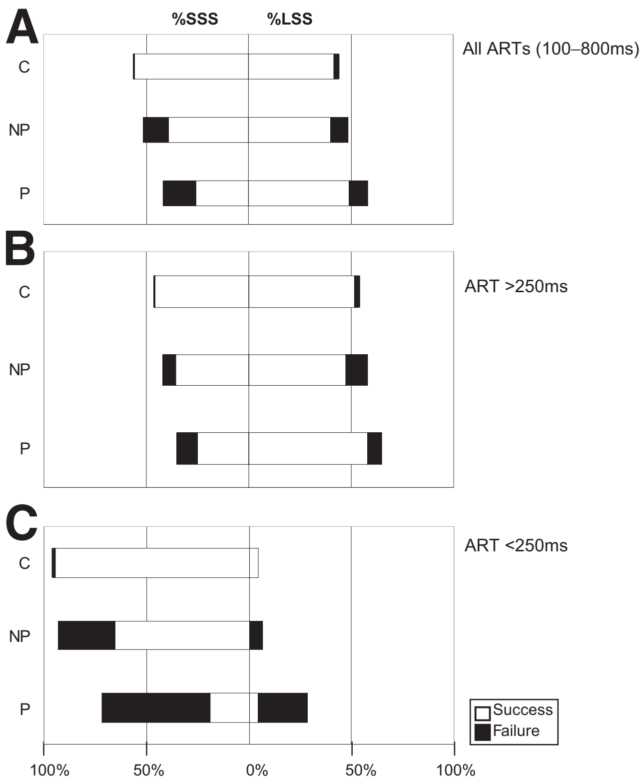

Fig 4. The mean percentage of total shortening (left side of the graphs) and lengthening steps (right side of the graphs) for the control leg (C) and for the nonprosthetic (NP) and prosthetic (P) legs. The black parts of the bars indicate the mean percentages of failures. (A) All available response time categories (range, 150–800ms); (B) the trials with available response times higher than 250ms; and (C) the trials with available response times lower than 250ms.

higher failure rates compared with controls. Although there was no significant effect of strategy choice, the highest mean failure rate was observed with the prosthetic leg and the SSS (15.8%±14.6%).

When considering only the trials with high time pressure (available response time <250ms), controls almost completely shifted toward using the SSS. There was a similar shift to SSS in the amputation group that was somewhat more pronounced for the nonprosthetic leg than for the prosthetic leg. Failure rates were much higher, however, for both the nonprosthetic leg and the prosthetic leg compared with controls ($z=-2.06$, $P<.05$; $z=-4.21$, $P<.001$, respectively). Patients occasionally used the LSS when under time pressure, but nearly all of these resulted in a failure for both legs.

Patient Characteristics

For the prosthetic leg, the time since amputation correlated significantly with the failure rate ($\rho=-.645$, $P<.05$) (fig 5). None of the remaining variables showed a significant correlation with the failure rates of the left leg in the control group or with the failures made by either leg in the amputation group.

DISCUSSION

In this study, we investigated if and under what circumstances patients with a transtibial amputation are less successful in avoiding unexpected obstacles while walking than are healthy adults. It appeared that for both legs the failure rates of these patients were significantly higher than they were for healthy controls. This result is in line with the higher fall risk in patients using a leg prosthesis reported by Miller et al.[8] They found that compared with other patient populations, falling among community-dwelling patients with a leg prosthesis was at the high end of the reported incidences. In a sample of 435 patients with either transfemoral or transtibial amputation (mean age, 62±15.7y), nearly 53% reported having fallen in the past year, compared with 30% to 40% among community-dwelling elderly,[24] and 50% among institutionalized elderly.[25]

There were also abnormal failure rates during similar obstacle avoidance tasks in patients with stroke,[26,27] Alzheimer's disease,[28] and even in healthy elderly with a recent history of falling.[29]

Influence of Available Response Time

Patients with a lower-limb amputation were very sensitive to time pressures, which was reflected in disproportionally high failure rates with either leg in the case of short reaction times (available response time <250ms). Even with long reaction times (available response time >500ms), they contacted the obstacle more often than did healthy controls. Apparently, even when under low time pressure, it is difficult for patients using a leg prosthesis to adapt their stepping pattern to avoid the obstacle successfully, irrespective of the leg used to cross the obstacle. During the swing phase of unperturbed walking in healthy subjects, the lower leg acts largely as a pendulum rotating about the knee.[30,31] To avoid an unexpected obstacle, this pendulum must be accelerated or decelerated quickly, which requires strong activations of upper leg musculature such as the quadriceps and hamstrings muscles. For lower-leg amputee patients, such a fast and strong adjustment of the swinging prosthesis may be troublesome because the thigh muscles in the prosthetic leg gradually lose their strength[32,33] and volume.[34,35] Furthermore, the reported thigh muscle atrophy may contribute to the already impaired stance-phase control on the prosthetic leg.[7] This deficit in prosthetic leg stance control is likely to affect the swing of the nonprosthetic leg as well, since the prosthetic leg is presumably unable to generate sufficient ground reaction forces to counterbalance the necessary avoidance reactions on the contralateral (nonprosthetic) side.

Strategy Selection

In the control group, failure rates were very low with both SSS and LSS, irrespective of the available response time.

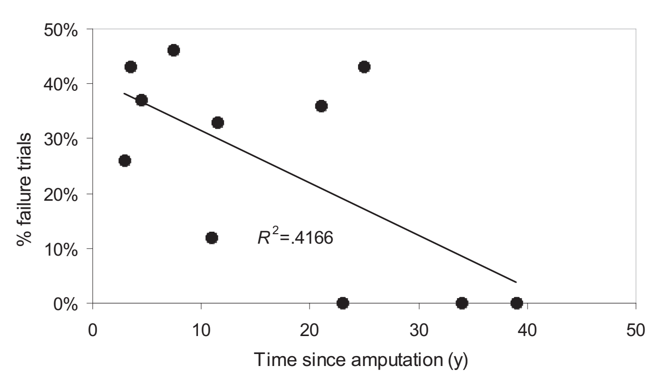

Fig 5. A scatterplot of the failure rate against the time since amputation for the prosthetic leg of the amputation group.

Apparently, healthy subjects are well able to modify their gait pattern within the time frame of 1 step,[14] even when under high pressure timewise. In the amputation group, failure rate was also not dependent on the selected strategy for either leg when available response time was longer than 250ms. In all instances, the mean failure rate was between 9% and 15%. This result is similar to that reported by Hill et al,[10] who found no consistent lead limb preference among subjects with a lower-leg prosthesis when anticipating obstacles without time pressure. Together, our results and those of Hill imply that the complexity of avoiding obstacles under low or no time pressure in people with a lower-leg prosthesis does not depend on the leading limb or the strategy selected. A different picture emerged, however, from the trials when subjects were under high time pressure (available response time <250ms). The control subjects clearly showed that under such circumstances shortening the step of the swinging limb, followed by a crossing maneuver, is the preferable response strategy. This is in line with Patla's minimal foot displacement criterion[36]; when the alternative landing area of the foot must be chosen in the line of progression, subjects are likely to use the stepping strategy that minimizes the amount of foot displacement relative to the normal landing area. With lower available response times, less alterations in gait trajectory are necessary when using the SSS compared with the LSS. The SSS appeared very difficult for either leg in the amputation group, but most particularly for the prosthetic leg. The failure rate increased up to 28% for the nonprosthetic leg and to 54% for the prosthetic leg, accounting for a substantial proportion of all errors. Still, the SSS was the best response under time pressure for patients with an amputation as well, given the fact that failure rates approached 100% when they used the LSS with either leg. Hence, it can be concluded that under time pressure, patients with a lower-leg prosthesis perform best when they use their nonprosthetic leg as the lead limb in the SSS, using their prosthetic leg to provide postural stability. This conclusion would imply that for the prosthetic leg a fast postural adjustment during the stance phase is not as complex as a fast kinematic adjustment during the swing phase. This notion suggests that an SSS under time pressure depends on highly automated sensorimotor responses that are not easily reacquired by patients who must acquire walking skills with a leg prosthesis.

Time Since Amputation

Remarkably, no errors were made by 3 of the 5 subjects who had used a lower-leg prosthesis for more than 20 years after a traumatic transtibial amputation (subjects 8, 9, 11; see table 1). One of these subjects was 59 years old. In general, there was a substantial association between failure rate of the prosthetic leg and time since amputation, yielding an explained variance of more than 40%. These findings suggest that although balance and gait characteristics are disturbed because of the amputation,[1-7] it is possible to relearn the appropriate avoidance reactions sufficiently fast, although this may take many years and may only be true for otherwise healthy subjects. A relevant question is what these results could mean in general for the rehabilitation of subjects with a transtibial amputation, including patients with vascular problems. Although this study did not provide definitive answers to this question, it seems appropriate to try to improve the performance of SSS responses under time pressure of all subjects with a lower-leg prosthesis to enhance their gait safety under complex conditions. Although such a strategy may be less difficult to execute using the nonprosthetic leg as the lead limb, it is probably best to teach SSS responses with the prosthetic leg as well, because under time pressure there is often no possibility to select the leading limb. In general, it seems useful to train patients who have just undergone leg amputation in how to avoid obstacles, in much the same way as those programs that are currently used to reduce the fall incidence in elderly with a history of falls, by creating a "natural" environment with several types of obstacles,[37] sounds, and other sources of distraction.[38]

Study Limitations

A possible limitation of our study may be the difference in mean age between the amputation and the control group (41y vs 29y, respectively), which can perhaps partly account for some of the group effects. Yet, in a study by Den Otter et al,[27] in which the same experimental setup and walking speed were used, there was a mean failure rate as low as 0.5% in a control group that was much older (age range, 54−73y) than our control group. With the same experimental setup, but with a slightly higher walking speed (.83m/s), Weerdesteyn et al[29] showed that within a group of healthy elderly (65−88y) the failure rates of a subgroup of people 65 to 69 years old were not different from those of young adults (20−37y). In our study, it appeared that the more experienced prosthesis users, who were more successful in avoiding unexpected obstacles, were older than the less successful patients. Hence, we can conclude that the higher failure rate in the amputation group while walking at .56m/s is mainly because of the amputation itself, and not by the (relatively small) age differences between that group and the control subjects.

Also, there was not a similar proportion of men and women in the groups. Schultz et al[39] found that in obstacle avoidance tasks that were time critical but did not have high strength requirements, women were not notably more at risk for injury than were men. Therefore, it is not plausible that the sex difference between the groups might influence the failure rates.

Many factors could have influenced the failure rate in this study. Stride characteristics (eg, walking speed, step length), prosthetic mode, prosthetic training, a history of having fallen in the past, and the time since amputation are factors that could interfere in one's ability to avoid obstacles. Hence, in this study, overall homogeneity within the amputation group was preserved by our most important inclusion criterion: a high activity level (K3 level), indicating that all our subjects were excellent prosthesis walkers. Consequently, the other group's characteristics (age, cause of amputation, prosthetic mode, stride characteristics) had a relatively limited influence on the homogeneity within that group.

Another possible limitation of this study is the limited ecological validity of walking on a treadmill compared with normal level walking.[40] Consequently, one's gait pattern and way of avoiding obstacles may not be the same as the movement strategies applied in daily living. An important reason why the experiments were performed on a treadmill was that the gait assessments were standardized, that is, walking speed was kept constant, and the obstacles could be released at fixed moments during the gait cycle. Moreover, the distance between the subject and the obstacle could be kept constant, requiring subjects to adjust their stepping pattern within short time windows, which added an element of time pressure that proved to be an important risk factor. The drawback to these methodologic advantages is that gait was presumably more symmetrical than when walking over ground. Improved symmetry during treadmill walking has indeed been reported for various lateralized disorders.[41-43] As a consequence, differences in behavior between the nonprosthetic and prosthetic legs while making avoidance reactions may have been influenced by an improved symmetry of the basic gait pattern, although it is not readily

predictable in which direction this influence may have played a role in individual subjects.

CONCLUSIONS

Patients with a transtibial amputation had much higher failure rates than the controls when avoiding unexpected obstacles while walking on a treadmill. Although this was true for all available response times, the group differences in failure rates were most prominently attributable to the trials with high time pressure (available response time <250ms). Under these circumstances, the SSS is preferable because the swinging limb must be quickly decelerated to make ground contact to be able to safely cross the obstacle during the next step. Although it appears to be difficult for patients with a lower-leg prosthesis to initiate the SSS with either leg, crossing the obstacle with the nonprosthetic leg seems somewhat easier than with the prosthetic leg. Subjects who had walked with a leg prosthesis for more than 20 years made no errors at all. This finding suggests that learning to make fast avoidance reactions with both the nonprosthetic and prosthetic legs is a worthwhile effort for patients with a transtibial amputation in order to reduce their fall risk.

In future research, it may be useful to investigate the correlation between the history of falls and the failure rate while avoiding unexpected obstacles on a treadmill. In this way, the obstacle avoidance task could be used as an assessment tool to identify potential fallers.

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Suppliers

a. Type EN-tred Rea; Enraf-Nonius Nederland, Postbus 810, 2600 AV Delft, the Netherlands.
b. Precision Motion Analysis System, Delft University of Technology, Postbus 5 2600 AA Delft, the Netherlands.
c. WinRead 1.55; HLJ Software created by Hans van Veenendaal. Available at: HansvanV@hq3.sega.co.jp.